THE STATISTICAL PROPERTIES
OF EXTRAGALACTIC
RADIO SOURCES

by

Anthony Hooley

Clare Hall

Cambridge

Submitted for the Ph. D. degree

June 1976
To Elspeth
Acknowledgements.

Many people have helped directly and indirectly in the effort to produce this dissertation. Special thanks are due to Malcolm Longair, my supervisor, for his continued assistance, advice and encouragement, without which this thesis would not have been completed. Various members of the laboratory have confided their radio astronomical thoughts to me, in particular Julia Riley and Philip Hargrave. John Hartley provided much technical and practical assistance with the photographic reductions of the maps for the big morphology diagram of Chapter 6; Stuart Birnbaum assisted in the processing of the photographic prints and provided invaluable help with some cocoa — I thank them both. Helen Kiefer punched much of the early manuscript onto IBM cards and kept me sane during the period of maximum effort. To her I am truly grateful. I am indebted to Edward Kibblewhite who deserves mention for the patience and understanding he has shown to his would be employee. The Cambridge Computer Laboratory are to be thanked for their continual helpful assistance with all aspects of the computing. I am grateful to the SkC for a research studentship which supported me for most of this work and to the Cavendish Laboratory for their
contribution. Lastly, I wish to thank all my friends for their tolerance, and their collective encouragement to finish the job.

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration.
"To be conscious that you are ignorant of the facts is a great step to knowledge."

Benjamin Disraeli
1804—1881
## CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter 1</strong></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Why a Computer Data System?</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Brief Historical Note</td>
</tr>
<tr>
<td>1.2</td>
<td>Necessity of a Computer Data System</td>
</tr>
<tr>
<td>1.3</td>
<td>The Computer Data System</td>
</tr>
<tr>
<td>1.4</td>
<td>Astronomical Investigations</td>
</tr>
<tr>
<td><strong>Chapter 2</strong></td>
<td>Design of an Automatic Data Storage and Analysis System</td>
</tr>
<tr>
<td>2.1</td>
<td>Data-Base</td>
</tr>
<tr>
<td>2.2</td>
<td>Data Storage Technique</td>
</tr>
<tr>
<td>2.3</td>
<td>Nature of the Stored Data</td>
</tr>
<tr>
<td>2.4</td>
<td>Updating the System Files</td>
</tr>
<tr>
<td>2.5</td>
<td>File Security</td>
</tr>
<tr>
<td>2.6</td>
<td>Sample Selection</td>
</tr>
<tr>
<td>2.7</td>
<td>The Program Control System</td>
</tr>
<tr>
<td>2.8</td>
<td>Data Retrieval</td>
</tr>
<tr>
<td>2.9</td>
<td>Tabular Output</td>
</tr>
<tr>
<td>2.10</td>
<td>Miscellaneous Organisational and Operational Commands</td>
</tr>
<tr>
<td>2.11</td>
<td>Some General Notes on the Command System</td>
</tr>
<tr>
<td>2.12</td>
<td>The Logging System</td>
</tr>
<tr>
<td><strong>Chapter 3</strong></td>
<td>A Representative Sample of Radio Sources</td>
</tr>
<tr>
<td>3.1</td>
<td>New Observations with the 5Km Telescope</td>
</tr>
<tr>
<td>3.2</td>
<td>Selection of a Representative Sample</td>
</tr>
<tr>
<td>3.3</td>
<td>Summary of the Observations of the Representative Sample Made by the 5Km Telescope</td>
</tr>
<tr>
<td>3.4</td>
<td>Identifications</td>
</tr>
<tr>
<td>3.5</td>
<td>Results of the Survey</td>
</tr>
<tr>
<td>3.6</td>
<td>General Statistical Properties of the Sample</td>
</tr>
<tr>
<td>3.7</td>
<td>Conclusion</td>
</tr>
<tr>
<td><strong>Chapter 4</strong></td>
<td>Radio Source Structure, Clusters of Galaxies and the Complex Sources</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>4.2</td>
<td>Selection of a Complete Sample of Bright Radio Galaxies</td>
</tr>
<tr>
<td>4.3</td>
<td>Source Sizes and Cluster Membership</td>
</tr>
<tr>
<td>4.4</td>
<td>Source Morphology and Cluster Membership</td>
</tr>
<tr>
<td>4.5</td>
<td>Cluster Membership</td>
</tr>
<tr>
<td>Page</td>
<td>Section</td>
</tr>
<tr>
<td>------</td>
<td>---------</td>
</tr>
<tr>
<td>4.6</td>
<td>Conclusions</td>
</tr>
<tr>
<td>4.26</td>
<td></td>
</tr>
<tr>
<td>Chapter 5</td>
<td>The Statistical Properties of Extragalactic Radio Sources</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>5.2</td>
<td>The Complete Sample</td>
</tr>
<tr>
<td>5.3</td>
<td>Angular Scales</td>
</tr>
<tr>
<td>5.4</td>
<td>Morphological Types</td>
</tr>
<tr>
<td>5.5</td>
<td>The Distribution of Structural Types</td>
</tr>
<tr>
<td>5.6</td>
<td>Central Components</td>
</tr>
<tr>
<td>5.7</td>
<td>Quasars and Radio Galaxies</td>
</tr>
<tr>
<td>5.8</td>
<td>Subclasses of Double Sources</td>
</tr>
<tr>
<td>5.9</td>
<td>The Distribution of Optical Types</td>
</tr>
<tr>
<td>5.10</td>
<td>Relationships between the Properties of the Components of Double Sources</td>
</tr>
<tr>
<td>5.11</td>
<td>The Brightness of Radio Components</td>
</tr>
<tr>
<td>5.12</td>
<td>Luminosity, Linear Size and Redshift</td>
</tr>
<tr>
<td>5.13</td>
<td>Component Size and Separation</td>
</tr>
<tr>
<td>5.14</td>
<td>Conclusions</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>The Morphology of Powerful Extragalactic Radio Sources</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>6.2</td>
<td>Technical Considerations</td>
</tr>
<tr>
<td>6.3</td>
<td>Features of the Scaled Diagram</td>
</tr>
<tr>
<td>6.4</td>
<td>Conclusions</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>The Angular-Diameter-Redshift Test for Quasi-Stellar Radio Sources with Large Redshift</td>
</tr>
<tr>
<td>7.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>7.2</td>
<td>The Data</td>
</tr>
<tr>
<td>7.3</td>
<td>The Results</td>
</tr>
<tr>
<td>7.4</td>
<td>Comparison with other Work</td>
</tr>
<tr>
<td>Chapter 8</td>
<td>Theories of Extragalactic Radio Sources</td>
</tr>
<tr>
<td>8.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>8.2</td>
<td>The Evolutionary Phases of Radio Sources</td>
</tr>
<tr>
<td>8.3</td>
<td>Variations of Observable Parameters with Source Age</td>
</tr>
<tr>
<td>8.4</td>
<td>The Luminosity-Size Diagram</td>
</tr>
<tr>
<td>8.5</td>
<td>The Compatibility of a Specific Model with Observational Evidence</td>
</tr>
</tbody>
</table>
Conclusions

References

Appendix I 9.1 The RADARS User Manual
9.4 Contents of the Manual

Appendix II 10.1 HPP User Manual
CONTENTS

Chapter 1 Why a Computer Data System?

Chapter 2 Design and Implementation of an Automatic Data Storage and Analysis System

Chapter 3 A Representative Sample of Radio Sources

Chapter 4 Radio Source Structure, Clusters of Galaxies and the Complex Sources

Chapter 5 The Statistical Properties of Extragalactic Radio Sources

Chapter 6 The Morphology of Extragalactic Radio Sources

Chapter 7 The Angular-Diameter-Redshift Test for Quasi Stellar Sources with Large Redshift

Chapter 8 Theories of Extragalactic Radio Sources

References

Appendix I RADARS User Manual

Appendix II HPP User Manual
PREFACE

The work described in this dissertation was carried out at the Mullard Radio Astronomy Observatory between 1971 and 1976. It is concerned principally with the application of electronic data processing (i.e., digital computers) to large bodies of radio-astronomical data. My purpose has been to produce a first generation tool for use by radio astronomers. I hope that this first attempt to assemble a cohesive body of data in machine readable form will demonstrate its usefulness sufficiently to encourage a more comprehensive approach as the quality of data improves and the quantity increases. Much work has gone into the production of a system that is reliable, flexible and easy to use, and nearly as much into writing a detailed manual for would-be users (see Appendix I). The availability of such a system and manual is not necessarily sufficient to coax astronomers into using it. The work of chapters 3, 4, and 5 was almost exclusively done using the system and I hope the results presented there will indicate the potential capabilities of automated data systems. However, I have only touched on the whole range of studies that might be carried out with such a system.
The studies of Chapters 3 and 4 were begun at the suggestion of my supervisor, Dr. M. S. Longair, but their development is my own work. The morphological study of Chapter 6 was something I had wanted to do almost since first joining the laboratory. However, the sparseness of available material deterred such a project until late in 1974 by which time the 5Km Telescope had produced many beautiful maps of previously unresolved sources. The ideas of how best to present the map data took some time to gel and were heavily dependent on the available photographic technology. I believe the final outcome, a 5 x 12 foot diagram of radio sources reduced to a common linear scale, to be sufficiently informative to justify the time spent in its production. The work of Chapter 7, an analysis of the angular diameter - redshift information for complete samples of quasars, was suggested by Dr. M. S. Longair, my supervisor, and will form the basis of a publication later this year. No originality is claimed for the theoretical models described in Chapter 8 though the interpretations of the data, expressed there, are thought to be new and are my own ideas.

It was originally hoped to present nearly all the diagrams in this dissertation as unretouched computer output from the RADARS system. Unfortunately the print contrast was generally poor and very unreliable and most have had to be
Appendix II describes HPP, a sideline application of computers to research generally. HPP is a program designed by the author that aids the rapid production and modification of printed matter. It was used to print this dissertation and is now in use by many other people inside and outside the Cambridge Astronomy Departments. Several dissertations already submitted, and many papers, have been produced using the program, an indication of its usefullness.

The following abbreviations are frequently used in the text and are conveniently collected here.

OMT = One Mile Telescope
5Km = Five Kilometre Telescope
WSRT = Westerbork Synthesis Radio Telescope
VLBI = Very Long Baseline Interferometer
LBI = Long Baseline Interferometer
MKN = MacDonald, Kenderdine & Neville (111)
KPN = Kellerman, Pauliny-Toth & Williams (134)
CCC = Compact Central Component (of a Double radio source)
3CR = Revised Third Cambridge Catalogue of Radio Stars
Notation

FORTRAN-like E-notation is generally used to denote numbers with exponents of 10.

\[ \text{e.g. } 1.73 \times 10^{-6} = 1.73E-6 \]

(This is typographically much more convenient)

** is used to denote exponentiation

\[ \text{e.g. } A + B \times C = A + \frac{b}{C} \]

\[ \uparrow \text{ is sometimes used to denote exponents within physical dimensions} \]

\[ \text{e.g. } \frac{W}{Hz} \uparrow^{-1} \text{ sr} \uparrow^{-1} = \frac{W}{Hz} \text{ sr}^{-1} \]

(The author feels that a unit for luminosity is long overdue)

References are given a unique 3-digit number, underlined and enclosed in parentheses. These are collectively listed at the end of the main body of the text, but before the Appendices.

The computer-generated annotation on many of the figures was lost in the photographic reduction process. Where of direct relevance, the annotations have been enlarged by hand. Illegible annotations are of no direct consequence in this dissertation.
Radio Astronomy is a very young field, its origins going back no further than the Second World War when scientists working on Radar and radio communications discovered signals in their equipment which could not be explained by any terrestrial sources. Since that time enormous advances have been made in observational equipment culminating in sophisticated 'automatic' instruments such as the Cambridge 5Km telescope ('the 5Km') and more recently in the Very Large Antenna (VLA) system now being constructed in the U.S.A.

The use of these large synthesis telescopes was made possible through the development of the high speed digital computer in the late 1950's and early 1960's. These are able to perform in a reasonable time the complex repetitive calculations necessary to convert the interferometer output signals into sky brightness distributions, using the Fourier Transform. Instruments such as the Westerbork Synthesis Radio Telescope (WSRT), a development of the original Cambridge One Mile Telescope (OMT) with 12 separate antennae
and enough receivers to operate at 36 spacings and two
frequencies simultaneously are now capable of producing
prodigious amounts of data.

1.2 Necessity of a Computer Data System

Although the development of synthesis instruments has
been very closely linked to that of digital computers,
little use has been made until now of the computer for
storing, collating and analysing the data. When only the
OML was operational and a 64-spacing map required 64 days
observing time, the problem did not really arise as it took
far less time to analyse the results than to produce them.
Today there exists a large body of data generated over ten
or so years by the OML, together with much new information
from the 5Km and other telescopes. For a comprehensive
analysis, we must incorporate all the available optical data
as well since this can give us a most important piece of
information not readily obtainable from radio observations,
the distance of the radio source. Moreover, new data become
available every day and to keep up to date one's 'data bank'
without recourse to some form of automation is fast becoming
an impossible task.

Of particular interest for this dissertation is the
enormous increase in detailed information on extragalactic radio sources (ERS) that has resulted from the operation of synthesis telescopes. The complementary development of optical image tube equipment and the development of the IIIaJ emulsion has also contributed to our knowledge of the fainter radio galaxies and has made possible many new identifications. One subset of the ERS that has been extensively studied in the radio and optical wavebands is the 3CR complete sample (Longair & MacDonald, 1969 [113]) selected from the Third Cambridge Catalogue of Radio Stars (3CR) (Bennett 1962, [121]).

To the radio astronomer wishing to make statistical studies of ERS this "information explosion" is clearly very welcome. However, when undertaking any particular investigation, difficulties arise because the data on the sources (optical, radio, X-ray etc.) are scattered throughout the literature, some (particularly the optical) over a period of many years, and to attempt even a fairly simple analysis in a comprehensive manner has proved to be a formidable task. This being the case, most investigations have been undertaken only when there seemed likely to be a reasonable chance of a positive result, and many others just not done at all because the high probability of a null result simply did not justify the amount of effort
necessary.

Also, during the period of the investigations, new results might become available and to incorporate these at a late stage would involve a large amount of recalculation, and also perhaps a second literature search to obtain the other data for the sources to be included (e.g., the optical data, such as redshift). On completion of any investigation the collated data was effectively lost as far as other workers in the group were concerned leading to much duplication and waste of effort.

This being the case, and because the author was involved in such statistical investigations from the beginning of his research, he concluded that what was needed for this sort of work was a computer data system that could readily be interrogated and updated at will, as soon as any new results became available and be used for such analyses whenever an investigation was suggested, no matter how unlikely the outcome of a positive result. Such a system would ensure that nothing that was at all possibly worthy of study would be disregarded through lack of available time or effort.
1.3 The Computer Data System

The author set about designing such a system, the outcome of which is RADARS (Radio Astronomy Data Analysis and Retrieval System), a large computer program which together with its system-files fulfils most of the needs of such a system. The program is the end-product of about 3 man-years of equivalent commercial programming effort, and has been extensively modified throughout its short life to comply more exactly with operational needs. It has been much utilised in the author's research and also has provided a data service to other members of the authors department.

Chapter 2 describes in detail the requirements of such a system, how effectively RADARS fulfils these requirements and also describes the shortcomings and limitations, some of which are imposed by the constraints of disc-file size, core size and rate of processing in the c.p.u. of the computer used, and also the limited time available for writing more extensive programs.

Whilst the initial design of the program was being formulated, the author undertook a comprehensive literature search for data on the 3CR sources. Some of the optical
identifications go back as far as 20 years and since no complete list appeared to exist, one was produced which has been kept up to date since its creation. Since little of the important radio data became available until the OMI went into operation the majority of the work involved tracking down optical identifications, galaxy types, colours, cluster data and quasar confirmations, and also rationalising the data where several sources contradicted each other. Optical and radio variability measurements, VLBI and LBI observations of the very small sources, polarisation data and lunar occultation studies of the sources were also included in the search. Not all the information gleaned from the literature has been included in the computer system, partly because of storage considerations and partly because of its sparseness and inhomogeneity, but it is all recorded in indexed form and could easily be incorporated by others if required.

Another extremely useful document that has resulted from this study is a 3CR ‘source-manual’ in which all the synthesis maps of 3CR sources ever made have been gathered together complete with LBI, solar occultation and pencil beam observations where synthesis maps give insufficient resolution due to small source size or their low declination. A subset of the data on the computer files is
also kept alongside the maps and the manual has been extensively referred to by other workers in the authors laboratory. Lastly a continuously updated set of source sheets containing all system-stored information on each source, and property sheets (one for each of the stored properties of every source) have been available and used both by the author and his co-workers.

1.4 Astronomical Investigations

Chapter 3 describes the selection of a nearest 'representative' sub-sample of the 3CR complete sample and the results of observations made on this sample with the 5Km telescope. Because telescope time on a big instrument such as the 5Km is at a premium, it is important to try to glean the most information from the smallest number of observations. By choosing a set of sources whose properties effectively spanned the whole of the range found in 3CR, but which were the nearest such subset, we have attempted to gain the greatest physical resolution of these sources. In this way one hopes to obtain more insight into the structure of radio sources than would be possible by simply resolving more simple-doubles at greater distance than before. Secondly, in order to be able to plan future telescopes one needs to know now if there are still many structures unresolvable by present state-of-the-art instruments, and
clearly this sort if information can only be gained by looking at the nearest of each type of object.

Chapter 4 describes an investigation into the relationship between radio source structural properties and cluster membership. The work was originally performed to check the reality of the result of De Young 1972 (A22) who noted a correlation between source size and cluster membership. This was clearly important for source theories and so was worthy of some depth of reinvestigation. The results of the work were published in Hooley 1974 (A22) and since that time we have updated the analysis to include the latest data from the 5Km. telescope and some other work on clusters of galaxies, notably that of Karachentseva 1973 (A46). We also used our data to extend the analysis to other properties of radio sources in and out of clusters and in particular we investigated the differences between complex and non-complex sources, since it was suspected at that time, that complex sources were preferentially in clusters of galaxies.

In Chapter 5 we describe the overall properties of the 3CR complete sample ("the complete sample") using all the latest high-resolution map data and the recent optical
identifications of workers such as Kristian, Sandage & Katem 1974 (323), Strittmatter (private communication) and Longair & Gunn 1975 (366), as well as a few other less extensive works. We review the general properties of powerful radio sources found by McKay 1971 (114) and Fomalont 1969 (260) in the light of our higher resolution data and investigate some other trends in the data. We draw particularly heavily on the observational papers of MacDonald, Kenderdine & Neville 1968 (110), MacKay 1969 (111) and Elsmore & MacKay 1970 (112) who made observations with the DMT at frequencies of 408 and 1407 MHz; Branson et al 1972 (205), Mitton & Ryle 1969 (115) and Mitton (1970a, 1970b, 1970c (203, 204, 206)); Riley & Branson 1973 (306), Riley 1973 (401) who used the DMT at 2.7 and 5.0 GHz and on the papers of Pooley & Henbest 1974 (450), and Riley & Pooley 1975 (456) which report the latest observations with the 5 Km telescope at 5 GHz. In a few cases we use as yet unpublished map material but rarely will we deal with individual sources in the following work.

In addition we make a careful study of observational selection effects and how they affect our statistical work. We suggest ways to circumvent the problems, with particular reference to the RADARS facilities and exploit the flexibility of the sampling procedures.
A study of the unidentified sources attempts to explain the observational reasons for their continued non-identification in spite of recent deep surveys of blank fields, such as that of Longair & Gunn 1975 (366) which reached to between 23^m 5 and 24^m. We make speculative guesses as to their distances and optical identifications based on the available radio and optical data. We note that as recently as 1974, a new 3CR quasar was discovered (Wills & Wills 1974 (443)), namely 3C66A (3C66.01 in our notation, explained in the text); in this case the long delay between an accurate radio position becoming available and the optical identification was partly due to some spurious photometric data being attributed to the object, after which it was for some time believed to be a star. One wonders in how many other cases this type of confusion may have arisen. This work is included in Chapter 5 because the identification of radio sources is a process intimately bound up with observational selection effects and thus general statistical properties.

The general morphology of extragalactic radio sources is a topic that has been largely neglected in the past. In Chapter 6 we attempt to show that much information is
inherent in the ensemble of observed structures, that is not easily retrievable by studies of individual objects. We feel that morphological studies have met with little success until now partly because of lack of material to work with but mainly because of the mutual incompatability of the map data in raw form. We have transformed the set of maps of 3CR sources into directly comparable format by photo-reduction to a constant linear scale of 50 Kpc/inch. The resulting source maps, when orientated to some standard position, and spread out on the P-D (luminosity - size) plane, display many collective features that had remained hidden until now. It is unfortunate that the small number of maps in any given region of this overall picture is inadequate to fully substantiate the hypotheses proposed to explain their structural distribution. None the less, we feel that this analysis technique has a lot to recommend it, and hope that the results of this first attempt will inspire others to perform more comprehensive morphological analyses as more data become available.

We branch into cosmological studies in Chapter 7. Using a technique analogous to Schmidt's V/Vmax (Schmidt 1968 (253)) procedure, we use observations complete to a limiting flux density 50 Jy to predict the angular size distribution that would be observed at limiting flux density
S1 Jv, (S1<50) as a function of world model. Since we have observational data on two complete samples of quasars at flux densities of 10Jv (3CR) and 2.5Jv (4C) we are able to show that world models with density parameters =0.1 are consistent with observation and no longer show the deficit of large sources at high redshift first reported by Miley 1971 (041). We also further investigate the apparent tendency for source luminosity to be inversely correlated with source linear size, noted earlier in Chapter 5.

The relevance of our statistical and morphological observational studies to theories of extragalactic radio source mechanisms is the subject of Chapter 8. We briefly review the broad features predicted by current source theories and then discuss the compatibility of particular predictions with observational facts. It should be noted that radio source theory is not yet well advanced, and none of the available theories is sufficiently detailed to be capable of making definitive statements, open to direct observational test. Rather, they are still struggling to remain compatible with a few observational limits on optical and X-ray luminosity. This being the case, we content ourselves largely to stating those features that a viable theory must be able to explain.
The first Appendix is a User Manual for the RADARS computer data system. It describes the detailed structure of the data files and the operation of the system. It is intended to be read as a stand-alone document and thus to some extent overlaps the contents of Chapter 2. However, it is phrased in a much more pragmatic manner and is largely composed of example material and tables of factual information about the command and data structures. Amongst the subappendices of Appendix I may be found a user-oriented description of the plotting routines, and a short description of the simple statistical tests used by RADARS.

The references for the whole dissertation have been collected together in one section in number order. The numbers are in fact the RADARS system information reference numbers; many of the latter references are to specific data items and are not referenced directly in the text, and so do not appear in the list presented here. Thus the reference list is in numerical order but will contain gaps. This does not detract from the ease with which any particular numerical reference may be located (if it is present)
CHAPTER 2

Design and Implementation of an Automatic Data Storage and Analysis System

This chapter describes the design and implementation of a computer data system for radio astronomical data. Appendix I is a User Manual for the system and should be freely referred to, to clarify operational aspects of the system not described in detail in Chapter 2.

2.1 Data Base

The principal design consideration is the choice of the subset of ERS to be studied with the system, as this determines the size of the data base, and thus the amount of storage needed and, to a large extent, the length of time taken to perform any particular operation on the data. It would clearly be desirable to have a machine which could digest any amount of information on any number of radio sources, and reproduce it on demand in some desired format. However, practical considerations make this form of system out of the question, and one has to decide how best to compromise between width of study, and the development of a working system in a finite time on a commercial computer. Scanning the literature, one discovers that of all the
catalogued radio sources, only for a very small percentage
is much known other than position and flux density (at one
or more frequencies). Although this information is
sufficient for source counts it is entirely inadequate to
make a significant contribution to knowledge of
extragalactic radio source theory, which is the primary aim
of our studies.

The best sources of structural information on ERS are
observations with synthesis telescopes and it is this
structural information which gives rise to the great
unsolved problems of extragalactic radio astronomy.
Clearly, then, we want to try to include in our system all
those sources studied with high angular resolution as these
will have the most structural information at their
respective redshifts. Most observational effort on ERS with
the Cambridge One Mile Telescope (and lately with the 5km
Telescope) has concentrated on sources in the 3CR catalogue
which lists the 328 brightest radio sources in the northern
sky. Because of the enormous range of intrinsic luminosity
of celestial radio objects 3CR contains some very nearby
objects and some of the most distant ever observed, together
with a broad scatter in between. For this reason, from the
information point of view, 3CR seems a good choice to start
with, as 300 objects is quite a reasonable sample-size for
statistical purposes, and only a relatively few objects not in 3CR have been observed with such resolution as to make them relevant to our studies.

The sample has not, however, been observed with the same angular resolution because of the manner in which the Cambridge synthesis instruments work (and latterly, the Westerbork Synthesis Telescope too). Relying on earth rotation to move the antennas of the telescope around the synthesised aperture means that the synthesised beam varies as cosecθ in declination. Thus for example, at the north pole, the 5Km telescope has beamwidth 2 x 2 arcsec, at 30 degrees, 2 x 4 arcsec and at 0 degrees, no resolution at all in declination.

Use of all 3CR would impose observational inhomogeneity on the data due to such resolution effects, which would be difficult to take account of in any particular statistical test and for this reason it has been suggested (Longair & McDonald, 1969, Mackay 1971) that only the region north of declination 10 deg. be used being a compromise between good resolution and the elimination of too many sources from the sample.
Another problem is that radio angular-structure data on several sources are not directly comparable, without some knowledge of the distance of the sources, since it is the physical structure that is to be explained. At present there is no known method of reliably estimating the distance of an ERS purely from radio data. The 21cm hydrogen line can only be detected in nearby galaxies, much closer to the Earth than powerful radio galaxies and so the only available way is via an optical identification, for which a redshift may be measured, or at least an optical magnitude used as a rough distance indicator. Throughout the present work we have assumed that the redshifts of radio galaxies and quasars are reliably and consistently related to the distances of the objects, and for the sake of convenience we have computed a distance assuming an Einstein-de Sitter world model ($\Omega=1, \Lambda=0$). Since no object in our sample has (as yet) a measured redshift $'z'$ greater than 3, (and most have $z<1$), changing the model would only slightly affect the parameters derived from the distance estimates. Where only an optical apparent magnitude measurement is available, we have taken advantage of the fairly well defined redshift-magnitude relation for radio galaxies to estimate a redshift and thus a distance.
We can learn much more if we have an optical identification. Sources lying near the plane of the Galaxy are often subject to heavy obscuration due to Galactic dust and this introduces further observational inhomogeneities into the data which ought to be avoided if possible. Longair & MacDonald and Mackay therefore suggested that only sources with $|b| > 10$ deg. be used for statistical work. When one imposes these two limits (declination $> 10$ deg. and $|b| > 10$ deg.) on the sources in 3CR one is left with approximately 200 sources, known hereafter as the 'complete sample'. However, our 'complete sample' is not exactly the same as Mackay's for reasons explained later.

The above considerations also favour the use of 3CR as the data-base for our system, because an intense effort has been made over the past ten years to identify the 3CR sources using the most powerful optical telescopes. Identifications for this are now believed to be complete down to a limiting apparent magnitude of 19.5 to 20. All the 3CR source positions have been carefully examined on the Palomar Sky Survey (PSS) plates and prints, and because of the detailed structural information available from the synthesis radio telescopes it has been shown that the probability of correct identification has been high, when an optical object has been visible. Studies of the PSS-3CR
'blank' positions with larger telescopes than the 48-inch Schmidt, and in particular, with the 200-inch Hale telescope, have been undertaken and are now quite near to completion (Kristian, Sandage & Katem 1974 (393), Longair & Gunn 1974 (366), Spinrad, private communication). Using image-tube techniques these latter studies have placed a lower limit of approximately $23.5\text{ m}$.5 on some of the 3CR 'blank' field positions. These sources are classed as 'unidentified' and may be associated with very distant galaxies, or intrinsically faint optical objects. They are studied further in chapter 5.

Such reasoning led to the choice of 3CR as the set of sources to be included in the system files, with particular emphasis laid on the 'complete sample' subset for detailed statistical tests. For completeness, all 3CR including galactic objects, was included in the files but the data on galactic sources were not used in extragalactic studies.

2.2 Data Storage Technique.

A second important consideration, related to the first, is how many parameters per source are to be held on the files. This number multiplied by the size of the
data-base determines the number of words of storage to be used to hold all the data and so clearly it must be chosen carefully as either there will be too little information stored or insufficient machine to handle it. The 5km Telescope was not producing maps when this work was started and the majority of available information was contained in Papers I, II and III (by MKN, Elsmore and Mackay, and Mackay) from observations with the One Mile Telescope at 408MHz and 1407MHz. Yet to come were the analysed maps made at 5GHz with the OMT. The wealth of detail in some of the 5km maps is not found in most of these older maps, and so at that time there was less necessity for a large number of parameters per source to be chosen. Since it was desirable to be able to expand the file system by a small amount without any program modifications, space was initially allocated for 400 sources (328 of which were used for 3CR sources). An initial number of 25 parameters per source was chosen, and this implied storage of a total of 400×25 = 10,000 data words. Since the data had to be gathered from the literature and punched onto cards by the author, even this seemed a somewhat formidable task at that time, and also an adequately large choice. Other considerations relate to the machine on which the system was to run, the University of Cambridge IBM 370/165 which has 32-bit words and is byte oriented. 1 byte of 8 bits is the smallest addressable piece of storage and a 32-bit word can hold a 7
digit real number. On this machine, a job running in less than 120K(bytes) of main storage will be classified as a quick job if it runs for less than 5 seconds, giving very acceptable turn-round time and low charging for the job. Since it was realised from the outset that the program itself would need to use a large amount of storage, it was felt desirable to keep the data stored in the main-store minimal. 10,000 words implies 40,000 bytes, and with buffer space necessary for file reading and writing there is already little room for the program.

Yet another consideration relating to the data storage is the following. When performing operations such as comparison of two sources or selecting samples of sources (a most important operation, as discussed later) one wants to know about all the properties of one source. However, when for example plotting one property against another for a particular sample of objects, one needs to know about the two properties for all sources. Since the system had to be easily expandable it seemed inappropriate to rely on main-storage for holding all the data because core-store is always at a premium and is 'expensive'. Disc-files are the obvious choice and are much more suited to mass-storage as envisaged here (especially for an expanded version). Their one main drawback is that they are serial-stores and not
random-access like a core-store array. This means that if we store all the properties of each source, one source after another, then we can readily perform operations on individual objects involving all of their properties simultaneously (as for example when choosing a set of sources for a sample, on the basis of some function of their properties), but it is very inefficient when performing operations on single properties (such as printing tables, sorting, or plotting) as we have to read right through the file for just the one property. The converse is true if we store the data serially by property rather than by source.

Two steps were taken to alleviate this problem. The first was to make use of an IBM FORTRAN feature called the Direct Access File. This is a piece of software incorporated in the FORTRAN compiler which makes the disc files look random-access by block rather than like a long serial 'tape' that has to be read sequentially. A description of the difference between a normal disc file and a Direct Access File (DAF) is helpful here. When reading or writing a conventional file it is presented to the program as a sequential chain of words and when the end is reached (on reading), nothing more can be done until it is rewound. Reading or writing as far as some arbitrary position within
the file implies that only the following sections may be accessed without a REWIND instruction. One has to continuously 'remember' how much of a file has already been read and pass this information to every subprogram that accesses it. It is also very time consuming when reading and writing in random order to sections of the file. A DAP on the other hand, is only accessible by BLOCK (a certain fixed number of words, defined by the programmer) but the blocks themselves may be accessed in any order whatsoever, without having to consider the current position of the file pointer. Further, if it is known in advance, which block will be needed next, an instruction may be given to 'FIND' that block, and this rather slow operation (by central processing unit (cpu) standards) may be carried out whilst the cpu is busy performing the intervening section of program (before the next READ instruction). This is clearly both a time saving feature and also a great help in writing concise programs.

One has to make a compromise here as to what size of block to use - too small a block means many read/write operations which are time consuming, too big a block means that one isn't saving much main store by filing the data onto disc. Notice also that DAP's will not in themselves help with the problem of accessing the data both by property
and by source. However, because of the relative ease of access of DAF's and also because of the economy of speed in access, it becomes quite feasible to use two DAF's, one holding the data in source order, and one in property order, and after performing any write operations (all on one of the two files) a subprogram is invoked which copies one file to the other. This latter is, in itself, a relatively slow process for the very same reasons that suggest the use of the two files, though fortunately it is an operation that is only infrequently needed.

It will be seen, therefore, that use of the two DAF's solves two problems simultaneously: viz. the access by property-order and by source-order, and also the reduction in main storage requirements. We now only need to hold in main-store one block from each of the two files and in general only one of these will be in use at any time, allowing the use of the other block store-space as work-space. This is the solution adopted in RADARS and it has shown itself to be a very satisfactory way around the problems. The duplication of disc file is not too serious a problem as each file is only approximately 4 tracks in length (one track on the IBM 2250 disc files being approximately 13 Kbytes) and disc space is not as scarce as main (core) storage. A further advantage of this arrangement
is that if the files need to be enlarged, this may be done simply by increasing the number of blocks in the DAF's, the block sizes remaining the same, and thus only a minimal amount of programming is necessary, and there is no increase in the main-storage requirements. Such an increase in file size was found to be necessary after the first year of existence of RADARS and the system now holds up to 50 words of data on each source. Each DAF is thus about 8 tracks in length.

2.12 Nature of the Stored Data.

It is frequently useful when selecting a sample for statistical work to have at least some knowledge of the observational homogeneity of the sample-members, and it was felt necessary to include in the files information such as which radio telescopes had observed each source and at what frequencies. Optical observational details are also important since these determine the magnitude completeness-limit of the sample. Since the source can only be observed or not-observed by a given telescope at a given frequency, a 'value' of '0' or '1' may be attached to the source corresponding to a particular observational description, and it would be grossly uneconomical to use a whole word of store (32 bits) to hold such a two-valued datum. The machine, being byte-oriented, does not lend itself easily to incorporation of binary storage from a
FORTRAN program and therefore to avoid such inefficient storage, a coding technique has been used to pack 15 bits of binary information into one word. Two of the stored properties for each source are of this binary type, allowing a total of 30 different yes/no types of information to be held on each source, together with 48 other properties. Each of the 30 binary properties may be interrogated individually for use as sample selection criteria. The method used to store structural descriptions, both optical and radio is as follows. When studying radio sources it is useful to know roughly what type of structure is present - for example, whether the source has two compact components well separated from the optical object, with a central component coincident with the nucleus of the optical object, or whether it is, say, unresolved. This is non-numerical information and no simple (meaningful) means of mapping this data onto the real-line, or even the real-plane exists, as we do not yet have sufficient knowledge of the creation, evolution and extinction of sources to be able to 'order' them in any particular way.

We are thus faced with the task of storing brief descriptions of sources on the files so that we can choose for investigation, say, all 'simple-doubles' associated with E-galaxies, with the minimum of effort. Certain letters of
the alphabet are used as mnemonics for appropriate key-words (e.g. 'D' for 'Double', 'T' for 'Triple') and each source given an (up to) three-character description, where the position of the characters also has significance. For example, a source listed as type 'T' would mean that it was a 'Triple' (three components, approximately colinear, with the central of the three being approximately coincident with any optical identification), whereas the second 'T' in type 'TT' would mean 'Tails' (i.e. that the outer components had extensions on them). The first character of the triplet is the primary classification, the second usually denotes some feature of the components, and the third is generally an additional description of the whole source. A full description of the classification scheme may be found in Chapter 5 in the section 'Morphological Types'.

Since there are many easily remembered key features of radio source structures describable by one word, this scheme works well. The computer however is inefficient in handling alphanumeric characters and real numbers within the same programs and to avoid the necessity of writing special programs for all operations involving descriptive properties, a subprogram is dedicated to encoding the characters on input to the system, by converting each character combination into a unique real number like any
other datum, upon which the system may operate. A further subprogram is used on output to decode the description, to make it user-readable.

This process is used on two data types, radio structural type and optical type, the latter having a different set of keywords for its descriptions (e.g. 'U' in radio-type means 'Unresolved', whereas in optical-type it means 'Unidentified'). Many radio structural features are also either present or not-present and so are amenable to binary storage as previously described, and one of the two binary-property words on each source is used to hold such structural data, all of which again may be used for sample selection.

Another consideration is how to label data that is not entirely 'reliable' in some way — for example, it may be only an upper or lower limit on some value; it may simply be very poorly determined; it may only be an estimate (e.g. a redshift estimated from a magnitude rather than directly measured); or it may be a value derived using such an estimate or limit. In RADARS, use has been made of the fact that most of the data to be handled has only positive meaningful values (e.g. angular or physical sizes) and thus
other datum, upon which the system may operate. A further subprogram is used on output to decode the description, to make it user-readable.

This process is used on two data types, radio structural type and optical type, the latter having a different set of keywords for its descriptions (e.g. 'U' in radio-type means 'Unresolved', whereas in optical-type it means 'Unidentified'). Many radio structural features are also either present or not-present and so are amenable to binary storage as previously described, and one of the two binary-property words on each source is used to hold such structural data, all of which again may be used for sample selection.

Another consideration is how to label data that is not entirely 'reliable' in some way - for example, it may be only an upper or lower limit on some value; it may simply be very poorly determined; it may only be an estimate (e.g. a redshift estimated from a magnitude rather than directly measured); or it may be a value derived using such an estimate or limit. In RADARS, use has been made of the fact that most of the data to be handled has only positive meaningful values (e.g. angular or physical sizes) and thus
a negative sign prefixing a datum may be used to indicate that the data is not known with precision. This avoids the need to use a second word of store related to every data word to hold 'quality' information on the data, and thus avoids doubling the store size. One could take the approach that only high quality data should be included, but this would reduce greatly the size of samples available for analysis, and also would throw away a lot of information. Where properties (such as absolute magnitude or spectral index) may meaningfully take a negative sign, the signs are retained and no attempt made to store poor quality data for these types. Fortunately, in practice, this throws away very little information. System programs which make use of the negative tags for labelling poor data have available to them a table of those property types for which the negative sign is not an indication of poor quality data.

Where no information at all is available for a certain datum its value is set identically to 0.0 and all such occurrences are ignored during graphical display operations so as not to distort the best scales for the data values present. Where a datum has an actual value of 0.0 to the precision of measurement (e.g. a spectral index) its value is stored as some small negative or positive quantity, (to avoid confusion with null data), chosen small enough to
avoid significant error.

2.4 Updating the System Files:

A system of the kind being described, to be useful, must be simple to update (i.e. to add/delete or modify stored information) as only in this way can errors be corrected, and the data held be an up to date representation of one's knowledge of radio sources. Secondly, the data system must be robust, and to some extent self checking so that errors are not produced by operator carelessness. Lastly, it should be as automated as possible so that all operations to be performed on reception of new data are done without further intervention from the user. These latter tasks are to produce a new data card, store the new data in both the DAF's and finally to recompute all the properties whose derivations are dependent on the new data. For example, one of the source properties on file is the overall angular size of the sources and when this is updated a new value of physical size may be computed, if a redshift or distance estimate exists.

It might be felt that such derived properties could be
computed as and when needed, and not stored at all. This approach was considered but rejected for the following reasons. First, a large number of the derived properties are physically more meaningful than the directly observable quantities and are thus more important for analyses of the set of sources. In operation this means that their values are frequently required, and thus a lot of otherwise unnecessary computations would have to be carried out if their values were not available from file. Also, some of the dependencies are relatively 'deep' in the sense that a property may be derived from another, which in turn is a function of some third, and so on. A good example of this is property #24 in the files, 'P-5GCENT', the central component luminosity at 5 GHz. To compute this, one needs a flux density at 5 GHz \( (#35, = 'S5GCENT') \), a spectral index \( (#47 = 'ALPHCENT') \) and a redshift \( (#04 = 'Z') \). However, to obtain the spectral index one needs the component flux density at two or more frequencies and so the updating system computes a value of 'ALPHCENT' when it has newly available to it a value of 'S5GCENT' and a value of the central component flux density at 1400 MHz \( (#34 = 'S14CENT') \). Furthermore, if a measured value of the redshift is not available, a value has to be estimated from the magnitude of the identification (if that is available) \( (#05 = 'MV') \) and the latter may have to be corrected for galactic obscuration if it lies close to the plane of the Galaxy (Sandage 1974, 446) according to the
2.19

stored value of galactic latitude (#19 = 'BII') for the source. Last of all, the relationship between redshift and magnitude used to make the estimate is dependent on the optical nature of the source (#01 = 'OPT.TYPE') and the updating system in fact checks whether the source is a galaxy or quasar before doing the computation.

The above example demonstrates the advantages of performing such conversions automatically. To make such derivations possible all the necessary data for the sources in question must be in main store simultaneously and this is not always possible within the environment of many of the command operations that require the derived data values. The updating system is designed in such a way as to make this data so available without exceeding main-storage limitations, and to do so with the minimum possible read/write operations to disc.

2.5 File Security

The robustness of a data system is a function of its resistance to accidental corruption. Safeguards are incorporated into RADARS to prevent certain types of
stored value of galactic latitude (#19 = 'BII') for the source. Last of all, the relationship between redshift and magnitude used to make the estimate is dependent on the optical nature of the source (#01 = 'OPT.TYPE') and the updating system in fact checks whether the source is a galaxy or quasar before doing the computation.

The above example demonstrates the advantages of performing such conversions automatically. To make such derivations possible all the necessary data for the sources in question must be in main store simultaneously and this is not always possible within the environment of many of the command operations that require the derived data values. The updating system is designed in such a way as to make this data so available without exceeding main-storage limitations, and to do so with the minimum possible read/write operations to disc.

2.5 File Security

The robustness of a data system is a function of its resistance to accidental corruption. Safeguards are incorporated into RADARS to prevent certain types of
deliberate 'corruption', but those are only designed to thwart mistaken attempts at file modifications and not to compete with the 'determined-wrecker', a task which is all but impractical on a 'public' machine such as the Computing Service's IBM370. Accidental file corruption could occur in several ways: e.g. by inputting 'old' (out of date) data cards; by overwriting stored data from a FORTRAN subprogram with access direct to the files; by mispunching data cards; by inputting invalid data cards; by 'labelling' the data incorrectly on input (i.e. by telling the machine incorrectly what the data is, that is being read in).

Many problems associated with file corruption have been alleviated (and in some cases completely eliminated) in RADARS by the use of the rule: 'one datum, one card'. This might sound a little extravagant, but in practice most cards will only be repunched infrequently. This technique also reduces greatly the punching effort involved in filing data because of the format of the data cards. Each property-type is held on a separate deck of cards, one card per source. Punched on each card are: i) the source name (e.g. 3C465); ii) the source number, an internal file number which generally increases with 3CR number but with one or two exceptions; iii) the code number of the data type on this deck (e.g. '05'); iv) the description of the data type (e.g.
The optical magnitude:\n\nvi) the value of the data;\n
vi) the date of input of the card into the filing system and\n
vii) the data-source reference number. Because the cards are\nstored in decks of one property, it is possible to have the\ndata-cards prepunched with all information on them except\nthe data value, the date and the reference number. This\nmeans that each card is uniquely labelled in such a way that\nits labels are readable equally easily by user and by\nmachine because of the duplication of names and numbers.\nAlso very important is the fact that shuffling (usually\naccidentally, by dropping) a deck of cards containing many\nsources' different data types does not destroy the labelling\nattached to each datum, and the machine can sort out the\nshuffled data with ease.

Use of a program-card on a standard keypunch allows\nthe cards to be fed through the punch and the punch set to\nthe data field automatically; a push on the 'skip' key will\nthen transfer punching to the reference number field and the\nnext card will be fed, and set to the data field,\nautomatically. The format of the cards is such that the text\nis visible in the keypunch window when the data-field is\nbelow the punch-head, which allows visual checking of the\nidentity of the card about to be punched.
The actual updating operation is performed by supplying the control-input stream (the 'command-stream') of a RADARS job, with a card containing the 'DATA' command, followed by an arbitrary number of standard data cards. All RADARS commands are self-terminating (in the sense that when a further command is encountered on the input stream, the current command is deemed terminated, and the new one takes over) and so when all data cards have been read, the updating procedures begin their 'housekeeping' operations, updating the derived properties, and printing out new property listings, before handing over control to the next command.

Another procedure used to ensure the continued integrity of data decks is that when a card is removed from a deck for repunching, the succeeding card is manually turned through 180 degrees. Since the standard punched cards used have one corner clipped, the rotated card(s) gives visual indication of the removal from the deck of one or more cards and acts as a reminder until the repunched cards are replaced (they also act as indicator of the position of the new cards in the deck to aid replacement). Further, the updating system always punches a new card (as output from the 370) for each one updated and it is these that are
replaced in the master file decks. This ensures that the desired updating was in fact performed and eliminates the possibility of the repunched cards being replaced and the possible failure of the updating procedure escaping the notice of the user. As the output cards from the 370 are a unique colour, otherwise unobtainable for manual punching, there can be no chance of mistaken identity. Lastly, the computer punches the date of the updating on its output cards, again uniquely identifying them, as the original card must necessarily have had an earlier date or none at all.

Some of the property types (e.g. luminosities) are normally only ever entered into the files by means of the derived-properties section of the updating routines and thus no card-record exists for these numbers. This means that in the event of their corruption, they can only be reinstated by running one of the decks from which they are derived through the updating system, which might involve an unnecessary amount of work for the system. To this end, a 'DECK' command exists which punches out property decks for the types requested, onto standard format data cards, and labels the data with a system reference number as source, and the current date. These decks may be used for the reinstatement if no updates have been performed since their production. They are also useful as data input streams for
other programs not connected with RADARS.

The card decks are stored in a metal cabinet and are not subject to rapid deterioration and so could always be used to regenerate the data files in the event of their becoming corrupt or deleted by machine or operator error. However, this is a lengthy procedure as there is a large number of cards to be read in, and a second back-up file is held on a magnetic tape, using the Tape Library System (TLS), a piece of software developed in Cambridge which allows use of a magnetic tape for bulk storage with some of the convenience of a disc file. This back-up copy is regenerated from the disc file at regular intervals (its generation date is logged by TLS), or after any particularly heavy piece of updating work, and if regeneration becomes necessary, it simply has to be refiled onto disc, and any updates carried out since the last tape-file generation, re-run. The latter task is facilitated by the updating system producing a dated listing of all the updates performed, and these are stored in date order in a filing cabinet.

Punching-errors are generally difficult to trace since there is no way the computer can know the correct value of the data being input. However, a major source of errors is
punching keys in the wrong 'case': all the digits on a standard key-punch are upper case and if one should be punched lower case by mistake, the FORTRAN input routines will trap the error and print out a warning message which will allow the user to correct the error. However, the only way to ensure that the values are correctly punched is to compare them with the original source material. As the update program prints out listings (from disc file) of all data types affected by an update operation, these may be checked against the source material and in this way, the entire process from start to finish is monitored.

The system allows the user to write FORTRAN programs to perform special tasks. These are necessarily 'one-off' procedures and thus are not subject to much testing as have been the system routines. There is therefore some danger of data files being overwritten by these programs. This is greatly reduced by using system routines to perform all file read/write operations rather than the direct FORTRAN 'READ' and 'WRITE' instructions. These routines check the status of the user (indicated to the system by the optional submission of a password with the rest of the job commands) against the file security ratings, and if the user is of low (system) status, prevent him from overwriting 'secure'-marked system files. This feature should encourage inexperienced users to
experiment with the system by eliminating their fear of corrupting it.

An up to date record of all data on file is also easily maintained because, as mentioned above, the updating procedure produces a new listing of all data-types affected by an update operation. These listings are filed in a cabinet as soon as they become available and the old ones removed. All output is dated so there is no risk of confusion here.

The combination of all the above procedures is felt to represent an adequately secure arrangement for the maintenance of the data files. To date, no accidents have occurred that have corrupted the files, except occasionally during the rewriting and testing of some of the system programs. In these cases, the tape and card back-ups proved quite sufficient to restore the files and it may be concluded that the security measures taken have been successful.

2.6 Sample Selection.

The statistical work involved in the present project
is mainly concerned with the comparison of the properties of samples of objects drawn from some larger set. In our case, the larger set is 3CR and we are interested to know the relationships (if any) between the properties of the sources in this sample. To investigate these, we must continually strive to choose our sub-samples in such a way that they are statistically complete, and not subject to selection effects; if the latter are present, they should be quantifiable so that due account may be taken of them in the statistical analyses. One example of this has already been described, and that was the necessity for the selection of the 'complete-sample' for use as a data-base in most investigations.

When one comes to a particular investigation however, many more observational selection effects need to be eliminated if the results are to be useful. For example, comparing the optical types of very high and very low redshift objects might suggest that there are no high-redshift galaxies, but this result is due to the neglect of the selection effect that only optical objects brighter than some limiting apparent magnitude can be associated with radio sources. In most investigations, the selection effects are much more complicated and even their partial elimination requires very careful selection of
This implies that one of the prime functions of the system should be to allow samples with complex definitions to be selected simply, as this process is the forerunner of any further statistical work that might be attempted. Often the result of applying sufficient sample selection criteria to the data-base, to significantly reduce selection effects, results in too small samples to allow adequate statistical tests to be performed. This is the penalty one pays for working with a reasonably small number of sources. However, as was pointed out earlier, it is not obvious that anything significantly better could be achieved by including more sources in the data-base because the observational data for them is not available.

The sampling system in RADARS is designed to be as flexible as possible without making the programs needlessly lengthy, and is organised in such a manner that if one pass of the sampling routine is inadequate to take care of all the sampling criteria, then successive passes may be performed as often as necessary to complete the selection. One defines a sample by specifying up to 13 equalities and/or inequalities of the 50 property types with
user-defined constants. For example, these might be 'physical source size < 250 kpc', and, 'Luminosity at 178 MHz > 10 W Hz sr'. Simply choosing these relationships allows one to select samples in only a limited way, because unless told otherwise the program assumes that the sample-sources must satisfy all the given relationships simultaneously. This is inadequate to select samples such as the 'complete-sample' because one needs to say 'b > 10 degrees' or 'b < -10 degrees'. Also, the relationships are limited to the types '<', '=', or '>' only. The flexibility desirable is achieved by allowing a logical relationship to be written down relating the (up to) 13 specifications. This logical relationship is allowed to contain up to 80 characters, multiple nested brackets, and the functions 'AND', 'OR' and 'NOT' using a compact Boolean algebra-like notation, in which each of the 13 specifications is referred to by the appropriate letter from the 1st 13 in the alphabet. Thus, for example, to select the 200-Sample from 3CR we need the following specifications:

A  b > 10 degrees
B  b < -10 degrees
C  $\delta > 10$ degrees

and the logical relationship: $(A+B) \cdot C$

where '+' is the 'OR' function and '•' the 'AND' function.

In practice, for our 200-Sample, we allow 'b > 10 degrees', 'b < -10 degrees', and '$\delta > 10$ degrees' and this can simply be
written
A \text{ } b > -10 \text{ degrees}
B \text{ } b < 10 \text{ degrees}
C \text{ } b < 10 \text{ degrees}

with the logical relationship \((\neg A \land \neg B) \land \neg C\)
where \(\neg\) represents the 'NOT' function which applies to the immediately following expression, be it a single operand, or a bracketed expression. Note that in Boolean expressions all operands must be separated by at least one operator other than brackets.

Clearly, with expressions even more complicated than \(\neg (D \land (\neg (A \lor \neg B \land C) \land J \land (M \lor K \lor L)) \lor J \land C \lor (F \lor H \lor \neg I)) \lor E \land \neg G\)
allowable, the selection criteria may be extremely well defined. Last of all, in case this isn’t sufficient to define the sample precisely enough, or when reasons of convenience require it, one may select the sample from the whole data-base (3CR) but from a previously selected sample which resides on a system file now to be described.

This is a third DAF which holds 50 pre-selected samples of up to 400 sources, which have been stored there
by the 'STORSAMP' command, (see the section on the command system). When sampling from a previously stored sample is requested, the sampling system retrieves that sample from disc and looks only through its members for sources satisfying the quoted relationship between the property relationals. Samples may be 'merged' in a logical 'OR' or 'AND' fashion (i.e. either their union or intersection formed) by use of the 'MERGE' command, altered 'manually' by the 'SAMPALTR' (SAMPLE ALTER) command which allows the addition or removal of specified sources, and also defined 'manually' by use of the 'DEFSAMP' (DEFINE SAMPLE) command, by giving a list of the 3C names and/or the file numbers of the desired set of sources. This last routine sorts the given sources into file number order, and also eliminates any duplicate entries before storing the sample as the 'current'; (see below).

The combination of all these facilities makes sample selection both simple and straightforward, no matter how complicated the desired sample, and one is encouraged to attempt analyses whose sample selections would, without a computerised data system such as RADARS, represent an almost intractable piece of work by hand.
During operation of the program, one sample is held in main storage, and this is known as the 'current' sample, and may be referred to within the command environment as sample #00. Whenever a new sample is formed either by direct definition, merging of previous selected samples, loading from files by means of the 'LOADSAMP' command or by a selection procedure, that sample becomes the current sample, and the previous current sample is lost (it should have already been filed using the 'STORSAMP' command if wanted later). The current sample is also lost at the end of a program run. Any sample may have its members listed using the 'PRNSAMP' command (PRINT SAMPLE), though this command is always invoked automatically whenever a sample has been newly created or altered. To aid the user, each sample may be given a name of up to 240 characters (3 standard computer cards of text), and the name will then be automatically printed out alongside all tabular and graphical output related to the sample. Also, for reference purposes, the current set of sample names for all samples may be listed using the 'PSAMPNMS' (Print Sample Names) command.

2.7 The Program Control System:

Any program such as RADARS, designed to perform a complicated series of tasks definable by the user must have some means of obtaining its instructions from the user. This
could most simply be done by having the user write a program in the language of the system programs which would initiate the appropriate sub-programs in the correct sequence. This would also give the user the most flexibility as it would allow him access to all the internal functions available to the system programmer and also enable him to perform program condition tests and to use loops for a very complicated set of instructions.

However, such a scheme has many disadvantages for the general user, not the least of which is the necessity of learning the language of the system programs (in this case FORTRAN). It also means that he has to have an intimate knowledge of all the sub-programs in order to be able to 'CALL' them correctly, and of all the communication linkages within the program through which information is passed from one sub-program to another. Lastly, he has to know how the subprograms depend upon one another and how they are arranged in the overlay-structure (described later). This means practically, that the only person easily able to write useful control instructions in the system language is the system programmer himself.

What is needed is some interface between the user and
the program that allows flexibility of operation, with little knowledge of how the system operates, whilst maintaining system security. An attempt has been made with the RADARS system to implement these requirements.

It would be convenient to the user, also, if he could sit at a teletype or similar on-line computer terminal, and work interactively with the program, having his results sent back to his console for display, to guide him in his next choice of commands. However, the current facilities available in Cambridge in this direction are inadequate for the implementation of such a system and the 'on-line' system is only capable of data input for the files, editing of files, and off-line submission of jobs. Also, the lack of CRT-type consoles capable of rapid display of data (be it text or graphical) precludes the use of the on-line system even for checking the output from off-line submitted jobs. For these reasons, RADARS has been written as an off-line system, and the primary output medium is the line printer. Since large amounts of tabular data are not always very useful, graphical output is used whenever possible and this too is produced on the line-printer because it is cheaper, faster and more easily produced than graph-plotter output; the great accuracy and high resolution of the latter is simply not necessary for the types of output envisaged
here, where most of the data values are known to a precision worse than 1%.

The system, then, should be run off-line, using either punched cards or teletype terminal as input media, and line printer as output medium. (Occasionally, punched cards are also produced by the program). Since the program control statements must therefore be all inputted by typing, and not chosen from a 'menu' with a light-pen on a CRT-screen or some such device, they must be short and easily remembered. Several steps have been taken to reduce the amount of effort involved in writing input instructions.

All steps are initiated by writing a key-word, called a 'command'. Commands may require an argument list to perform their designated functions, though some have null argument lists. To save writing, most commands are optionally repeatable simply by supplying them with further suitable arguments. The commands themselves are 8-or-less character mnemonics for the operations they perform (several examples have already been given). They are easily and quickly remembered as the formation of the mnemonics is consistent throughout the whole set of commands. When samples are to be referred to in command argument lists, the
sample numbers only are written. As these lie in the range 00 to 50 (always two digits) they involve little written effort, and they are generally only needed 'locally' in a set of commands so there is no necessity to learn the number of all samples. The property types too are referred to by number, rather than by name. This involves a small amount of memory work for the user but this may be supplemented by a small cross-reference table (on the back of a computer card for example) and any disadvantages are completely offset by the reduction in the likelihood of punching or spelling errors. The balance between the amount of necessary punching and amount of memory work necessary is quite difficult to achieve. However, since property types are used much more frequently than commands (each command may have many property types in its argument list) the most effort is saved by using property type-numbers rather than, for example, using command-numbers and mnemonics for the properties.

The commands may be formatted in one of two ways. Either, every command key-word and each of its sets of arguments forming components of an argument list must appear on a new line, (or new card, for punch card input), or a slash (solidus='/') used to denote end of line and the 'next-line' started immediately after the slash. Trailing
blanks before slashes are unimportant and are ignored by the command-reading system but blanks following a slash must not appear unless the rest of the line is also blank. Special considerations apply to commands having complete lines of text in their argument list and these argument lists are generally more safely begun on a new physical line or card. The possibility of putting several command keywords plus arguments on one card allows the rapid production of several slightly different command strings by using the duplicating facility of the IBM keypunch. For example, one may wish to plot several property pairs and draw histograms of a few properties for several samples for comparison. Duplicating the instructions for the first sample and just changing the sample number allows this to be done rapidly and with little probability of error.

So far, we have shown how the RADARS control system allows rapid and simple communication between the user and the program, but it is clear that some of the flexibility available to the programmer in system language is lost, as the user is limited to those operations possible through use of the available commands. This shortcoming is removed by the facility of the 'PROGRAM' command. This allows the user to interface a set of FORTRAN subprograms with the system programs, thus giving him the desired flexibility, whilst in
addition allowing the simplicity of use of the command language for most of his work. The 'PROGRAM' command keyword takes a single digit argument from 0 to 9, allowing, effectively, up to 9 different FORTRAN control subprograms to be written each of which may be called in any order, any number of times by means of the repeated use of the command, and each of which may also call any other user subprograms desired. They also have access to all the internal system subprograms as well as the routines designed to allow controlled reading and writing from the data files. Lastly, they may read from and write to the sample file directly. Full details of such program interfacing are given in the User Manual.

Because of the possible danger to the system from inexperienced use of this command it is password protected. It is particularly useful for the computation of further derived properties (e.g. source component surface brightness) which do not normally reside on the system files. At present there are three spare property types allocated for such purposes and if more are needed it is possible (with a little experience) to read out some of the unwanted system-stored properties to a file at the beginning of a job, make use of the extra space for the duration of the job, and then refile the system files at the end. This
however should only be done by those confident that they can perform the necessary operations without a large probability of error, and the system files must be dumped onto a catalogued file (and not a temporary dataset) in case the job terminates prematurely. An alternative technique is to use the TLS backup system immediately before and after the job, but this is a less desirable method, since frequent write-usage of the TLS tape means that it gradually becomes filled and has to be re-indexed, an operation not entirely without risk.

There are certain penalties to be paid for making use of the 'PROGRAM' command in terms of increased job run time. This is because it is necessary to invoke the FORTRAN compiler and the Linkage Editor to compile and couple the user supplied programs with the system programs which themselves are pre-compiled and linkage-edited. However, this process is entirely automatic and is not a high cost to pay for the increase in flexibility so obtained. Since in practice one only infrequently needs to invoke the 'PROGRAM' command this is not a serious disadvantage.

Some of the commands available have already been described in the sections on updating and sampling. Those
related to output production are discussed in the next section, and the remainder are described in the section on job-organisation.

2.8 Data Retrieval

So far we have discussed the requirements of data acquisition, data manipulation, and program control. The purpose of these three operations is to make possible the retrieval of the data in the desired organisation and format. The output routines are equally important since they generate the end-product of the whole system and so should be as versatile and as automated as possible.

Two distinctly different types of output are necessary - graphical and tabular. The graphical output of RADARS takes the form of correlation (scatter) diagrams and histograms which are designed to be clear to read and quick to produce. As mentioned previously, they are drawn using line-printer characters and so do not have the 'smoothness' of plotter output, but this is not really a drawback due to the coarseness of the data. By printing each diagram across a pair of pages of printer output, a 100-line by 100-column display area is available, giving an upper limit of 1% resolution on the diagrams. This area is used as effectively
as possible by incorporating auto-scaling within the routines, which determines the optimum starting points for the ordinates and abscissae and also the step size along the axes. A choice of logarithmic and linear scales on both axes (in any combination) greatly aids the production of useful diagrams, or if desired, the autoscaling system may be left to make this choice as well. Up to ten different plotting symbols are available simultaneously, chosen from three different character sets, allowing multiple plots where necessary. An attempt has been made with these plotting routines to optimise the use of available plotting area for a given set of input data, without producing 'silly' scales which are awkward to read. However, when necessary, the programs will respond with quite extraordinary scale values.

The histogram routine is very similar to the plotting routine except that it draws histogram bins rather than co-ordinate pairs. In addition to scales, it will also automatically select a statistically useful number of bins (approximately \( \sqrt{N} \)) when desired, and in this way one's tendency to select that number of bins which maximises the sought-after effect is eliminated. Another tendency when drawing histograms is to select the starting and end points of the base axis somewhat arbitrarily, and often these too
are chosen 'fortuitously'. The program always selects the smallest and largest data values for the beginning of the first box and the end of the last, thus avoiding such effects.

To invoke the plotting routine, the 'PLOT' command is used, the arguments being the sample number for which the plot is required, a parameter called 'MAP' if required, and then the properties to be plotted on the correlation diagram, followed lastly by a scale option specifying logarithmic, linear or automatic scales. Some pre-processing of the data is carried out which eliminates from the plot sources for which there is no available data (this avoids having to plot points with data value 0.0, which would make a logarithmic plot impossible). It also produces a message at the bottom of the plot stating how many such sources there are. A second task it performs is choosing the plotting symbols for the data, and also taking the moduli of negative data before plotting wherever appropriate. There is a table available to this routine that holds the type-numbers of data-types that may have physically real, negative values (such as spectral indices, or 'B-V' colours) and these are not forced positive. The plotting symbols are determined by the 'quality-tags' of the data on each axis. Good (positive) data on each axis is plotted with symbol
'•', poor (negative) data on the X-axis with symbol 'X', poor data on the Y-axis with symbol 'Y', and where both X and Y values are negative the symbol 'B' (=Both) is used.

Use of the 'MAP' option produces an additional plot, with sources plotted with the 52 symbols 'a to z' and 'A to Z', in sequence, so that for plots with 52 or less sources, each point is uniquely labelled. An index table is also printed out allowing one to relate the plotted points on the scatter diagram with the 3C-names of the sources they represent. This facility is useful for picking out odd sources which, for example, lie at extremes of a plot.

The 'PLOTR' command is used in exactly the same way as the 'PLOT' command, the only difference being that the program additionally tries to fit four simple functions to the data on the scatter diagram. The functions are i) straight line, ii) log-function, iii) simple power function, iv) exponential function, and a least squares fit is made. The correlation coefficients of the data-fit around the lines are also computed and printed out alongside the equations of the lines in order of best fit along with a measure of their statistical significance. This routine is usually only invoked when a run of the 'PLOT' command has
'*', poor (negative) data on the X-axis with symbol 'X', poor data on the Y-axis with symbol 'Y', and where both X and Y values are negative the symbol 'B' (=both) is used.

Use of the 'MAP' option produces an additional plot, with sources plotted with the 52 symbols 'a to z' and 'A to Z', in sequence, so that for plots with 52 or less sources, each point is uniquely labelled. An index table is also printed out allowing one to relate the plotted points on the scatter diagram with the 3C-names of the sources they represent. This facility is useful for picking out odd sources which, for example, lie at extremes of a plot.

The 'PLOTR' command is used in exactly the same way as the 'PLOT' command, the only difference being that the program additionally tries to fit four simple functions to the data on the scatter diagram. The functions are i) straight line, ii) log-function, iii) simple power function, iv) exponential function, and a least squares fit is made. The correlation coefficients of the data-fit around the lines are also computed and printed out alongside the equations of the lines in order of best fit along with a measure of their statistical significance. This routine is usually only invoked when a run of the 'PLOT' command has
produced a scatter diagram showing promising signs of correlation, and an estimate of the statistical significance of the (apparent) correlation is required.

The histogram routine is operated using the 'HIST' command, the arguments this time being the sample number and property type for which the distribution is required, the number of bins wanted in the histogram (setting this negative implies auto-selection), and lastly the scale option as for 'PLUT'. Again, a preprocessing routine is used to remove zero data.

Where the 'quality' of data in a histogram needs to be checked (when, for example, something significant is apparent) this may be done by using the 'NEGHIST' command which operates similarly to 'HIST' except that the moduli of the data are not taken before plotting. This is useful because if the negative data are reasonably good, the histogram on the left of the zero point will be a rough mirror image of the histogram of the good data on the positive side of zero. If they are grossly dissimilar and thus have caused significant distortion in the diagram, this will be immediately apparent.
2.9 Tabular Output:

One command that produces tabular output has already been mentioned, viz: 'PRNSAMP', that prints a list of sample members for the sample number(s) in its argument list. Another is 'PROPRN' (PROPERTY PRINT) that prints a simple list of one property for all sources in the order that the sources are stored in the files.

'SRCPRN' (SOURCE PRINT) is a command that prints a list of all the fielded data available on the source(s) appearing in its argument list. It performs the necessary decoding to display the binary types of data in a more legible format. 'SMPSRCPRN' (SAMPLE SRCPRN) has, as arguments, sample numbers, and its operation is to execute a 'SRCPRN' command for each member of each sample in the argument list, in the order determined by the sample numbers. Clearly, such a command can produce a large amount of printer output with very few instructions and should be used with caution.

Data lists sorted by value are available by means of the 'SORTDPRN' (SORT Data, PRINT) command. This produces two lists of each of the properties specified in the arguments,
one sorted by the value of the data as it appears on file, and the other sorted by the modulus of the data. This latter is useful for putting the estimated or poor quality data in perspective with respect to the rest of the data. When applied to the optical and radio type data (alphanumeric) it sorts these into order of the coded values held on file, but this closely approximates to alphabetic order and it is useful as it clusters sources of similar type.

The most versatile of the tabular output routines is 'SAMPPERN' (SAMPLE Data PRINT) which is used to make multi-column listings for a given sample of sources. The first argument is the number of the sample, and the following arguments are the property types in the order in which the columns are to be printed on the output sheets. This is quite a complex task for the program because of the widely differing types of data to be printed (e.g. luminosities which are so large they have to be printed in E-format such as '1.725E+26'; spectral indices, most conveniently read in F-format, like '0.760', and alphanumeric data such as 'TEP', which must be in A-format). This implies that the program has to assemble a suitable line of format instructions before it can perform any printing operations. Up to six columns of data, plus the source name, file numbers, and an index column giving the
position in the list are available on one page width. Where more than six arguments have been requested, these are broken up into groups of six or less and each group printed for the whole sample in turn.

Of course, where special purpose listings are needed, these may be generated by the 'PROGRAM' command, use being made of the sorting routines (for example) available from within the program, as well as the encoding and decoding routines if necessary. However, in practice it has been found that the above types of listings fulfil most operational requirements and to date no other special purpose listings have had to be produced.

2.10 Miscellaneous Organisational and Operational Commands.

In this section we describe commands which are useful for the organisation of jobs, and also a few similar in nature to 'PROGRAM' which perform specific operations not falling into any of the categories so far discussed.

'DUMMYNAM' (DUMMY NAME) is used to give an (up to) 8 character name to a property type. This is mainly of use to the general user when he is using properties 48, 49 and 50
(undefined) to hold job-generated properties in addition to those already on file; giving them a name ensures that whenever they appear in the output they are correctly labelled. Failure to make use of the command will result in the last assigned label being used, and this may cause some confusion. Password protection is applied to the names of all the system data (types 1-47) but submission of the password will allow these too to be altered at will, a feature useful to the system programmer and the more experienced user. The argument list for the command consists of a 2 digit property type number followed by a character name.

The two complementary commands 'PROTECT' and 'RELEASE' are used to set and unset a protection flag associated with each stored sample. Once a flag is set, that sample file may not be overwritten by any steps in a job until it has first been unset by use of the 'RELEASE' command. The arguments of both commands are simply the numbers of the sample files to be flagged. No password protection is applied to the PROTECT command but a password must be given before protected samples 1-30 may be released. This is because the first 30 sample files are 'semi-permanent' library samples and are not intended to be changed by the general user.
The 'PASSWORD' command is invoked to give the user higher status than is generally obtainable, and if his submitted password is acceptable to the system he will be allowed to perform operations otherwise denied to him. Many of these have already been described. In particular, he is allowed to change the password by a second use of the 'PASSWORD' command.

The 'TITLE' command may be used any number of times within a job to reset the title which is printed at the top of each output page, along with the time of job-run and the date. The title may be up to 80 characters in length and can contain any character printable on the 370 printers. It is initially set to null. The argument is one line of text, and if none is supplied, the title is reset to null.

'SRC_CNT' (SOURCE COUNT) is a special purpose command designed specifically for performing source-counts on subsets of 3CR. Its arguments are the numbers of the samples for which source-count calculations are required and an optical apparent magnitude down to which those samples are thought to be observationally complete. A plot of log(N)
against \( \log(S) \) is produced; the mean value of \( \frac{V}{V_{\text{max}}} \) computed assuming firstly a Euclidean Universe and then an Einstein - de Sitter World Model (see Schmidt, 1968 (053)); a best fit value of Beta (the slope of the source count defined by \( N(S) \propto S^\beta \)) is also computed using the maximum likelihood method, (Jauncy 1967 (305), Crawford et al 1970 (307)).

The 'STOP' command tells the system to ignore any further commands and terminate execution of the job. The program will automatically stop upon encountering 'end-of-file' on the control input-stream, but it is frequently convenient to run only part of a deck of commands at once, without having to split the deck, and 'STOP' cards may be inserted anywhere in the deck to cause job termination.

2.11 Some General Notes on the Command System:

Since RADARS is an off-line system it was felt necessary to make all the commands plus (optional) argument lists self terminating, in the sense that the system should recognise automatically when one step is over and another beginning. In on-line systems this is generally no problem because one tends to type 'carriage return' or a special
character string at the end of a set of instructions to signify return of control to the machine. Everything else that the user does is ignored until the machine has finished that task, and signalled to the user its 'ready' state by typing some suitable message to him.

One solution that was originally implemented was the use of a blank card in the input stream to act as a delimiter between commands, but this was found to be inconvenient, wasteful and did not aid legibility of command decks, apart from making them needlessly bulky. A second method would have been to ensure that every command had a fixed number of arguments in its argument list, and that the command system would assume that it had a correctly assembled deck of instructions as input. Mistakes in the command input would then have almost certainly caused premature termination of the job, but more important, the resulting damage caused would have been unpredictable and difficult to determine later.

The solution finally adopted was a technique similar to that used in language compilers, which is to look for 'key-words' in the input text and take appropriate action when one is found. Until one is found, the program attempts
character string at the end of a set of instructions to signify return of control to the machine. Everything else that the user does is ignored until the machine has finished that task, and signalled to the user its 'ready' state by typing some suitable message to him.

One solution that was originally implemented was the use of a blank card in the input stream to act as a delimiter between commands, but this was found to be inconvenient, wasteful and did not aid legibility of command decks, apart from making them needlessly bulky. A second method would have been to ensure that every command had a fixed number of arguments in its argument list, and that the command system would assume that it had a correctly assembled deck of instructions as input. Mistakes in the command input would then have almost certainly caused premature termination of the job, but more important, the resulting damage caused would have been unpredictable and difficult to determine later.

The solution finally adopted was a technique similar to that used in language compilers, which is to look for 'key-words' in the input text and take appropriate action when one is found. Until one is found, the program attempts
to make sense of the input presented to it in the context of
the last keyword encountered. A certain amount of 'softness'
on the part of this interpreting system is allowed, in that
when it feels that a command keyword is needed and none is
found, it issues a warning message, and reads on in the hope
of finding something usable in the input stream further
along. At present, a total of ten non-fatal errors of
various types is enough to cause the system to give up, and
terminate the job.

This system is implemented by means of a hierarchical
set of subprograms, which pass control amongst themselves
according to whether each one 'thinks' it can cope with the
current input line. At the top of the chain of command is
the main program which is short, and is used primarily for
setting up the direct access files for the system. Command
is passed down to COMSYS (COMMAND SYSTEM) which is generally
used for initiating a particular command when READER has
 signaled the presence of one on input. Depending on the
number of the command, either COMND or COMND2 is then called
which organises the necessary operations.

The main additional advantage of such a system is that
each command may have a completely arbitrary number of
arguments, giving great flexibility in use. A good example of this is the 'PLOT' command.

Example:

Input Commands:

```
....;/PLOT/24 MAP/40 4/04 05 3/01/40 22 3/HIST.....
```

The third and fourth groups between slashes represent descriptions of what and how to plot, but '01', the fifth group, is inadequate as such a description, so the program tries to interpret it as a new sample number. This is successful (-1 < 01 < 51) and so the following group is used for plotting instructions. The plotting commands are assumed terminated on receipt of the key-word 'HIST'. In general, then, any command may be supplied with multiple arguments if it is logically possible to properly interpret them. This speeds up punching, and processing too as there is no need to repeatedly call the appropriate routines.

A convention used throughout is that where a sample-number argument is given value '00', the current sample is used.

2.12 The Logging System
After some time, it became apparent that a comprehensive record of all jobs run using RADARS would be useful for system debugging, and also to hold notes on the success, failure and purpose of all experiments performed. For this purpose a logging-system has been constructed which prints out as a separate document from the program output, a page-numbered list of the commands and input data processed in each job, with the real-time and date at the top of each page. Page numbers are continued from job to job so that missing log-pages are easily noticed. All users are asked to ensure that any log-output that is printed out with their jobs is filed in the current log-book in correct sequence. Because a complete log for a job cannot be printed until the job has finished, and because when a job step abnormally terminates succeeding job steps are not executed, it is arranged that any unprinted logs are produced at the beginning of the next job run. In this way logs are not lost through program errors, and help in debugging is often available as the curtailed log will indicate which command was executing when failure occurred.
CHAPTER THREE

A Representative Sample of Radio Sources

SUMMARY

The requirements and method of selection of a first 'quick-look' sample of extragalactic radio sources, for observation with the 5Km telescope are explained. The new information gained from the survey and its implications are described, followed by an analysis of the results.
3.1 New Observations with the 5Km Telescope

With the advent of the 5Km telescope it became possible to make high (linear) resolution observations of radio sources, out to greater redshifts than had been possible with any previous synthesis telescope. This opened up great possibilities for statistical work such as that presented in this dissertation, because at last one had the opportunity of observing in great detail some of the really powerful sources (which, because of their low space density, are in general very distant). However, there were many other programmes for the new telescope including the astrometric work of Ryle and Elsmore, 1973 (403) which was of crucial importance if the telescope was to fulfil its design aims to the limit. This being the case, we had to think very carefully about which sources were the most important to observe first, as it was unlikely that most of the sources in 3CR would be observed for several years after the completion of the telescope, particularly as the larger sources would need several nights of observing time.

To perform statistically satisfactory analyses one must generally work with complete samples and what could have been done was to choose a suitably small region of the sky and observe all the 3CR (or 'Complete-Sample') sources
within that region. This would have resulted in a smaller but more fully resolved complete sample and statistical inferences could have been made from it. However, because of the small number of sources we could reasonably expect to observe in the short time available, it seems unlikely that this would have provided much new information, other than resolving a few more distant double sources and turning up one or two new features by chance in the partially resolved nearer sources.

A second consideration was that in order to plan for future (higher resolution) telescopes, one needed to know as soon as possible, if there were likely to be structures in sources representative of all types already known, that still could not be resolved with the 2 arcsec beam of the 5Km telescope, as this would indicate the necessity for building such higher power instruments. Another related consideration was to determine the observational value of operating the 5Km at 15GHz.

For these reasons it was decided that work on complete samples should be postponed until enough time had elapsed for a larger number of sources to be observed, and that the initial programme would be to try to observe all sources in
a "representative" sample, to roughly the same minimum resolution in terms of Kpc at the source.

3.2 Selection of a Representative Sample

By "representative" sample we mean a set of sources chosen to be as small as is consistent with the set containing at least one of every 'type' of known source. Since we wanted to be able to study the intrinsic properties of this subsample as well as the directly observable properties, we had to have some distance indicator for each member, and so we insisted that the sources be identified with a quasar or galaxy of known apparent magnitude, although we did not demand that a measured redshift should exist. Lastly, since we wanted to see as much physical detail as possible in each member, where we had a choice of several objects of the same type, we chose only the nearest three for our sample. In this way we hoped to produce an observational programme that would yield the maximum new information in the shortest time.

Fig. 3.2.1 is a flowchart, detailing the selection procedure for the representative sample. It can be seen that we used the 3CR sources as our base sample, and in order that we might have a good chance of identifying the chosen
Fig. 3.2.1 Selection of the 'Representative Sample'.

Divide into 5 Groups 5 Ways (in order of property value)

- Select 3 with smallest redshift in each group
- Remove Multiple Entries

START

WHOLE SKY

NO

Throw Away

YES (328)

DCR SOURCES

NO

Throw Away

YES (198)

COMPLETE SAMPLE

NO

Gal. or QS with

Throw Away

STAGE 1

STAGE 2

STAGE 3

STAGE 4
sources and because we wanted a reasonably homogeneous resolution over the sample, we rejected sources near the Galactic plane or at low declination. We then selected only those identified with a quasar or galaxy and with a measured apparent magnitude, so that where a redshift was not available, we could estimate the source distance by assuming a reasonable value for the apparent magnitude. The RADARS system was used for the sample selection and the code for this stage is:

SAMPSAMP/24/RELTN/(A+B).C
01 E GGG/01 E Q5/05 G 0.0/STORSAMP/50

(which means; choose from sample #24 (already preselected complete-sample) all objects with optical type (Galaxy OR Quasar)-AND magnitude >0.0. Then store the sample as sample #50)

This initial selection, called 'stage-1', left a sample of 119 sources. To make our subsample representative we chose sources throughout the range of the following parameters: source-size (in Kpc), luminosity at 178MHz, low frequency spectral-index, radio-structural-type and lastly, optical-structural-type. These were chosen because the first two (size and luminosity) are the most important characteristics of a source, as one is an indicator of the
total rate of energy production in the source, and the other
is a rough indicator of its age. Spectral-index was chosen
as it may also be an indicator of the stage of evolution of
the source (spectra should steepen with age, see e.g. Slingo
1974, (398)), and radio-structural-type is clearly another
important indication of the processes going on within the
source, though we by no means fully understand their
inter-relationship at present. Optical-type was included
because most theories of radio sources assume that the radio
structure or the mechanism responsible for it originated in
the central optical object, so there ought to be some basic
connection between what we see at optical and at radio
frequencies. So far no convincing correlation has been found
(except perhaps that quasars have a tendency towards smaller
spectral indices; however, even this effect is almost
eliminated from our sample because of its selection to a
limiting value of flux density at the low frequency of
178MHz: see e.g. Wall, 1975 (458)), and any further
information that we might obtain on this matter is very
important for those parts of source theory that deal with
the initial formation of radio sources.

Lastly, in order that the representative sample should
also be the nearest such sample, we divided each of the
properties described into 5 contiguous ranges detailed in
Table 3.2.1
Details of the property boundaries used in Stage 2 of the selection of the representative sample.

<table>
<thead>
<tr>
<th>Optical Type</th>
<th>Radio Type</th>
<th>L.I. Spec. Index</th>
<th>1700Hz Luminos.</th>
<th>Radio Linear size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range 1</td>
<td>D</td>
<td>C</td>
<td>0.8 - 0.3</td>
<td>&lt; 1825 (13)</td>
</tr>
<tr>
<td>Range 2</td>
<td>E</td>
<td>D</td>
<td>0.5 - 0.7</td>
<td>1825 - 1826 (20)</td>
</tr>
<tr>
<td>Range 3</td>
<td>N</td>
<td>E</td>
<td>0.7 - 0.9</td>
<td>1826 - 1827 (43)</td>
</tr>
<tr>
<td>Range 4</td>
<td>Q8</td>
<td>T4q</td>
<td>&gt; 0.9</td>
<td>1827 - 1828 (25)</td>
</tr>
<tr>
<td>Range 5</td>
<td>Spiral (4)</td>
<td>or Triplet</td>
<td>209</td>
<td>&gt; 1828 (10)</td>
</tr>
</tbody>
</table>

These ranges were chosen as a compromise between having equal numbers of sources in each range, and

The sources in the five ranges for each of the five properties were then sorted in order of redshift and the two

then sorted into ascending order of 2 by similar commands to the one above.

This produced a list of 75 sources and removing all but one of the multiple entries left a final sample of 41

sources. This was the cumulative sample and Table 3.1.2.
Table 3.2.2.
The representative sample showing why each source was chosen.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>Radio Size</th>
<th>Luminosity</th>
<th>LF.spec. indx.</th>
<th>Optical type</th>
<th>Radio type</th>
<th>times chosen</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C31</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3C33</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C35</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C43</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C47</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C48</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C76.1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C83.11</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C84</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3C98</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C123</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C181</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C192</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C196</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C219</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C231</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C236</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C249.1</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C264</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C272.1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C274</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C277.3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C286</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3C303</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C305</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C310</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3C323.1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3C338</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C346</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3C380</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3C386</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3C390.3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C433</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3C442.01</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C449</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3C454.3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C460</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3C469</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The numbers in the table indicate the ranges as defined in Table 3.2.1.
lists the members and the reasons for their inclusion in the sample. Since this work was done, it has come to the notice of the author that 3C371 comprises two confused 4C sources both of which, fall well below the 3CR flux limit of 9Jy and consequently 3C371 has been omitted from further discussions leaving a sample of 40.

Fortunately, some of the 40 sources have large angular sizes (>100 arcsec) and observations with the OMT at 408, 1400, 2700 and 5000 MHz have resolved most of the structure present. This meant that we could concentrate our 5Km observations on the smaller (in general more distant) sources and so produce some measure of homogeneity of linear resolution with the minimum number of days observing time. The programme of observations was kindly taken over by Martin Ryle. We now give details of the observations of the sources and then continue with a discussion of the new information that the programme has produced.
3.3. Summary of the observations of the Representative Sample

made by the 5km Telescope

Fig. 3.3.1 illustrates the definition of the various structural descriptions we shall use. This is a map of 3C133 made with the 5km telescope (Pooley & Henbest, 1974) and was chosen as it is rather an extreme example of several features found. The cross marks the position of the galaxy with which the source is identified and it lies well off the line joining the peaks of the two outer components, referred to here as the 'principal source axis' or simply as the 'axis'. The angle 'a' is called the alignment angle and has value zero for a source with the optical identification on the source axis. 't1' and 't2' are the angles the 'tails' of the components make with the source axis. Component '1' always refers to the most westerly of the components; where the source is aligned in the N-S direction, the N-component is labelled '1'.

3C111 (total angular extent approx. 8'). The earlier map of this source was made with the GMRT at 408MHz and has a linear
resolution of approx. 38kpc. The 5Km shows the presence of a compact component coincident with the galactic nucleus, with a very weak linear extension ('jet') directed to the NW. There are no compact emission regions in the remainder of the source. Some similarities to 3C66.02

**3C331:**

A convolved map indicates that there may well be a bridge of emission connecting the two outer components of this source (Hargrave, private communication). The earlier 1400MHz map of MKN indicated a faint central component close to the DE4 galaxy, connected only to the southern component by a single contour bridge of emission. These latter features are also present in the model fit observations of Fomalont (311). The northern component is now resolved into two sub-components with a weak tail pointing about 25 degrees off the source axis. The southern component is also seen to have a weak tail but this is directed approximately along the axis, and the component is otherwise still only slightly resolved.

**3C35:**

Not mapped (total angular extent approx. 10'). A short run at a long baseline indicated that this source contained no compact features and the 408 and 1400 MHz maps probably
show all the structure present.

**3C43:**

The source is barely resolved and is seen to be approx. one arcsec in extent.

**3C47:**

A compact central component (CCC) is visible, not visible on the 5GHz OMT maps. The outer components are seen to have diffuse off-axis tails, very similar to that of 3C33(N). There is a slight (approx. 5 degree) non-alignment of the lines joining the CCC to the peaks of the outer two components.

**3C48:**

Unresolved. < 1.0 arcsec.

**3C76.1:**

No compact components (total angular extent approx. 150 arcsec). The 1400MHz OMT map has a resolution of about 21Kpc.

**3C83.11:**

Previous maps have shown a conspicuous lack of emission from the galaxy associated with this source. However, the 5Km observations at 5GHz have revealed the
presence of an unresolved component, coincident with the nucleus of the galaxy.

3C84:
Unresolved. There is no evidence for structure on a scale of 10 arcsec observed at 408 MHz (314).

3C98:
The new map indicates that this source has no bright CCC, and also that there are very compact regions in the components not so clearly visible in the 5GHz OMT map.

3C123:
The 5GHz OMT map contained some spurious sidelobe responses. The 5km map has eliminated the confusion caused by these and shows the E component to be unresolved and with a weak tail pointing almost perpendicularly to the source axis. The 19.5 galaxy with which the source is identified is significantly off-axis (approx. 30 degree alignment angle).

3C181:
There were no previous synthesis maps of this source and we can now see it to be a double source. Both components are unresolved and well separated from the quasar (Z=1.382) with which the source is identified. There is no evidence for a central component.
3C192:

The 5GHz OMT map indicated that only the western component contained unresolved structure (38) (the map had a resolution of approx. 9kpc) and the LBI observations (314) indicate that this component has an angular size in the range 0.9 - 1.2 arcsec. The 5Km map has confirmed the presence of the very compact westerly structure but seems to show compact unresolved structure in the E component too, though much weaker than that in the W component. Unfortunately there is a zero-level shift across the only map available at present (11/12/74) that has lowered the W side into the noise.

3C196:

An unpublished 5GHz OMT map (Hargrave, private communication) indicated that the source might be a 5 arcsec double. The 5Km map has confirmed this but has also shown the reality of the tails on the components almost perpendicular to the source axis, suggested by LBI observations (314).

3C219:

OMT maps at 1400 and 5000 MHz had shown this source to be a slightly asymmetric double with a bridge. The new 5Km telescope observations have revealed a most striking
feature. Very close to the CCC coincident with the D1 galaxy, is a narrow, elongated component pointing directly towards the more compact of the outer components. There is significant non-collinearity of the three principal components of the whole source, (alignment angle 10 degrees), whilst the less compact outer component has a tail pointing slightly away from the galaxy, at an angle of about 110 degrees to the source axis. The more compact component has a small tail pointing approximately towards the tip of the 'jet' from the CCC. The observations of Fomalont (445) indicate that the 'jet' may be polarised approx. perpendicularly to the source axis. Turland 1975 (452), has described this source in great detail.

Hargrave 1974 (430) has discussed the 5km observations of this source. Suffice it to say that the latest map has revealed several compact components superimposed on the diffuse emission from the central region of the galaxy. These compact components are approximately aligned with the major axis of the galaxy, and all are unresolved (<0.6 arcsec). The linear resolution on the map of this very nearby source is a remarkable 62pc.

5km telescope observations revealed only the presence
of a small source (1.3 arcsec) in p.a. 155 degrees, coincident with the nucleus of the DE4 galaxy. Subsequently published results from the WSRT (41a) have shown this source to be a remarkably large (approx. 5.7 kpc) double source with a CCC, the latter being the only feature seen in our 5GHz observations. The p.a. of the large double (125 degrees) is approximately the same as that of the CCC, whose size is only 3.2 kpc, less than one thousandth that of the whole source. Previous observations had missed the large-scale structure of this source because of the enormous range of surface brightness present.

3C249.11

The structure of the components of this source had been only poorly determined previously by the 5GHz DMT observations (Mitton, 1964). The source is now seen to consist of 3 compact components with alignment angle of 10 degrees, one component being coincident with the 15.7 quasar with which the source is identified. There is probably a bridge of emission linking the whole source, and the outer components both have inwards pointing tails, the western being extended, the eastern narrow.

3C264:

This is an unusual source because it consists of only
one component which is compact at the position of the nucleus of the associated DE1 galaxy and diffuse away from it. The compact part is still unresolved by the 5Km telescope and no more structure is observed in the outer regions than was visible on the 2.7 and 5 GHz OMT maps, indicating that there are no features smaller than approx. 6Kpc, apart from the CCC.

**3C224.1:**

5GHz OMT observations have provided a resolution of 600pc in this very close (Z=0.004) source. It shows similarities to 3C264, consisting of a single compact structure becoming most compact at the position of the nucleus of the E2 galaxy. A 'two-tail' structure is slightly more pronounced than in 3C264 though the central feature is not as compact. The 5Km map shows no new features, but does refine the limit on the size of the compact component.

**3C274:**

5GHz observations with the OMT indicated a 3-component structure: the present observations show this to be an over-simplification and the source is best described as having an overall elliptical distribution of emission with several subcomponents superimposed on this. Two of the peaks lie directly along the optical jet while a third is coincident with the nucleus of the galaxy (type E2, 'M87').
The eastern edge of the source is very sharply defined and this feature was not clear in the earlier maps. (See Turland 1975 for a fuller discussion).

**3C272.3**

The 5GHz DMT map was very similar to the 408MHz map of 3C76.1, having an almost rectangular outline with two peaks visible well inside the outer boundary of the emission. No internal structure was visible. The 5Km map has revealed a CCC, an unresolved feature at the N extremity of the source and the general overall complexity of the structure. The peaks are not aligned (\(a=22\) degrees), and the S component is seen to be extended away from the CCC. The extensive tail on the N component points approx. due south, rather than towards the nucleus of the galaxy.

**3C286.1**

Unresolved (total angular extent approx 0.05 arcsec (315)).

**3C303.**

The present observations cast some doubt on the validity of the identification of this source with any of the previously suggested objects and prompted Lelievre & Mlerick (1975, 462) to remeasure the optical field. They find the N-galaxy with \(Z=0.141\) to be coincident with the E
component: in addition, they find a \( V=21.7 \) object with UV excess coincident with the \( W \)-component. The \( W \) component is resolved sufficiently to show extension approx. 60 degrees away from the source axis but is still unresolved perpendicular to the extension. The \( E \) component remains unresolved. The flat spectrum (\( \alpha < 0.15 \)) and small size of the latter component suggest that it may be the central component of a high flux-density-ratio double source. Indeed, there is a weak suggestion (in the 1400MHz DMT map) of low brightness structure on the eastern side of the \( E \) component. We feel that this is sufficient evidence to tentatively identify both components as part of a triple source centred on the \( N \)-galaxy, the third (weak) component to the \( E \) having been missed by the 5Km, 5GHz observations.

**3C305**

Sporious side-lobe responses on the 5GHz DMT map made this source appear 12 arcsec across. The 5Km map shows it to be a partially separated double, 3.4 arcsec across with a weak suggestion of a transverse tail on the weaker component. The stronger component is almost coincident with the nucleus of the galaxy which has a 'definite one-armed spiral structure', (120). Both components are probably unresolved implying a size of <2.25 Kpc and their separation of 7.5 Kpc is much less than the visible extent of the optical structure, viz: 25 Kpc x 33 Kpc. It is
interesting that the extension of the source from the nucleus is approximately in the direction of the single spiral arm.

3C3101

The 1400MHz QMT map (411) was unfortunately badly distorted by the large percentage polarization of this source. The maps made by the WSRT at the same frequency illustrate this point. The total intensity structure is very simple, comprising an almost smooth bridge between two broad components without any compact features. However, the polarization structure is very complex, with several peaks of polarized emission scattered circumferentially around the N (most extended) component. The polarization vectors around the edges of the component are approximately radial, similar to those seen in 3C219 and 3C353 (448). These latter two sources also had only one component with a radial polarization structure. The 5Km telescope observations showed only the presence of a compact feature coincident with the nucleus of the galaxy, the rest of the source structure being resolved out.

3C323.11

The new map shows that both the outer components of this source have narrow tails, that on the S component pointing along the source axis and that on the N making an
angle of approx. 40 degrees with it. The central component is weak and is not exactly coincident with the QSS, though the discrepancy is less than the combined optical and radio positional errors. The quasar is probably in a cluster of galaxies (359).

353.26.11

The 5Km has shown this previously unresolved source to consist of two unresolved components separated by 5 arcsec. The discrepancy in flux densities at all frequencies between total power and interferometer measurements indicate that this source may have a very large halo surrounding it (313). The latest optical observations by Sandage (393) show that the field of this source is empty and it has been re-classified as unidentified.

353.338

A peculiar double source with no compact features visible at lower frequencies, this has now been shown to possess an unresolved CCC coincident with the brightest nucleus of the multiple galaxy NGC6166. The only other features visible in the 5Km map were the outer edges but these were very faint and nearly resolved out. The 5GHz MSRT map shows that both the outer components possess compact structure, and that the E component has a diffuse tail extending away from the CCC.
**3C346:**

Not previously mapped, the source is now seen to have a curious 'double plus tail' structure, with the 10 m galaxy suggested by Wyndham (1994) as identification approximately coincident with the central peak. The separation of the double structure is approx. 6kpc though the envelope has an overall extent closer to 40kpc.

**3C371:**

(4C69.24) Unresolved (Total angular extent <1.0 arcsec).

**3C380:**

Small (Total angular extent 0.85 arcsec). A position angle of 123 degrees for the source axis was measured.

**3C386:**

The source is large (approx. 220 arcsec) and diffuse, and the only feature not completely resolved by the 5Km observations was a weak structure coincident with the nucleus of the galaxy, not visible in the earlier maps. This is nonetheless very interesting because it is a well resolved central feature which is strongest at the position of the optical nucleus and curves slightly away to the S.
There is a wealth of detail to be seen in the new maps of the outer components of this source which has been described by Hargrave & McEllin 1975 (401). The central component is still unresolved (<1.5Kpc), but the northern component has 2 compact regions separated by about 25 arcsec, the first lying at the extreme northern edge of the source, and the other further toward the N-galaxy but slightly off axis. This structure is reminiscent of the double outer components seen (with less resolution) in 3C204. There is a diffuse bridge connecting both the N components and both have tails extending approximately towards each other. The S component has only one compact emission region, extended approximately perpendicularly to the source axis and diffusely extended more parallel to the source axis.

This peculiar, large source (approx. 340 arcsec) has been shown by the WSRT (414) to be strongly polarized in all three components, the latter being linked by a weak bridge of emission. The 5Km map shows the presence of compact unresolved features at the S and central components but no compact features are visible in the region of the N component, despite the presence of a compact polarized emission region (414).
Although considerably more extended than the OMT 5GHz beam, this source showed no features other than a single broad component to the S with a long, weak, completely featureless tail, asymmetrically placed about the parent D4 (double) galaxy. The 5Km telescope has shown that the 'broad component' consists of 4 or 5 individual peaks of emission and the polarization vectors around the edge of the S component are approx. radial (see notes for 3C310). The weak tail is seen to have a weak, extended peak which is very approximately symmetrically placed about the galaxy with respect to the stronger component. If one attempts to parameterize this source as a double, one measures an alignment angle of approx. 70 degrees though it is by no means clear from which of the S peaks one should measure.

Completely resolved by the 5Km. (Total angular extent approx. 300 arcsec). OMT resolution at 1400MHz is 17 Kpc.

Only a CCC coincident with the galaxy was seen with the 5Km (total angular extent approx. 300 arcsec). OMT resolution at 1400MHz is 12 Kpc.
3C454.3

Unresolved, <1 arcsec.

3C460:

Not previously mapped, this source is now seen to be a compact double (components unresolved) with the stronger component nearly coincident with the centre of the E5 galaxy.

3C465:

5Km telescope observations showed only the two components (C and D of Riley, 1973 [396]) coincident with and adjacent to the nucleus of the giant D4 galaxy. The central component is unresolved (<0.8kpc) whilst the following component is resolved into an asymmetric double structure with axis pointing away from the nucleus of the galaxy.

3.4.1. Identifications

It was not expected that this programme would produce any new identifications of sources since all the objects under investigation were nominally identified. However, the higher resolution of the new observations has clarified the case of 3C303 as already described.
Recent work published by Katem, Kristian and Sandage (1974, (394)), has indicated that the field of 3C326.1 is effectively empty of likely identifications (down to a limiting magnitude of approx 23) and we have rejected the previous identification of Wyndham (094). 3C326.1 has also been eliminated from our sample, which now contains 39 sources.

3.4.11 Misclassifications

Since the original sample was selected, observations by the WSRT (418) at 1400 MHz have revealed that 3C236 consists of two very large low brightness components, (with a projected separation of approx. 5.7Mpc) as well as the compact component (approx. 4Kpc) seen in the DMT observations. This has resulted in there being one less object in the smallest selected linear size range, and one extra in the largest such range. Since 3C236 was selected on the basis of its small spectral index (because it was the spectral index of the central component only that was used) it would seem reasonable to now reject this object. In view of the extraordinary size of the source however, it was felt advantageous to retain it as without such a large source, the sample would not be representative.
3.5 Results of the Survey

Since 5Km maps of many of the sources in the representative sample have been published elsewhere (Pooley & Henbest, 1974 (460), Riley & Pooley 1975 (456)), and because we do not intend to analyse individual sources here, we shall not present the maps themselves. However, it will be clear from section 3.3 that a wealth of new information was gained from the survey. Since the inception of the survey of the representative sample, many other 3CR sources have been observed with the 5km telescope. It is thus a little artificial to now consider our results in isolation and most appear in Chapter 5. However, certain aspects are best dealt with only in the light of our survey and these will be discussed first.
a) **Compact Features**

Probably the most striking result is that although the 38 sources were chosen to be the nearest of their respective types, and thus would be observable with the greatest possible resolution, all but three contained some compact unresolved features when observed with the 5Km telescope. The exceptional sources were 3C35, 3C76.1 and 3C449, all large, radio-weak diffuse objects. These were completely resolved by the 5Km. Over half the sources have structure in the components, still unresolved and this clearly necessitates even higher resolution observations by future telescope designs. This also indicates that the vast majority of powerful radio sources should be expected to contain very compact regions of emission on a scale of approximately 4 Kpc or less, as many of the sources in our sample have been observed with a resolution better than this.

Amongst the unresolved features are:

a) most of the central components. It seems likely that many of these will not be resolved until resolutions of ~100pc are achieved if 3C405 is typical (Hargrave, private communication).
b) the details of the 'jet' structure seen in 3C219 (and also in M87, 3C272 and 3C66.02, Turland 1975 (45Z))

c) the compact heads or hot-spots seen either singly or multiply in the outer components of many powerful doubles. These features are intimately bound-up with the radio emission mechanism and until we understand their role in this, we shall not be able to formulate a comprehensive radio source theory. It is vital to know the details of the most compact parts, as these should tell us whether the energy is being supplied continuously from the central object or not (and if so, perhaps in what form). For example, if energy and/or matter beams are impinging on the surrounding intergalactic gas at the hot spots we would expect to see asymmetric shock fronts, whereas if an intrinsic energy source resides there, we should expect the finest details to be approximately spherically symmetric.

Observations of the nearest powerful source, 3C405 (Hargrave & Ryle 1974, (421)) have gone some way to answering these questions, but even here unresolved features still remain, and it is important to study many other sources to verify ones conclusions. The types of features seen within the outer components are described collectively in the following section ('Extended Features'): it should be borne in mind that these 'extended' features generally comprise several
compact emission regions linked by diffuse structure.

It is interesting to note that of the 4 sources which are totally unresolved, 3 were included in the sample because of their abnormally low or abnormally high spectral indices ($\alpha < 0.3$, 3C286, 3C454.3 - both quasars; $\alpha > 0.9$, 3C84). Two other sources were only slightly resolved (but not sufficiently for structure to be apparent) and these were from the QS and high luminosity classes.

Seven sources were shown to possess previously undiscovered compact central components. These were 3C47, 3C83.11, 3C219, 3C277.3, 3C310, 3C338 and 3C386. This brings the total number of sources in the sample having central components, up to 20; i.e. $> 50$ per cent.

b) Extended Features

The main contribution of the 5Km to map quality in this survey has been due to its ability to resolve features within components. A few sources were newly resolved into components but since most sources in the sample are relatively close (i.e. small redshift), because of the way the sample is defined, this did not often occur. The
components themselves are now frequently seen to consist of two or more compact emission regions with surrounding more diffuse envelopes, forming tails. The line defined by the position of the dominant pair of subcomponent peaks is often highly non-aligned (>45 degrees) with the source major axis (3C33, 3C123, 3C196, 3C219, 3C390.3, 3C433) (see e.g. Harris 1974, (390)).

There also appears to be a critical scale size for structure in the outer subcomponents. An examination of the maps indicates that wherever a source has been observed with a resolution better than 5Kpc, component substructure appears (14 sources). Only in 3 cases where the resolution is worse than this (approx. 10 Kpc) do the components still appear structured (3C123, 3C196, 3C249.1). There are two classes of exceptions to the above rule. One is the set of sources (three members, 3C35, 3C76.1, 3C442.01) which are completely resolved out when observed with better than 5Kpc resolution and the other is the class of very small sources (total size <7.5Kpc) (two members, 3C84, 3C305) whose components are still unresolved. The scale size of 5 to 10 Kpc may be closely connected with the energy conversion mechanism in the source components and if found to be statistically significant in a complete sample of sources, will need to be investigated theoretically.
Many other novel extended features have been seen in this survey as detailed in the notes on individual sources, one of the most remarkable being the 'jet' apparently connected with the central component of 3C219 (Turland 1975 (452) has investigated the theoretical implications of this observation). The very complex asymmetrical structure of 3C433 was also most unexpected in view of the previous maps. This source is now the most powerful 'complex' source known (P178 is approx. 1.9E26 W Hz sr⁻¹) and this indicates that even more-powerful sources may be found to possess complex overall structure when looked at with sufficient resolution.

The central components of 3C236 and 3C386 have both been resolved in this survey. These are the only 2 central components to have been resolved with a synthesis instrument. In addition, structure closely associated with the central component was well resolved in 3C219. That we found these three extended structures in such a small survey-sample is an indication of the usefulness of this method of selecting a sample for observation by a new instrument with higher resolving power.
The small size (approx. 1kpc), low luminosity ($P_{178} = 5.1E21 \text{ W Hz}^{-1}\text{sr}^{-1}$) and flat spectrum ($\alpha = 0.24$) make 3C231 a most unusual source, though these characteristics are vaguely reminiscent of those of a central component of an old (i.e very large) double radio source like, for example, 3C236. Large very diffuse components may well be awaiting discovery though the association will be difficult to confirm as 3C231 is very close (approx. 3Mpc), placing us at about the same distance from the source as the components of 3C236 are from their parent galaxy.

### q) Twin-sources

Many of the poorly resolved sources look similar to each other merely because of the sparsity of measured differences. However, one pair of unusual sources are quite similar in detail. 3C338 (as mapped by the WSRT at 5GHz (435)) and 3C277.3 (5Km, 5GHz) have a similar overall size (within a factor of 2); both have central components coincident with giant D-galaxies, highly bent major axes (130 and 150 degrees, respectively) and both have one compact component and one diffuse component, the latter having a steeper 'trailing' edge than 'leading' edge. They also have surrounding diffuse bridges of emission extending well beyond the peak of the diffuse component. The spectral indices are significantly different however; 3C277.3 has
J.J3, \[ \alpha_{\text{LF}} = 0.71, \alpha_{\text{HF}} = 0.65, \] whereas 3C33B has \[ \alpha_{\text{LF}} = 1.1, \alpha_{\text{HF}} = 1.54. \] The 178MHz luminosities are within a factor of 2 of each other. Given that in general, spectral indices steepen with age, it is a little surprising that the smaller (by a factor of 2) of these sources has the smaller (by a factor of 1.6 at LF or 2.4 at HF) spectral index. Any source theory capable of describing in detail, how sources with this type of structure may be formed, must also be able to explain how the spectral histories may deviate so much during the formation, with such little apparent effect on the physical distribution of emission.

3.6 General Statistical Properties of the Sample

Table 3.6.1 lists the important numerical data for the 39 sources in our sample, including the new information gleaned from the 5Km observations. We now briefly assess the current sample properties.

Of the 26 double and triple sources, 65 per cent have one observed component coincident with the optically associated object. Of the remaining 12 sources, at least 7 (=58%) have radio emission from the optical centre and a further four have a radio size which places the entire emitting region within a distance of 5Kpc of the centre of
Table 3.6.1. Data for the 39 sources in the representative sample after the 5Km observations had been completed.

<table>
<thead>
<tr>
<th>INDEX</th>
<th>SOURCE-HD.</th>
<th>SOURCE-NAME</th>
<th>OPT. TYP</th>
<th>REDSHIFT</th>
<th>RAD. TYP</th>
<th>P-1774</th>
<th>12</th>
<th>RAD. LINRESL</th>
<th>LIMRESL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2C</td>
<td>3C 31.00</td>
<td>SUB</td>
<td>0.01700</td>
<td>DCP</td>
<td>1.537E+24</td>
<td>168.656</td>
<td>38.3966</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>3C 33.00</td>
<td>E4F</td>
<td>0.06400</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>3C 35.00</td>
<td>D3</td>
<td>0.26700</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>3C 43.00</td>
<td>E5</td>
<td>-0.36413</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>33</td>
<td>3C 47.00</td>
<td>E5</td>
<td>0.42500</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>36</td>
<td>3C 49.00</td>
<td>D5</td>
<td>-0.26400</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>50</td>
<td>3C 76.10</td>
<td>DE3</td>
<td>0.32360</td>
<td>TST</td>
<td>4.523E+24</td>
<td>592.2527</td>
<td>3.1546</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>53</td>
<td>3C 83.11</td>
<td>ER3</td>
<td>0.02560</td>
<td>CCE</td>
<td>5.031E+24</td>
<td>367.0048</td>
<td>1.6234</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>55</td>
<td>3C 96.00</td>
<td>EDY</td>
<td>0.01700</td>
<td>DCP</td>
<td>1.537E+24</td>
<td>168.656</td>
<td>38.3966</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>61</td>
<td>3C 98.06</td>
<td>F9</td>
<td>0.03860</td>
<td>DCP</td>
<td>1.537E+24</td>
<td>168.656</td>
<td>38.3966</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>72</td>
<td>3C 112.00</td>
<td>G</td>
<td>0.65790</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>139</td>
<td>3C 181.00</td>
<td>G5</td>
<td>1.39240</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>115</td>
<td>3C 192.00</td>
<td>DE1</td>
<td>0.05960</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>117</td>
<td>3C 196.00</td>
<td>CS5</td>
<td>0.81160</td>
<td>DTP</td>
<td>1.657E+24</td>
<td>41.7987</td>
<td>13.6171</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>132</td>
<td>3C 219.00</td>
<td>DTF</td>
<td>0.12740</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>145</td>
<td>3C 231.00</td>
<td>IR</td>
<td>0.001017</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>147</td>
<td>3C 236.00</td>
<td>DE4</td>
<td>0.02970</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>158</td>
<td>3C 249.10</td>
<td>QS</td>
<td>0.31160</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>164</td>
<td>3C 264.00</td>
<td>DE1</td>
<td>0.07200</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>177</td>
<td>3C 277.10</td>
<td>E2</td>
<td>0.02290</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>179</td>
<td>3C 278.00</td>
<td>E2</td>
<td>0.04100</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>196</td>
<td>3C 277.30</td>
<td>D2</td>
<td>0.06790</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>199</td>
<td>3C 281.00</td>
<td>D2</td>
<td>0.44590</td>
<td>U</td>
<td>6.410E+27</td>
<td>7.60041</td>
<td>4.6914</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>207</td>
<td>3C 303.00</td>
<td>SAP</td>
<td>0.001107</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>209</td>
<td>3C 305.00</td>
<td>T</td>
<td>0.09410</td>
<td>DTP</td>
<td>2.506E+24</td>
<td>183.8911</td>
<td>15.5162</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>213</td>
<td>3C 307.00</td>
<td>T</td>
<td>0.26490</td>
<td>TST</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>225</td>
<td>3C 327.10</td>
<td>G5</td>
<td>0.43010</td>
<td>TST</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>237</td>
<td>3C 339.00</td>
<td>DAD</td>
<td>0.52890</td>
<td>TST</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>243</td>
<td>3C 346.00</td>
<td>G</td>
<td>-0.03994</td>
<td>E2T</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>256</td>
<td>3C 389.00</td>
<td>G5</td>
<td>0.69110</td>
<td>E2T</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>259</td>
<td>3C 389.10</td>
<td>G</td>
<td>0.01770</td>
<td>E2T</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>264</td>
<td>3C 395.20</td>
<td>N</td>
<td>0.03600</td>
<td>E2T</td>
<td>2.232E+24</td>
<td>364.8628</td>
<td>16.6326</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>278</td>
<td>3C 602.00</td>
<td>D3C</td>
<td>0.02470</td>
<td>CTE</td>
<td>2.729E+24</td>
<td>267.0304</td>
<td>1.0347</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>300</td>
<td>3C 673.00</td>
<td>DD</td>
<td>0.10750</td>
<td>CDB</td>
<td>1.911E+26</td>
<td>135.0292</td>
<td>5.2935</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>310</td>
<td>3C 674.01</td>
<td>DD1</td>
<td>0.10750</td>
<td>CDB</td>
<td>1.911E+26</td>
<td>135.0292</td>
<td>5.2935</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>312</td>
<td>3C 699.00</td>
<td>DE4</td>
<td>0.31840</td>
<td>D2</td>
<td>1.517E+24</td>
<td>279.0876</td>
<td>14.7305</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>317</td>
<td>3C 664.30</td>
<td>QS</td>
<td>0.85000</td>
<td>TD</td>
<td>2.877E+27</td>
<td>-8.01908</td>
<td>-10.6776</td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>322</td>
<td>3C 660.30</td>
<td>G</td>
<td>0.27000</td>
<td>DDS</td>
<td>2.621E+28</td>
<td>325.3067</td>
<td>13.8159</td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>324</td>
<td>3C 668.40</td>
<td>D2E</td>
<td>0.03010</td>
<td>CCM</td>
<td>1.049E+25</td>
<td>440.3904</td>
<td>1.6619</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.6.1 (continued)

<table>
<thead>
<tr>
<th>INDEX</th>
<th>SOURCE-ID.</th>
<th>SOURCE-NAME</th>
<th>FLOW</th>
<th>CDSTRICT</th>
<th>LF.SPEC</th>
<th>ABS CD</th>
<th>L(D1-D2)</th>
<th>L(S1-S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>3C 33.52</td>
<td>11.401</td>
<td>0.7</td>
<td>0.5900</td>
<td>-23.005</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>3C 33.00</td>
<td>15.048</td>
<td>-3.0</td>
<td>0.6700</td>
<td>-22.005</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>3C 35.00</td>
<td>14.659</td>
<td>-1.0</td>
<td>0.9100</td>
<td>-23.555</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>3C 43.00</td>
<td>19.962</td>
<td>-2.0</td>
<td>0.7370</td>
<td>-26.168</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>33</td>
<td>3C 47.00</td>
<td>18.468</td>
<td>-2.0</td>
<td>0.9700</td>
<td>-24.184</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>34</td>
<td>3C 48.00</td>
<td>16.095</td>
<td>-2.0</td>
<td>0.4100</td>
<td>-25.782</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>3C 76.10</td>
<td>14.611</td>
<td>-2.0</td>
<td>0.7100</td>
<td>-23.935</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>8</td>
<td>53</td>
<td>3C 83.11</td>
<td>13.659</td>
<td>-2.0</td>
<td>0.7270</td>
<td>-22.340</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>9</td>
<td>54</td>
<td>3C 84.10</td>
<td>11.999</td>
<td>-2.0</td>
<td>0.9200</td>
<td>-23.987</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td>61</td>
<td>3C 111.00</td>
<td>15.673</td>
<td>-2.0</td>
<td>0.7600</td>
<td>-21.385</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>11</td>
<td>68</td>
<td>3C 121.00</td>
<td>14.117</td>
<td>-1.5</td>
<td>0.7700</td>
<td>-22.964</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>12</td>
<td>106</td>
<td>3C 193.00</td>
<td>13.673</td>
<td>-2.0</td>
<td>0.6800</td>
<td>-26.197</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>13</td>
<td>115</td>
<td>3C 192.70</td>
<td>16.829</td>
<td>-2.0</td>
<td>0.7400</td>
<td>-23.771</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>14</td>
<td>117</td>
<td>3C 192.00</td>
<td>14.973</td>
<td>-1.5</td>
<td>0.7700</td>
<td>-22.964</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>15</td>
<td>135</td>
<td>3C 219.00</td>
<td>17.707</td>
<td>-2.0</td>
<td>0.6700</td>
<td>-26.197</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>16</td>
<td>145</td>
<td>3C 221.00</td>
<td>15.245</td>
<td>-1.5</td>
<td>0.7400</td>
<td>-20.795</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>17</td>
<td>147</td>
<td>3C 216.00</td>
<td>15.787</td>
<td>-2.0</td>
<td>0.4200</td>
<td>-23.346</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>18</td>
<td>156</td>
<td>3C 249.10</td>
<td>15.658</td>
<td>-2.0</td>
<td>0.6200</td>
<td>-25.638</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>19</td>
<td>166</td>
<td>3C 249.40</td>
<td>12.795</td>
<td>-2.0</td>
<td>0.7600</td>
<td>-22.672</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>20</td>
<td>177</td>
<td>3C 272.1</td>
<td>9.356</td>
<td>-1.0</td>
<td>0.5700</td>
<td>-21.654</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>21</td>
<td>179</td>
<td>3C 279.10</td>
<td>9.237</td>
<td>-1.0</td>
<td>0.7900</td>
<td>-23.226</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>22</td>
<td>186</td>
<td>3C 277.30</td>
<td>15.827</td>
<td>-1.5</td>
<td>0.7100</td>
<td>-22.993</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>23</td>
<td>191</td>
<td>3C 274.00</td>
<td>17.249</td>
<td>-1.5</td>
<td>0.1900</td>
<td>-26.583</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>24</td>
<td>217</td>
<td>3C 313.00</td>
<td>17.232</td>
<td>-1.5</td>
<td>0.7200</td>
<td>-22.797</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>269</td>
<td>3C 305.00</td>
<td>13.678</td>
<td>-2.0</td>
<td>0.7900</td>
<td>-23.477</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>26</td>
<td>283</td>
<td>3C 312.00</td>
<td>15.185</td>
<td>-1.5</td>
<td>0.8900</td>
<td>-22.584</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>27</td>
<td>285</td>
<td>3C 313.00</td>
<td>16.658</td>
<td>1.0</td>
<td>0.6200</td>
<td>-24.464</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>28</td>
<td>237</td>
<td>3C 346.00</td>
<td>14.486</td>
<td>2.0</td>
<td>1.0000</td>
<td>-23.893</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>29</td>
<td>263</td>
<td>3C 346.10</td>
<td>14.931</td>
<td>-1.5</td>
<td>0.5700</td>
<td>-26.6891</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>256</td>
<td>3C 372.00</td>
<td>11.668</td>
<td>-2.0</td>
<td>0.7400</td>
<td>-26.689</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>31</td>
<td>259</td>
<td>3C 386.00</td>
<td>11.300</td>
<td>-2.0</td>
<td>0.5900</td>
<td>-21.355</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>32</td>
<td>264</td>
<td>3C 394.00</td>
<td>14.674</td>
<td>-1.0</td>
<td>0.7000</td>
<td>-23.153</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>33</td>
<td>286</td>
<td>3C 622.1</td>
<td>12.657</td>
<td>-1.0</td>
<td>0.5600</td>
<td>-22.160</td>
<td>1.3767</td>
<td>1.1387</td>
</tr>
<tr>
<td>34</td>
<td>312</td>
<td>3C 622.4</td>
<td>14.519</td>
<td>-1.0</td>
<td>0.7200</td>
<td>-24.548</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>35</td>
<td>340</td>
<td>3C 622.1</td>
<td>13.710</td>
<td>-1.0</td>
<td>0.7900</td>
<td>-22.668</td>
<td>-0.4258</td>
<td>0.0</td>
</tr>
<tr>
<td>36</td>
<td>317</td>
<td>3C 664.0</td>
<td>12.481</td>
<td>-1.0</td>
<td>0.5500</td>
<td>-22.795</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>37</td>
<td>317</td>
<td>3C 664.0</td>
<td>12.481</td>
<td>-1.0</td>
<td>0.5500</td>
<td>-22.795</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>38</td>
<td>322</td>
<td>3C 641.00</td>
<td>12.590</td>
<td>-1.0</td>
<td>0.5400</td>
<td>-23.571</td>
<td>-0.2516</td>
<td>0.0</td>
</tr>
<tr>
<td>39</td>
<td>324</td>
<td>3C 641.00</td>
<td>12.590</td>
<td>-1.0</td>
<td>0.6200</td>
<td>-23.377</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
the parent object; i.e. well within the bright optical envelope.

Eleven (=61%) of the 18 'simple' double and triple sources have 'bent' (non-aligned) tails on their components whilst 8 (=44%) of them have observable bridges of emission linking the whole source. At least 14 (=37%) of the whole group of 38 sources are linked by such a bridge. Eight (=44%) of the 'simple' doubles and triples have major axes which are bent by 10 degrees or more. It is not very meaningful to talk about bent axes when referring to other types of source as there appear to be no principal axes within them which have particular physical significance. Seven (39%) of the doubles and triples have one component much more compact than the other and all have unresolved structure in at least one of the outer components. We have also looked for similarities between sources in each of the selection groups, (e.g. between the sources included in the sample because they all had steep spectra), but no new significant effects have appeared in the 5Km data.

3.7 Conclusion

We have discussed the specification of an 'optimum' sample for initial observation by the 5Km, and shown how it
may be simply selected using the RADARS system. We have described the new information about individual sources that emerged from this programme, how it affects the sample itself and how it has led to the discovery of the first resolved central components of powerful double radio sources. It is apparent that much unresolved structure remains in the outer components of most doubles and the survey clearly indicates the need for future instruments to have even higher resolution. Finally we note that a particular scale size of approx. 7 kpc is apparent in the structure of individual components.
Correlations between the properties of extragalactic radio sources and membership of clusters of galaxies are examined for a complete sample of radio galaxies. It is found that there is no significant difference in the overall sizes of double radio sources in clusters and those in the general field. There is no preference for complex radio sources to be associated with clusters of galaxies. Complex structure is observed mainly in low power sources, though this is partially explicable in terms of resolution effects. No evidence is found for any difference in properties between radio sources in clusters and those in the general field. It is inferred that there is no evidence from the radio data for increased ambient gas density in clusters of galaxies.
4.1 Introduction

It is generally believed that the structures of extended extragalactic radio sources are influenced by the density of the surrounding gas (De Young & Axford 1967 (022); Longair, Ryle & Scheuer 1973 (404), Scheuer 1974 (425), Gull & Northover 1973 (389)). Since the intergalactic gas in clusters may well be of higher density than in the general intergalactic medium, one can attempt to test this hypothesis by looking for differences between radio sources known to be in clusters and those in the general field. The analysis in the present paper is based upon a complete sample of radio galaxies which is itself a subset of a complete sample of 199 extragalactic radio sources in the 3CR Catalogue which have $S_{178} > 9\, \mu$Jy, $|b| > 10^\circ$, and $\delta > 10^\circ$ (Longair & Macdonald 1969 (213)). This latter sample has been studied extensively both at optical and radio wavelengths, and detailed structural information is available for all of the sources identified with relatively nearby galaxies ($m_v < 17.5$). It is almost certain that optical identifications with such galaxies are complete.

The selection procedure for the sample of galaxies is
described in Section 4.2 and in Section 4.3 we investigate the claim by De Young 1972 \((\text{a28})\) that the average sizes of simple double radio sources in clusters of galaxies are smaller by a factor of about two than those not in clusters. We then investigate (Section 4.4) the relationship between source structure and cluster membership, and finally look more closely at the 'complex' sources. This analysis follows closely that described in Hooley 1974 \((\text{d22})\), but takes advantage of the latest optical and radio data acquired since the writing of the original paper.

4.2 Selection of a Complete Sample of Bright Radio Galaxies

If radio sources are confined by ram pressure (De Young & Axford 1967 \((\text{l27})\)), the deceleration is expected to be greater in regions of high ambient gas density \(\rho\) and the average component separation correspondingly less. By comparing the sizes of simple double sources in and out of clusters, De Young 1972 \((\text{a28})\) hoped to test this model. Since it entails no assumptions about the initial state of components and treats only their later confinement, there seems no \textit{a priori} reason to consider only simple double sources but our analysis was initially restricted to these so as to be directly comparable with that of De Young.

We have also investigated the relationship between source
4.4 luminosity of the nearest and most luminous galaxies, as well as the luminosity of the nearest and most luminous star clusters. The definition of 'D', 'D_1', and 'D_2' for the single double sources (also applies to triple sources). 'D' without a suffix is used interchangeably with 'I' in the text.

![Diagram](image-url)
richness class (0) being defined such that there are between 39 and 50 galaxies in the cluster not less than 3 magnitude fainter than the brightest cluster member, whilst Zwicky counted very few clusters containing less than 50 members. Furthermore, these catalogues are not complete down to any well defined limiting magnitude of brightest cluster member.

In the present investigation we have extended the range of groupings which can be accepted as clusters. Galaxies are here assigned a 'cluster-richness' which for those in 'rich' clusters is defined in the same way as in Abell's catalogue, and takes values from 0 to 5. Galaxies which have been reported to be in clusters or groups by the authors who identified them as radio galaxies, or by subsequent workers, have been assigned a cluster richness of -1, except where those workers have explicitly stated that the cluster is of Abell-richness 'x', in which case 'x' is the value assigned. Galaxies which have never been reported to be in clusters, or which have explicitly been stated to be field galaxies, are assigned a value of cluster richness -2. This scheme can be further refined in subsequent work, if and when more optical data become available.
3C236 has been excluded from this analysis (although it satisfies all the selection criteria for our sample) because it is by far the largest double radio source known, and if unique should not be used in the comparisons we are about to make. If it is not unique, then we must first know how this class of very large objects is distributed amongst the various galaxy clusterings, for it is worthless to include only one such source. Alternatively, one may take the point of view that 3C236 is already so large that its outer components are already outside the cluster of galaxies.

Since we are trying to estimate the effect of embedding a radio source in a cluster of galaxies, sources smaller than 20kpc in extent, the components of which will almost certainly still be within the inner envelope of the parent galaxy, have been excluded. We should also bare in mind that the cores of Abell clusters are only 200 to 300 kpc in diameter, smaller than some of the larger radio sources in our samples. The resulting sub-sample of 37 sources is listed in Table 4.2.1 and measured redshifts are available for all but two (3C288 and 3C341.1) of these. It should be noted that 3C303, which appeared in the original analysis has been omitted here since recent optical data (Lelievre and Wierick, 1975 (452)) show that it does not
Table 4.2.1.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>TYPE</th>
<th>D(Kpc)</th>
<th>D1/D1</th>
<th>D2/D2</th>
<th>CLUSTER RICHNESS</th>
<th>P178</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C33</td>
<td>T</td>
<td>392</td>
<td>&lt;0.045</td>
<td>0.036</td>
<td>-2</td>
<td>6.1E25</td>
</tr>
<tr>
<td>3C76.1</td>
<td>D</td>
<td>40.3</td>
<td>&lt;1.83</td>
<td>&lt;1.26</td>
<td>-2</td>
<td>3.5E24</td>
</tr>
<tr>
<td>3C98</td>
<td>D</td>
<td>233</td>
<td>&lt;0.278</td>
<td>0.267</td>
<td>-2</td>
<td>1.3E25</td>
</tr>
<tr>
<td>3C219</td>
<td>T</td>
<td>547</td>
<td>0.151</td>
<td>0.347</td>
<td>+2</td>
<td>4.8E26</td>
</tr>
<tr>
<td>3C338</td>
<td>T</td>
<td>34.3</td>
<td>&lt;0.682</td>
<td>&lt;0.750</td>
<td>+2</td>
<td>1.3E25</td>
</tr>
<tr>
<td>3C388</td>
<td>T</td>
<td>70.9</td>
<td>0.585</td>
<td>0.479</td>
<td>0</td>
<td>6.4E25</td>
</tr>
<tr>
<td>3C442</td>
<td>D</td>
<td>196</td>
<td>&lt;0.697</td>
<td>&lt;0.521</td>
<td>0</td>
<td>4.8E24</td>
</tr>
<tr>
<td>3C31</td>
<td>D</td>
<td>168</td>
<td>-1</td>
<td></td>
<td></td>
<td>1.5E24</td>
</tr>
<tr>
<td>3C35</td>
<td>T</td>
<td>927</td>
<td>0.15</td>
<td>0.17</td>
<td>-1</td>
<td>2.0E25</td>
</tr>
<tr>
<td>3C184.1</td>
<td>D</td>
<td>473</td>
<td>&lt;1.35</td>
<td>&lt;1.10</td>
<td>-1</td>
<td>5.9E25</td>
</tr>
<tr>
<td>3C192</td>
<td>T</td>
<td>289</td>
<td>0.04</td>
<td>0.12</td>
<td>-1</td>
<td>2.4E25</td>
</tr>
<tr>
<td>3C223</td>
<td>D</td>
<td>929</td>
<td>0.073</td>
<td>0.141</td>
<td>-1</td>
<td>9.6E25</td>
</tr>
<tr>
<td>3C223.1</td>
<td>D</td>
<td>186</td>
<td>0.437</td>
<td>0.210</td>
<td>-1</td>
<td>3.8E25</td>
</tr>
<tr>
<td>3C234</td>
<td>D</td>
<td>430</td>
<td>&lt;0.474</td>
<td>&lt;0.347</td>
<td>-1</td>
<td>3.6E26</td>
</tr>
<tr>
<td>3C277.3</td>
<td>T</td>
<td>62.6</td>
<td>0.870</td>
<td>1.35</td>
<td>-1</td>
<td>2.9E25</td>
</tr>
<tr>
<td>3C285</td>
<td>D</td>
<td>271</td>
<td>0.439</td>
<td>0.368</td>
<td>-1</td>
<td>2.4E25</td>
</tr>
<tr>
<td>3C314.1</td>
<td>D</td>
<td>595</td>
<td>&lt;1.05</td>
<td>&lt;4.04</td>
<td>-1</td>
<td>6.8E25</td>
</tr>
<tr>
<td>3C322</td>
<td>D</td>
<td>248</td>
<td>0.408</td>
<td>0.139</td>
<td>-1</td>
<td>8.5E25</td>
</tr>
<tr>
<td>3C357</td>
<td>D</td>
<td>274</td>
<td>&lt;0.587</td>
<td>&lt;0.501</td>
<td>-1</td>
<td>8.7E25</td>
</tr>
<tr>
<td>3C381</td>
<td>D</td>
<td>245</td>
<td>&lt;0.08</td>
<td>&lt;0.03</td>
<td>-1</td>
<td>1.1E26</td>
</tr>
<tr>
<td>3C382</td>
<td>T</td>
<td>273</td>
<td>0.64</td>
<td>&lt;0.12</td>
<td>-1</td>
<td>2.4E25</td>
</tr>
<tr>
<td>3C390.3</td>
<td>T</td>
<td>319</td>
<td>0.031</td>
<td>0.035</td>
<td>-1</td>
<td>4.9E25</td>
</tr>
<tr>
<td>3C436</td>
<td>T</td>
<td>289</td>
<td>&lt;0.02</td>
<td>&lt;0.06</td>
<td>-1</td>
<td>2.6E26</td>
</tr>
<tr>
<td>3C452</td>
<td>D</td>
<td>506</td>
<td>0.05</td>
<td>0.10</td>
<td>-1</td>
<td>1.2E26</td>
</tr>
<tr>
<td>3C28</td>
<td>E</td>
<td>121</td>
<td>+3</td>
<td></td>
<td></td>
<td>2.0E26</td>
</tr>
<tr>
<td>3C66</td>
<td>C</td>
<td>159</td>
<td>0</td>
<td></td>
<td></td>
<td>4.3E24</td>
</tr>
<tr>
<td>3C83.1B</td>
<td>C</td>
<td>244</td>
<td>+2</td>
<td></td>
<td></td>
<td>1.5E24</td>
</tr>
<tr>
<td>3C197.1</td>
<td>U</td>
<td>36.7</td>
<td>-1</td>
<td></td>
<td></td>
<td>5.7E25</td>
</tr>
<tr>
<td>3C264</td>
<td>S</td>
<td>186</td>
<td>+2</td>
<td></td>
<td></td>
<td>3.5E24</td>
</tr>
<tr>
<td>3C288</td>
<td>C</td>
<td>34</td>
<td>-1</td>
<td></td>
<td></td>
<td>8.0E25</td>
</tr>
<tr>
<td>3C310</td>
<td>C</td>
<td>360</td>
<td>-1</td>
<td></td>
<td></td>
<td>5.3E25</td>
</tr>
<tr>
<td>3C315</td>
<td>C</td>
<td>361</td>
<td>0</td>
<td></td>
<td></td>
<td>7.3E25</td>
</tr>
<tr>
<td>3C386</td>
<td>C</td>
<td>102</td>
<td>-1</td>
<td></td>
<td></td>
<td>2.6E24</td>
</tr>
<tr>
<td>3C402</td>
<td>C</td>
<td>261</td>
<td>-1</td>
<td></td>
<td></td>
<td>2.7E24</td>
</tr>
<tr>
<td>3C433</td>
<td>C</td>
<td>52.7</td>
<td>-1</td>
<td></td>
<td></td>
<td>1.9E26</td>
</tr>
<tr>
<td>3C449</td>
<td>C</td>
<td>274</td>
<td>-1</td>
<td></td>
<td></td>
<td>1.5E24</td>
</tr>
<tr>
<td>3C465</td>
<td>C</td>
<td>440</td>
<td>+1</td>
<td></td>
<td></td>
<td>1.1E25</td>
</tr>
</tbody>
</table>

The subsample of 37 bright radio galaxies and their relevant parameters.
satisfy our sample criteria.

Prior to the selection of this subsample, the structures of the 197 sources in the 'complete sample' had already been classified on the basis of radio maps made with the One Mile Telescope and the 5km Telescope, together with VLBI information where appropriate. Of these 37 sources, only 23 were classified as 'simple' doubles. All of these have measured redshifts.

In 'simple' doubles the radio emission comes principally from two regions disposed roughly symmetrically on each side of the optical object and having similar luminosities and sizes. Two further types of source have also been included in this category: (i) double sources with compact central components associated with the optical objects (e.g. 3C390.3) and (ii) the few sources which appear to consist of pairs of components aligned on either side of the optical object (e.g. 3C61.1, 3C452). When observed with high resolution these are found to consist of outer compact components with trails of low brightness emission extending towards the galaxy.
A search of the literature reveals that for only 3 of these 23 sources is there evidence for membership of a cluster or group of galaxies. Of the rest, one object 3C338 lies in an Abell cluster (A2199) of richness class 2, and three others lie in clusters not in Abell's catalogue but which have been assigned similarly defined richness classes (Mathews, Morgan & Schmidt 1964 (122). The remainder have been described as belonging to clusters or small groups (Wyndham 1966 (293); Sargent 1966 (199), 1972 (467), (284); Burbidge & Strittmatter 1972 (664)). For convenience of description, the 23 sources have been grouped into 6 sub-samples. Sample 1 is the whole set of 23 objects; sample 2 those not known to be in any sort of cluster or grouping; sample 3 those in clusters with assigned Abell richness classes; sample 4 those in groups, or otherwise unclassified clusters; sample 5, those in either sample 3 or 4, the whole 'cluster' group; and sample 6, those not assigned Abell richness classes.

4.3. Source Sizes and Cluster Membership

The linear sizes (1) of the sources were computed from the redshifts and the angular extents of the objects, assuming \( H = 50 \text{ km s}^{-1} \text{Mpc}^{-1} \) and an Einstein-de Sitter world model. The choice of cosmological model is not critical since the greatest redshift under consideration is only
The luminosities were computed from the 3CR flux-densities at 178 MHz, the low-frequency spectral indices, and the redshifts. Table 4.2.1 lists the values of the source parameters under consideration, and the distribution of linear sizes for the whole sample of 23 is shown in Fig. 4.3.1. Table 4.3.1 lists the mean values and standard deviations for each sample.

The values of $d/D$ for each component were obtained directly from angular measurements. It is important to note that even with the high resolution of the One Mile Telescope at 5 GHz ($6.5 \times 6.5 \text{arcsec}^2$ arc sec) a large number of the source components are still unresolved perpendicular to the source axis (though a few of these sources, of small overall angular size, have now been observed with the 5 km Telescope and in some cases resolved) and so the values of $d/D$ used are mostly upper limits only. In Table 4.2.1, columns 4 and 5, those values of $d/D$ for which $d$ is known to be only an upper limit are preceded by the symbol '<'. Some of the remainder are also probably upper limits, as it is difficult to estimate when limiting resolution has been reached. The distribution of $d/D$ for all components is shown in Fig. 4.3.2 and the mean values and standard deviations for each sample are given in Table 4.3.1.

It is immediately apparent from the histogram that
Fig. A.3.7

The distribution of $d/D$ for the components of the 23 sources for which the parameter was measured. The hatched areas represent those components where the measurement of $d$ is known to be an upper limit only.
<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>N</th>
<th>$&lt;\Theta&gt;$ (Kpc)</th>
<th>s.e.</th>
<th>$&lt;\Theta(1/10)&gt;$</th>
<th>s.e.</th>
<th>$&lt;\Theta(2/20)&gt;$</th>
<th>s.e.</th>
<th>$&lt;\Theta_C&gt;$</th>
<th>s.e.</th>
<th>$&lt;\Theta_{CL}&gt;$</th>
<th>s.e.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL (I)</td>
<td>23</td>
<td>351.34</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
<tr>
<td>OUT (II)</td>
<td>7</td>
<td>231.6</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
<tr>
<td>ABELE (III)</td>
<td>4</td>
<td>212.2</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
<tr>
<td>SMALL (IV)</td>
<td>16</td>
<td>608.9</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
<tr>
<td>NOT OUT (V)</td>
<td>20</td>
<td>369.6</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
<tr>
<td>NOT ABELE (VI)</td>
<td>19</td>
<td>380.9</td>
<td>0.529</td>
<td>0.078</td>
<td>0.487</td>
<td>0.074</td>
<td>0.414</td>
<td>0.027</td>
<td>0.392</td>
<td>0.178</td>
<td>0.328</td>
</tr>
</tbody>
</table>

The means and standard errors of the linear size $<\Theta>$, size to separation ratios $<\Theta(1/10)$ and $<\Theta(2/20)$, high frequency spectral index $\phi_F$ and low frequency spectral index $\phi_L$ for the whole sample of 23 sources and the separate subsets discussed in the text. The upper row of figures for each subset are the arithmetic means and standard errors, whilst the lower figures are the geometric means and standard errors.
Abell-richness clusters. There is a selection effect which tends to lower the mean luminosity of the latter sample. If the identification of Abell-rich clusters is incomplete, it is likely to be the more distant ones that have been omitted. If these contain radio sources in our flux density limited sample, they are likely to be the more powerful sources. The difference in the means is however only 0.52σ, this being largely due to the large standard deviation of sample 3. Since the measured luminosities of the sources in the whole sample of 23 range from 3.5E24 (3C76.1) to 4.8E26 (3C219) it is useful to look at the logarithmic distributions instead, so that approximately equal weight is given to all sources in the samples when comparing their distributions. The logarithmic means for samples 2 and 3 are respectively 1.41E25 and 3.72E25 and their standard errors expressed as factors are 1.96 and 2.39. The ratio of the means (2.64) is then seen to be small compared to the product of their (logarithmic) standard errors, 4.67, this being equivalent to a 0.6σ result only. The result is nevertheless interesting because it is in the direction one might expect if powerful sources are confined by the pressure of a hot gas, and if such hot gas is indeed more plentiful in the richer clusters. It is also worth noting in this context that two of the most powerful radio galaxies, 3C295 and 3C405, are in rich clusters of galaxies (richness 1 and 2 respectively).
Sample 4 has the largest logarithmic mean (6.22E25) and the ratio of the means of samples 2 and 4 (4.41) is significant at only the 1.7σ level as measured by the test described above. Furthermore, as sample 2 has only 3 members and also since sample 3 (the clusters probably richer than those in sample 4) has a mean falling roughly halfway between the two undergoing comparison, this result is not significant.

Great care is needed when examining the d/D data. Many of the d-values are upper limits only, though De Young makes no mention of this, despite the fact that most of his data are obtained from lower resolution observations. The situation was further aggravated because, for 23 of the 34 sources he considered, Fomalont had assumed spherical source components. It is apparent from the synthesis maps that the sources cannot be adequately described in this way and we find that the components are much smaller than inferred by Fomalont; despite many of our values of d being upper limits, our mean values of d/D are approximately one half those deduced by De Young.
However, taking our data at face value, we see that the distribution of $d/D$ for the whole group has a long tail extending to large values. The majority of the components are in a group with $d/D$ between 0 and 0.75 and it is noteworthy that contrary to De Young's results, none of the three sources with values of $d/D$ greater than 1.0 are in Abell richness-classified clusters. The means and standard deviations show that there are no significant differences between any of the sample means. From the data in Table 4.2.1 it can be seen that there are no correlations between source size or $d/D$ ratio and cluster-membership, and our results do not support the findings of De Young.

In an attempt to improve the statistics we dropped the 'simple-double' criteria, replacing it by the requirement that the sources were merely to have one or more compact components separated from the optical object. The distances of each component from the optical object and its own dimensions were then considered as independent data. This procedure resulted in a list of sources virtually identical to that used in the first test, and the results were very similar and no more significant than the last.

Lastly, we repeated the test for the whole sample of
37 sources, regardless of radio structure, but omitting the d/D test because a large number of the sources do not possess well defined components for which meaningful measurements of d and D can be made. This produced a set of mean values for the sizes of sources in each cluster class that were less than 5 per cent different from those in the first test.

4.4 Source Morphology and Cluster Membership

An investigation was carried out to determine whether cluster membership influences the morphology of sources, if complex sources are preferentially associated with clusters of galaxies, for example. The sub-sample used in these investigations was the same as that in the last section. This sample of 37 sources was then partitioned in two ways, first by structural type, and secondly by cluster membership. The structural type classifications used were; complex (C), double (D), extended (E), triple (T), single (S), and unresolved (U). Of these, classifications U and E merely reflect an instrumental resolution limitation, while S implies that the source consists of one component but is resolved. The linear sizes quoted for the incompletely
Table 4.4.1.

The percentages of each type of structure in the cluster richness classes discussed in the text. The second column lists the percentages of each type expected if there is no correlation between radio source type and the richness of the cluster in which it is embedded.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OUT = 1 (3)</td>
<td></td>
<td>8</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>SMALL = 11 (23)</td>
<td></td>
<td>62</td>
<td>60</td>
<td>71</td>
<td>0</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>ABBELL = (11)</td>
<td></td>
<td>30</td>
<td>40</td>
<td>14</td>
<td>100</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>OUT+SMALL = 26</td>
<td></td>
<td>70</td>
<td>60</td>
<td>86</td>
<td>0</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Small+Abell = 26</td>
<td></td>
<td>92</td>
<td>100</td>
<td>86</td>
<td>100</td>
<td>90</td>
<td>100</td>
</tr>
</tbody>
</table>

The numbers in parentheses after the cluster types and the radio types are the numbers of those types in the whole sample of 37 sources.

The results of this classification are shown in Table 4.4.1. The similarity of the percentage values in each row is striking, indicating that there is no apparent correlation between source structure and cluster membership. To investigate further the complex sources a slightly different approach was used. Here we noted that 27 per cent of the sources in our sample were complex. This is in agreement with the extent of the detectability of complex sources in other surveys of comparable size. The result is thus not regarded as indicative of the true source size.

The sources were placed in one of three categories according to their cluster richness as previously defined: Class I is called 'out of clusters', having cluster richness of 0 and above; 8 per cent of the sources fell into class I. Class II is called 'small cluster', having cluster richness of 1-2, and 1 per cent of the sources fell into class II. Class III, having cluster richness of 3-4, and 39 per cent of the sources fell into class III. If there is a significant correlation between cluster membership and each structural type, then the percentage of the total number of sources in each class should be appreciably different from the percentages just quoted.
each cluster class that are complex allows a second comparison to be made. Table 4.4.2 shows the results of this test and it can be seen, for example, that 36 per cent of the sources in Abell clusters (class III) are complex, whereas the expected percentage from the statistics of the whole group is 27 per cent. The results for the other two classes are 0 per cent (none out of 3) and 26 per cent and in view of the small size of the sample these deviations from expected values are not significant.

The low- and high-frequency spectral indices, luminosity at 173 MHz and the total linear sizes of the sources were also examined in an attempt to find systematic differences between the complex sources and other structures. The mean values and standard deviations of these parameters are also listed in Table 4.4.2 for the two groups.

The mean values of both the high- and low-frequency spectral indices for the two groups are nearly identical and Fig. 4.4.1 shows that the distributions for the groups of complex and non-complex sources are very similar.

It is a remarkable achievement that in the short time since this work was first undertaken, the 5km Telescope has
Table 4.4.2.
The percentages of complex and non-complex sources in the various cluster classes. The second column indicates the expected percentages if there is no correlation between complexity of source structure and richness of clustering around the parent galaxy. The last four columns list the mean and standard errors of the source luminosity, low frequency and high frequency spectral indices, and the total linear size. The standard errors are parenthesised.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>EXPECTED</th>
<th>OUT-1</th>
<th>SMALL-II</th>
<th>ABELL-III</th>
<th>OUT-SMALL</th>
<th>NOT OUT</th>
<th>( \langle \gamma_{L,0} \rangle )</th>
<th>( \langle \gamma_{L,1} \rangle )</th>
<th>( \langle \gamma_{L,2} \rangle )</th>
<th>( \langle \gamma_{L,3} \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPLEX (10)</td>
<td>27</td>
<td>0</td>
<td>26</td>
<td>36</td>
<td>23</td>
<td>30</td>
<td>4.2E25</td>
<td>0.70</td>
<td>0.86</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1.2E25)</td>
<td>(0.03)</td>
<td>(0.06)</td>
<td>(69)</td>
</tr>
<tr>
<td>NON-COMPLEX (27)</td>
<td>73</td>
<td>100</td>
<td>74</td>
<td>64</td>
<td>77</td>
<td>70</td>
<td>8.7E25</td>
<td>0.76</td>
<td>0.82</td>
<td>319</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(4.0E25)</td>
<td>(0.02)</td>
<td>(0.04)</td>
<td>(45)</td>
</tr>
</tbody>
</table>
discovered two more complex sources, 3C288 and 3C433 both more powerful than any previously known, the latter having a luminosity about 10 times that of the mean value of the earlier known complex sources. An examination of the structure of 3C433 indicates that it has a two component structure, with very unequal component fluxes, a bridge of emission connecting the whole source and very extended and diffuse components. If it is the remnant of a simpler double structure it is not clear why the south component should be so close to the optical object(s) unless the source is significantly non-aligned with the plane of the sky. It is also interesting that 3C288 is smaller (62kpc) than any previously known complex source. Hoyle 1974 (422) remarked that the observed absence of powerful complex sources ($\log P>25.8$) in the complete 3CR sample of 197 sources might still be a selection effect due to angular resolution limiting the available 'kpc' resolution at larger redshifts, where complex sources might be expected to have greater luminosities. This suggestion has now been verified and it is clear that more complex sources may be awaiting discovery since 3C288 indicates that there are physically small complex sources too, which will need high resolution observations at even modest redshifts for adequate structural information to be obtainable. Fig. 4.4.2 shows that there is no correlation between size and luminosity for the complex sources.
The luminosity distributions of the complex and non-complex sub-samples are very different though it now seems clear that the distribution for complex sources may well be modified by telescope resolution effects. However, at least for the nearby galaxies (m < 17.5), the distribution of luminosity for the complex sources as shown in Fig. 4.4.3 must be almost complete as there are only two sources left in our complete sample of 37 sources which are not yet fully resolved. As neither of these have luminosities significantly different from known complex sources, their addition to Fig. 4.4.3 would not extend the high luminosity tail.

Fifty per cent of the complex sources have log P < 24.7 whereas only fourteen per cent (eleven per cent if 3C264, a single-component extended source, is removed) of the remainder have such low luminosities. 3C264 may be an example of a radio source which has no containment mechanism, the emission having a maximum coincident with the optical nucleus and broad featureless extended regions on either side. This source is in a cluster of richness 2.
We can try to estimate how many more as yet unresolved complex sources there might be in the complete-sample as follows. Let us also initially make the assumption that the luminosity distributions for the complex and the non-complex sources are the same and that the observed difference is entirely due to selection effects. This is a sort of 'worst-case' assumption since it looks from the previous discussion as if there really are more weak complex sources than simple structures. Let us then count the number $N_{pc}$ of sources in the complete-sample with luminosity not greater than $P_{c\text{max}}$, the luminosity of the most powerful known complex source. Of these, only a certain number, $N_r$, will have been observed with enough resolution to discern complex structure, if it exists. Of these $N_r$, $N_c$ are seen to be complex and thus a rough estimate of the proportion of complex sources is $N_c/N_r$. We have to check that all the $N_c$ complex sources are in the set $N_r$, otherwise we have made an error in our estimate of the number of beam sizes necessary to resolve complex structure. We can cross check the reality of the hypothesis about the luminosity distributions by seeing how many sources with $P > P_{c\text{max}}$ have been observed with enough resolution to see complex structure. Let this number be $N_{pc}$. On the basis of our hypothesis we expect to see $N_{pc} \times N_c/N_r$ complex sources in this set whereas in fact we see none. If the expected number is significantly greater than zero, then our hypothesis is wrong.
Performing the experiment, what we find is that 3C433 is the most powerful source seen to be complex, and there are 47 identified sources in the complete-sample less powerful than this. Of these 47, 32 have been observed with more than 6 beam sizes resolution (synthesis maps) and so any complex structure present should be known. We find that all 11 complex sources in the complete-sample are in the set of 32, and so a rough estimate of the proportion of complex sources with $P < P_{\text{cmax}}$ is $11/32$ or about 33 per cent. However, we should finally check that we have not overestimated this proportion (by demanding at least 6 beam sizes resolution) by looking at the structures of the remaining 15 sources for which the maps are less well resolved. If we know that all these are, for example, simple doubles, then higher resolution will not cause them to be reclassified as complex, and in that case our proportion should be only $11/47$. However, we find that for only 8 can we definitely say that the structures are not complex, so there remains the possibility that the proportion of complex sources in this set of 15 could be as high as $7/15$ ($>11/32$). We therefore accept 33 per cent as a reasonable estimate.
when we look at the sources with $P > P_{\text{cmax}}$ we find that 29 of them have been observed with more than 6 beams resolution. If our hypothesis about the complex and non-complex source luminosity functions is correct, we expect 33 per cent of these (i.e. about 10) to be complex: in fact there is not one. They are all simple doubles, some with central components, some with bridges and one with the proposed optical identification close to one of the components (3C254). We conclude that our hypothesis is incorrect and that there is only a small probability of finding any more complex sources in the complete-sample with higher luminosity than 3C433.

4.5 Cluster Membership

One of the salient points of this analysis is the finding that only 3 out of 37 sources in a complete sample have not been reported to be in a cluster or group of galaxies.

It is interesting to compare this result with the work of Karachentseva 1973 (436) who studied all galaxies brighter than $15^m.7$ on the National Geographic Palomar Sky Survey prints in the region of sky defined by $\delta > 3^\circ$, $|\lambda| > 20^\circ$. ($15^m.7$ is the Zwicky (437, 438) catalogue limit).
Karachentseva defined a galaxy of diameter 'd' to be isolated if there were no neighbours of diameter 'a' within a distance 20a, where $0.25d < a < 4d$. She found a total of 1051 such 'isolated' galaxies, representing 3.6 per cent of all the galaxies brighter than 15.7. Lastly, she estimated that of these 1051, 75 per cent were probably truly isolated in terms of energy interaction with neighbours.

These results are to be compared with those of de Vaucouleurs (440) who estimated that 85 per cent of all galaxies are in groups or clusters, and of Korwin (referenced by de Vaucouleurs, 440) who found 15 per cent of all the galaxies in a catalogue of 2595 to be isolated. Karachentseva notes that neither of the latter two authors makes a quantitative definition of the term 'isolated'.

To pursue this matter further we have compared the positions of all radio sources in 3CR identified with galaxies brighter than 15.7 with the positions of the objects in Karachentseva's catalogue and we find no correspondences at all. A few of these sources have been specifically reported to be isolated by Sandage 1973 (416) though in some cases, his observations are in conflict with those of others, and in particular, 3C382 appears to be
The available cluster information for the 3CR sources brighter than $15^m.7$, with declination greater than $-3^\circ$ and more than $20^\circ$ above the galactic plane.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>CLUSTER RICHNESS</th>
<th>CLUSTER MEMBERSHIP INFORMATION AND REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C29</td>
<td>Abell A119</td>
<td>(187): Isolated (284)</td>
</tr>
<tr>
<td>3C33</td>
<td>Abell A150</td>
<td>(187): Isolated (284)</td>
</tr>
<tr>
<td>3C71 (NGC1068)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C76.1</td>
<td>Isolated</td>
<td>(284)</td>
</tr>
<tr>
<td>3C78</td>
<td>Isolated</td>
<td>(284)</td>
</tr>
<tr>
<td>3C88</td>
<td>Probably in poor clustering (122): Isolated (284)</td>
<td></td>
</tr>
<tr>
<td>3C98</td>
<td>Isolated</td>
<td>(284)</td>
</tr>
<tr>
<td>3C293</td>
<td>Isolated</td>
<td>(284)</td>
</tr>
<tr>
<td>3C305</td>
<td>Isolated</td>
<td>(284)</td>
</tr>
<tr>
<td>3C15</td>
<td>-1 Brightest member of small group</td>
<td></td>
</tr>
<tr>
<td>3C192</td>
<td>-1 In cluster (001): In small group (284)</td>
<td></td>
</tr>
<tr>
<td>3C231</td>
<td>-1 In M81 group (172)</td>
<td></td>
</tr>
<tr>
<td>3C310</td>
<td>-1 In cluster (94): Faint, poor cluster (122)</td>
<td></td>
</tr>
<tr>
<td>3C357</td>
<td>-1 In cluster (094)</td>
<td></td>
</tr>
<tr>
<td>3C390.3</td>
<td>1 Has companion (277): At least 1 companion (199): Cluster or group of normal galaxies (104): At least 1 companion, possibly others too (286)</td>
<td></td>
</tr>
<tr>
<td>3C31</td>
<td>0 In cluster (94): In small group (284)</td>
<td></td>
</tr>
<tr>
<td>3C40</td>
<td>0 In A194 (122): In cluster (094)</td>
<td></td>
</tr>
<tr>
<td>3C75</td>
<td>1 In cluster (094): In A400 (195), (122), (187)</td>
<td></td>
</tr>
<tr>
<td>3C64</td>
<td>2 In A1367 (122), (185), (262)</td>
<td></td>
</tr>
<tr>
<td>3C70</td>
<td>1 In cluster (094): Virgo cluster (122)</td>
<td></td>
</tr>
<tr>
<td>3C72.1</td>
<td>1 In Virgo cluster (094), (122)</td>
<td></td>
</tr>
<tr>
<td>3C74</td>
<td>1 In Virgo cluster (094), (122)</td>
<td></td>
</tr>
<tr>
<td>3C296</td>
<td>0 Probably in small group (199): May be associated with A1890 (278)</td>
<td></td>
</tr>
<tr>
<td>3C117</td>
<td>0 In cluster (094): In A2052 (122), (187)</td>
<td></td>
</tr>
<tr>
<td>3C327</td>
<td>0 In cluster (094): Near edge of faint cluster (122)</td>
<td></td>
</tr>
<tr>
<td>3C38</td>
<td>2 In cluster (094): In A2199 (262), (255), (122)</td>
<td></td>
</tr>
<tr>
<td>3C371</td>
<td>0 In small cluster (287): N-galaxy in group (284)</td>
<td></td>
</tr>
<tr>
<td>3C442.01</td>
<td>0 Member of extended cluster (122): Has companion (094)</td>
<td></td>
</tr>
<tr>
<td>3C465</td>
<td>1 In A2634 (122), (187)</td>
<td></td>
</tr>
</tbody>
</table>
situated in a small cluster visible on the Palomar Sky Survey prints (Riley, private communication). The available observational data is summarised in Table 4.5.1.

Caswell and Wills (439) have looked for identifications of 4C sources with bright galaxies (mainly brighter than 15.7) and they list 80 '1st class' identifications and 27 '2nd class'. They estimate that less than 10 per cent of their 1st class identifications are incorrect, and that about 50 per cent of their 2nd class identifications may be due to chance. A comparison of their identifications with the galaxies in the Karachentseva catalogue reveals only one coincidence, namely 4C54.30.1, identified (1st class) with NGC5457, an 8.7 spiral, (hardly a 'typical' double radio source), and according to Karachentseva's estimate of the accuracy of her catalogue, there is a 1 in 4 probability that this galaxy is not truly isolated.

If the Karachentseva result is correct (i.e., if 2.7 per cent (=75 per cent of 3.6 per cent) of all galaxies are truly isolated) this implies that in 3CR with around 300 extragalactic sources, we should expect to find about 8 of them to be identified with isolated galaxies or quasars (if
there is no preference for a radio source to be in a cluster). In view of the incompleteness of the identifications and more importantly, the inhomogeneity and general sparseness of information regarding clustering around the sources, it will clearly be very difficult to decide whether radio galaxies are in fact more likely to be associated with cluster galaxies than isolated galaxies.

For our subsample of 37 we might expect to find \(0.027 \times 37 = 1\) isolated galaxy. In fact we find none, though there are three for which there is no reported clustering. Amongst Caswell and Wills' 80 1st class identifications we expect to see \(0.027 \times 80 = 2.1\) isolated galaxies and in fact we find one listed in the Karachentseva catalogue. One can draw no conclusions from this result except that there is no conflict between the available data and either of the hypotheses, i) 'All radio sources are in clusters', and ii) 'Radio galaxies are no more likely to lie in clusters than normal galaxies'. Since going down to the 4C flux limit still gives very small statistics for this test (i.e. we have to decide if '1' is significantly different from '0' or '2') it seems unlikely that one will be able to obtain a definitive answer until a fully automated system is available to extend the identifications of 4C and the clustered/isolated measurements of Karachentseva to
appreciably fainter magnitudes. Reducing the flux limit of the survey will not help since lower flux sources identified with galaxies brighter than $15^{m}7$ will be intrinsically weak and so will not really qualify as powerful radio galaxies. A source with flux density of 2f.u. at $z=0.086$ (typical for 15$^{m}.7$ galaxies) has $P=5E24$ W Hz$^{-1}$sr). This would reduce the procedure to a tautology.

It ought to be pointed out that although proving that 'radio galaxies have a different tendency to cluster membership than normal galaxies' is a very difficult task at present, spectroscopic observations of radio galaxies and their nearby neighbours (on the sky) would give positive confirmation of associations if they do exist. If, as the author suspects, radio galaxies always lie in clusters or groups, sufficient spectral observations could confirm this hypothesis for all the sources we know to be near enough to be amenable to measurement. It is only necessary to find one definitely isolated radio galaxy to disprove the latter hypothesis.

The above indicates that the expected small probability of truly isolated radio galaxies appearing in our complete sample of 37 sources is sufficient to explain
the lack of correlation between measured source properties and cluster richness.

Alternatively, it may be that the "interstellar" gas associated with all radio galaxies extends to much greater distances than the optical image of the galaxy. The work of de Vaucouleurs (1969 (322); de Vaucouleurs & de Vaucouleurs 1970 (321) and of Arp & Bertola 1969 (468) indicates that some galaxies in clusters have enormous outer envelopes (~300kpc) which are large enough to enclose the majority of radio sources without extending into intergalactic space. These envelopes, if they exist elsewhere, will be extremely difficult to detect optically, around all but the nearest radio galaxies. Recent observations of X-ray emission from certain radio sources are compatible with the existence of regions of hot gas in the vicinity of the sources but resolution is not yet sufficient to determine whether the emission comes from an extended region surrounding the radio galaxy or from the nuclear regions.

4.6 Conclusions

From radio structural data on a subset of a complete sample of sources we have shown that there is no significant difference in the sizes of sources in and out of clusters.
That our results have not been affected by introducing an intermediate cluster richness class is shown by combining class II objects with either class I or class III types. Again no significant results appear. We can find no evidence to support De Young's conclusion that there is an increased density of intergalactic matter around radio galaxies in clusters, nor that being in or out of a cluster has any bearing on the radio structure. The above lack of correlation of radio structure with cluster membership is probably explained by the sources in the sample all being cluster members, though some of the surrounding clusters still await detection.

Complex sources appear to be preferentially low power phenomena but it is still not possible to rule out the existence of distant, more powerful complex sources, though the latter will be relatively rare. Further optical investigations of the 3CR source fields are urgently required to provide a complete and homogeneous body of data on the 'cluster richness' of these fields.
CHAPTER FIVE.

The Statistical Properties of Extragalactic Radio Sources.

Summary:

The general properties of a complete sample of extragalactic radio sources are analysed using all the currently available radio and optical observational data. The findings, where appropriate, are compared with earlier work and it is shown how the effects of poor resolution and the shortcomings of one-dimensional brightness distributions have affected the conclusions of earlier workers concerning the radio source population. We then discuss the implications of our findings for theories of extragalactic sources.
2.1 Introduction

The great increase in the amount of observational data now available for the sources in the 3CR 'complete-sample' has already been described in chapter 2, together with the reasons for adopting this sample for our statistical studies. We now examine that data, concentrating not on individual sources but on the general properties of the various subclasses in the sample and how they relate to each other. Some time has now passed since Mackay 1971, [14] published a general summary of extragalactic radio source properties and since his results were based largely on the observations made with the OMT at 408 and 1400 MHz, there are many new observations now to be considered. We shall also examine the findings of Fomalont 1969 [60] and bring his results up to date where a change is necessary.

Throughout this chapter we shall make extensive use of the RADARS system for data analysis. One of the features of this system is that it is possible to ask for automatic least-squares fitting of four simple functions to the data in a scatter diagram. The program computes the correlation coefficients corresponding to the four curve-fits and for the best fit (in terms of largest correlation coefficient) estimates how much correlation one may deduce exists in the
whole population (of which the plotted data is but a small sample) with 95% and 99% confidence. The method used is described in Appendix III. Where we have stated in the body of the text that "no significant correlation exists..." we mean that we cannot reject the hypothesis that the population correlation coefficient is zero, at the 95% level.

We often use geometric (or logarithmic) means and deviations in addition to, or in preference to arithmetic means and standard deviations. This is because where a parameter varies over many orders of magnitude (e.g. 2, 3, 4), the arithmetic mean is almost entirely determined by the few largest values of the parameter and the standard deviation by the difference between this mean and the few smallest values. Logarithmic scales are frequently clearer and more natural, and we then generally compute the means as the antilog of the mean of the logs. of the data \( \left( = \sqrt[n]{x_1 x_2 \ldots x_n} \right) \) i.e., the geometric mean. The logarithmic deviation, we have defined as the antilog of the standard deviation of the logs. of the data. We then use the symbol ' \( \div \) ' (read 'times or divide') in place of the normal ' + ', for denoting log. deviations.
Table 5.2.1.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STATUS</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C46.01</td>
<td>included in our sample</td>
<td>Field of 3C46 contains two unrelated extragalactic sources both with $S_{843}$ greater than 9Jy, 3C46.01 (+3666) is a 15$^\circ$ quasar (Gill &amp; Wilh 1975 (443)); 3C46.02 (+3668) is a 14.9$^\circ$ E2 galaxy in a cluster.</td>
</tr>
<tr>
<td>3C46.02</td>
<td>included in our sample</td>
<td></td>
</tr>
<tr>
<td>3C358</td>
<td>rejected from our sample</td>
<td>Comprises two 4C sources (confused) each with $S_{843}$ less than 3Jy.</td>
</tr>
<tr>
<td>3C371</td>
<td>rejected from our sample</td>
<td></td>
</tr>
<tr>
<td>3C334</td>
<td>rejected from our sample</td>
<td></td>
</tr>
<tr>
<td>3C386</td>
<td>included in our sample</td>
<td>Now identified as a faint galaxy, and not a galactic supernova as previously suggested.</td>
</tr>
<tr>
<td>3C83.11</td>
<td>Non-association Differences Only</td>
<td></td>
</tr>
<tr>
<td>3C225.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C453.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C437.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3C442.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2.1 explains the differences between our complete sample and that of Mackay (1971).
information. We have computed its flux density by estimating the 178 MHz flux densities for the other 3 components of 3C437.1 by means of the 408 MHz and 1400 MHz OMT results (MKN) and subtracting their total from the 4C estimate of S178 for the whole field of 3C437.1. Since the estimate is only tentative but much less than 9Jy, we have felt justified in omitting the source from the sample.

The Radio Data.

Mackay 1971, (214) has described the completeness of the observations of the complete-sample by the OMT at 1400 MHz. Unfortunately, no such complete set of observations at 5 GHz is available, though about 40 sources have been observed by the OMT at that frequency with a resolution of \(6 \times 6 \cos \delta\) arcsec and more than 170 by the 5km Telescope also at 5 GHz, with a resolution of \(2 \times 2 \cos \delta\) arcsec. This places a degree of inhomogeneity on the data from an observational point of view, because the angular resolution with which different sources have been observed, varies. However, what is really important is not the angular resolution, but the linear resolution (in Kpc, e.g.) because it is the physical structure of the sources that is of interest. Because the sources have redshifts ranging over about 3 orders of magnitude, (approximately 0.002 to 2.0), the linear resolutions obtained with one
telescope at a fixed frequency vary by the same amount, so we should not be concerned that our angular resolution is inhomogeneous throughout the sample.

It is now clear that source structure does vary with frequency of observation (with a given angular resolution). The principal cause of this, in the powerful double sources, is the presence of central components with very flat spectra (approximately 0.0), usually coincident with the optical identification. Because most such sources have outer components with spectral indices in the range 0.6 to 0.9, the widely different index of the central component gives rise to changes in the overall source structure with frequency. This effect is worsened when using telescopes with small dynamic range. In addition to this, source components with long extended tails sometimes steepen in spectrum towards the centre of the source (but see Jenkins & Scheuer 1976 (465)) and this variation can cause the observed structure to change with frequency, (e.g. 3C452, Riley and Branson, 1973, (396)). There is also some evidence for the steepening of spectra along the tails of radio-trail sources such as 3C83.11 and 3C129 (e.g. Miley, G.K. (415)).

Where these effects might alter our results we have
tried to take account of them by checking with a sample all of whose members have been observed at 5 GHz. In fact, almost all central components have measured spectral indices in the range 0.0-0.1, and most are unresolved. This appears to be generally true and allows reliable upper limits to be set to the flux density of unobserved central components, independent of observing frequency.
Since Mackay's analysis was published, there has been a considerable increase in the quality and quantity of the optical data available for the 3CR fields. Many of the previously unidentified source fields have been studied with the Hale 200 inch telescope (Kristian, Sandage & Kates, 1974, (222); Longair & Gunn, 1975, (266); Spinrad, private communication) and other sources have been observed using image tube techniques and IIIaJ deep plates. This is in addition to the reasonably complete identifications (down to $m_v \sim 19.5$) from the National Geographic Palomar Sky Survey plates and prints (Wyman, 1966, (224)). Some subsets of the sample have now been completely observed down to a limiting magnitude of $m_v \sim 23.5$, which allows much better lower limits to be set to the distance of the unidentified sources, assuming that they are not intrinsically fainter optically than their identified counterparts. Fig. 5.2.1 illustrates the range of optical visibility of objects as observed by various methods.

In most cases we have derived an estimate of the redshift of unidentified sources by assuming that the optical object has an absolute magnitude, $M_V = -23.23$ (Sandage (415)) ($H = 50 \text{km s}^{-1}\text{Mpc}^{-1}$) and a lower limit of visual
magnitude consistent with the particular observations, corrected for galactic obscuration where appropriate. One can then cross check the validity of this estimate by calculating the linear size of the object at the derived redshift using the available angular structural information. Where estimated sizes of sources approached 1 Mpc or greater, further investigation was carried out, as such large sources are rare and cast suspicion on the distance estimate.

Following Mackay, we have rejected 3C326 from the sample as it is probably galactic in origin, but a definitive paper by Lynds 1971 (068) has shown that 3C386 is definitely associated with a galaxy with a redshift of 0.0177, and so we retain this source with confidence.

5.3 Angular Scales

There still exists only an upper limit on the largest angular size of 10% of the sources in the complete sample. These limits range from 0.1 to 25 arcsec, though only 3 upper limits are greater than 5 arcsec.

For 82% of the sources there is sufficient structural
Fig. 5.3.1 (top): The angular size distribution of all sources in the complete sample, including upper limits.

Fig. 5.3.2 (bottom): The angular size distribution of all sources in the complete sample, excluding upper limits.
Table 5.3.1.

The distribution of angular sizes amongst subsets of the complete sample.

<table>
<thead>
<tr>
<th>SUBSET</th>
<th>SIZE RANGE</th>
<th>NUMBER</th>
<th>PERCENTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unresolved</td>
<td>&lt;0.1&quot; to &lt;40&quot;</td>
<td>29</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>0.05&quot; to &lt;15&quot;</td>
<td>51</td>
<td>25.9</td>
</tr>
<tr>
<td>Resolved</td>
<td>15&quot; to &lt;45&quot;</td>
<td>51</td>
<td>25.9</td>
</tr>
<tr>
<td></td>
<td>45&quot; to &lt;120&quot;</td>
<td>36</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>≥120&quot;</td>
<td>30</td>
<td>15.2</td>
</tr>
<tr>
<td>A11 &lt;15&quot;</td>
<td>&lt;15&quot;</td>
<td>≥71</td>
<td>≥36</td>
</tr>
<tr>
<td>A11 &lt;2&quot;</td>
<td>&lt;2&quot;</td>
<td>≥23</td>
<td>≥11.7</td>
</tr>
</tbody>
</table>
information to allow morphological classification and for another 5 sources a tentative classification has been made. 7% of the sources are slightly resolved in only one direction and a position angle is generally measurable for these. Table 5.3.1 summarises the angular size distributions of the resolved and unresolved sources and Fig. 5.3.1 shows the distribution in graphical form.

The distribution of angular sizes has a sharp drop around the 10 arcsec region. This is caused by sources 'piling-up' just above the 10 arcsec region because they are unresolved and many observations (particularly those made with the OMT at 1400 MHz) gave upper limits of around 12 arcsec. There is then, quite naturally, a deficit of sources just below the 10 arcsec limit giving rise to the sharp edge in the distribution. It is emphasised that this is a purely observational effect; a similar situation arises around 1 arcsec, where lie the upper limits given by the 5km telescope. Fig. 5.3.2 shows the distribution with the unresolved sources removed, and it can be seen that both features (at 1.0 and 10.0 arcsec) have disappeared.

It is noted that at least 40% of the sources are smaller than 15 arcsec, and that 13% are smaller than
2 arcsec. These latter will need telescopes with higher resolving power than the 5km at 5 GHz to unravel their structures. It is interesting to note that Fomalont 1969 (Q§Q), using a sample selected at 1425 MHz, found 48% of his sample to be less than 15 arcsec in extent. This difference is due to his sample containing proportionately more sources with flat spectra: a higher proportion of these are expected to be distant quasars (Wall, 1975 (458)) which have smaller angular sizes (probably much less than 1 arcsec). However, since his observations were made with a 45 arcsec fan beam it is quite reasonable to suppose that many of the sources in his sample appeared unresolved only because they were partially aligned with the major axis of the telescope beam. We estimate that about another 6% of our sources would erroneously appear to have sizes less than 15 arcsec if observed with a 45 arcsec fan beam, enough to explain most of the difference between our result and that of Fomalont.

The synthesis observations have provided a great deal of information about the 'internal' dimensions of sources. Many sources have individual components well resolved in at least one direction, though only a quarter of the complete sample sources are certainly resolved perpendicular to their major components.
Although many sources are now known to possess compact central components coincident with the optical objects, only two such components have so far been resolved by the 5km Telescope, viz: 3C236, 3C386. 3C236 is an exceptionally large source (5.7 Mpc) and this contrasts sharply with the deduced size of the central component, 3.2 Kpc, a ratio of 1781:1.

It is becoming clear that many source components have a complex structure generally consisting of a very compact head (sometimes multiple) with a more extended tail of emission usually not well-aligned with the major source axis, and occasionally almost perpendicular to it. The compact heads are frequently the furthest part of the source from the optical nucleus, though there are several powerful sources where this is not true. The non-alignment of the component tails which was not apparent in many of the 1407 MHz OMT maps (short tails were unresolved) accounts for the values of $\omega_{\perp}$ (angular size perpendicular to source axis) quoted by MKN and Mackay being significantly larger than those we now find with higher resolution. In fact, what we now measure should strictly be called $\omega_{\max}$ and $\omega_{\min}$ since we measure relative to the component axis defined by its longest dimension ($\omega_{\text{max}}$). The $\omega_{\min}$ measurement is then generally perpendicular to that of $\omega_{\max}$. Also, our 5Km
measurements generally refer to the compact component heads, and not the diffuse emission surrounding these. The sizes of the features seen within the components vary over a wide range and to aid comparison of different sources we compare these dimensions with overall source sizes. The ratios then found vary from about 1:1 to > 60:1 and we shall study these small scale features more fully, when we reinvestigate some of the correlations found by Mackay.

5.4 Morphological Types

Before we go on to discuss the distribution of morphological types seen in the complete-sample, we should describe how our categorisation scheme works. There is necessarily some degree of subjectivity in the choice of types but it is felt that our classification has been reasonably self consistent. It should be born in mind that the resolution with which a source has been observed determines to some extent how it is classified.

We have retained the broad 'classical' categories, Single, Double, Triple and Complex but elaborated on these by adding further sub-features and also by recognizing a sub-class of doubles (arbitrarily coded as 'DQ' types)
Fig. 5.4.1: Examples of the principal types of source structures used in our classification scheme. S=single, 3C272.1; D=double, 3C171; DQ=double with one of the two components close to the nucleus, 3C254; T=triple, 3C390.3; C=complex; 3C288
wherein one of the two components is nearly or exactly coincident with the optical identification. We also use the terms Unresolved and Extended to mean sources which do not, and which only slightly, broaden the telescope beam. These two 'types' are simply functions of the observations and are not intrinsic to the sources.

Fig. 5.4.1 shows typical sources of each of our main types and we describe below those features that distinguish the categories:

Unresolved (U): source does not significantly broaden the telescope beam

Extended (E): no structural features apparent but source is sufficiently resolved in one direction to allow an estimate of the position angle of its major extension and an estimate of its size to be made; e.g. 3C28

Single (S): essentially one peak of emission only, though there may be extended regions or tails attached to the component. No evidence of 'doubling' or signs of an axis; e.g. 3C272.1

Double (D): two non-concentric components approximately
the same size and flux density with the optical identification somewhere between their peaks, not near enough to one of the components to be classified as a DQ (see below). No evidence for a central component; e.g. 3C171

Asymmetric double (DQ): as for double but ratio of component separations from optical object is greater than 3 or less than 1/3; e.g. 3C254 (the definition of this source type was inspired by 3C273 - see Section 5.8 for further discussion)

Triple (T): as for double but with a third component (associated with the optical identification) lying roughly halfway between the outer components and approximately colinear with them; e.g. 3C390.3

Complex (C): a source not possessing a well defined axis and not otherwise amenable to classification in the above categories. Generally there are multiple non-collinear components and large extended regions of emission around the whole source; e.g. 3C288

We may then append a second and possibly a third letter to the basic types described, and in these positions the letters have the following meaning:
B=(bridge); an extended, roughly linear region of emission linking the outer components of a source; e.g. 3C61.1=DBS

C=(compact); compact central component (usually unresolved) associated with the optical object; e.g. 3C315=CC

D=(double); as before

E=(extended); applies to the components of a source, indicating that they are not unresolved but are broad; e.g. 3C277.3=TBE

H=(halo); large weakly emitting region surrounding the whole source and roughly concentric with it; e.g. 3C84=SUR

M=(multiple); many (>2) components, not generally colinear; e.g. 3C288=CME

P=(peculiar); the source possesses an unusual characteristic otherwise undefinable within the classification scheme; e.g. 3C204=TSP

S=(simple); features are either absent or unresolved apart from other classification; e.g. 3C61.1=DBS
T=(tails); the components have tails of emission (i.e., extensions in one direction) usually, but not always pointing in the general direction of the other component (or the optical object); e.g. 3C390.3=TBT

There is one exception to this scheme and that is the classification 'CT-' where the 'T' in the second position stands for 'Triple' and not 'Tails': since complex sources are not usually separable into components and tails this causes no problems.

Where there is serious doubt about the validity of any particular classification it is truncated to the two most significant characters and preceded by a '?'.

The classifications assigned to sources are based on all the map data and other evidence available and this means that the structural types assigned are a composite of what is seen at many frequencies and resolutions. For example, bridges are seen in some sources only in the lower frequency maps because they tend to have a steep spectrum, whereas central components are mainly visible at 5GHz and above. Also, some bridges are resolved-out by the 5km Telescope, and at the lower resolution of the OMT at 408 and 1407 MHz, some central components are indistinguishable from the outer
Table 5.5.1.
The distribution of structural types amongst the well resolved sources in the complete sample and 3CR.

<table>
<thead>
<tr>
<th>STRUCTURAL TYPE</th>
<th>COMPLETE SAMPLE</th>
<th>3CR CATALOGUE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no.</td>
<td>percentage</td>
</tr>
<tr>
<td>Single</td>
<td>S</td>
<td>7</td>
</tr>
<tr>
<td>(Simple) Double</td>
<td>D+DS+OE</td>
<td>55</td>
</tr>
<tr>
<td>Doubles with tails</td>
<td>DT</td>
<td>14</td>
</tr>
<tr>
<td>Doubles with Bridges</td>
<td>DB</td>
<td>20</td>
</tr>
<tr>
<td>Asymmetric Doubles</td>
<td>DQ</td>
<td>4</td>
</tr>
<tr>
<td>Possible Doubles</td>
<td>DT</td>
<td>2</td>
</tr>
<tr>
<td>Triples (Simple)</td>
<td>TS+TE</td>
<td>16</td>
</tr>
<tr>
<td>Triples with Tails</td>
<td>T2</td>
<td>9</td>
</tr>
<tr>
<td>Triples with Bridges</td>
<td>TB</td>
<td>23</td>
</tr>
<tr>
<td>Complex</td>
<td>C</td>
<td>13</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td></td>
<td>162</td>
</tr>
</tbody>
</table>

Table 5.5.1. shows the distribution of the different structural types amongst the well resolved sources in the complete sample. It will be seen that we have been able to classify 155 (83%) sources as single, double, triple or complex. The remaining 40% have been classified as other, mainly unknown types. The numbers are those observed in the sample, and we also have included data on some of the sources in the sample that were only partially resolved. One general finding is that source components are not always well matched by the source components of the same type assigned to the same source. This should be borne in mind when computing the distribution of types of sources with each other:

Table 5.5.2 shows the distribution of structural types amongst the well resolved sources in the complete sample. It will be seen that we have been able to classify 155 (83%) sources as single, double, triple or complex. The remaining 40% have been classified as other, mainly unknown types. The numbers are those observed in the sample, and we also have included data on some of the sources in the sample that were only partially resolved. One general finding is that source components are not always well matched by the source components of the same type assigned to the same source. This should be borne in mind when computing the distribution of types of sources with each other:

5.18. A MATCHING map of the three-dimensional sample with which they may merge on the map. This means that the
spherical, and that sources are often asymmetric with respect to the optical object. This unfortunately implies that model fitting to interferometric data using simple symmetric two or three component models is unreliable, as for example, it is impossible to distinguish whether a component appears large because it is broad or because it is long. This casts some doubt on the reliability of the structural correlations found by Pomalont and we shall examine the evidence for these later.

Returning to Table 5.5.1, we see that a remarkable 88 per cent of all well-resolved sources show some degree of double structure, that only 8 per cent are complex, and a mere 4 per cent consist of only one component. In about 34 per cent of the double sources a compact central component is observed, and 30 per cent are seen to have a bridge of emission linking the whole source. The last two columns of Table 5.5.1 show similar data for the whole of 3CR; the number of classifiable sources rises to 218 (but only 66%) and the percentages of each source type are similar to those found in the complete sample. It is probably artificial to divide sources into 'simple doubles' and 'complex doubles' as has been done previously, because nearly all 'simple' doubles that have been subjected to greater scrutiny with the 5km Telescope have been shown to contain
Fig. 5.5.1: the effect of telescope resolution on the observed distribution of structural types. Each histogram shows the distribution of types seen when the telescope beam is 'n' times smaller than the source (the range of 'n' for each histogram appears at the right). Resolution improves from top to bottom. The structure abbreviations are, U=unresolved, E=extended (broader than beam), ?=uncertain structure, S=single, DS=simple double, D(T+E)=double with tails on components or extended components, TS=triple=simple, T(T+E)=triple as D(T+E), C=complex.
component-structural features when the linear rather than
the angular resolution has been sufficiently high (~10
kpc).

This effect is illustrated in Fig. 5.5.1 where we have
divided the sources in the complete sample with measured
redshifts into 5 approximately equal-sized groups, the beam
resolution (source size divided by beam width) increasing
from group to group; the distribution of structural types
for each group is plotted. Since bridges of emission are
sometimes not visible on the higher resolution, higher
frequency maps, we have omitted the bridge/no-bridge
distinction here. Some sources in Fig. 5.5.1 have been
observed with higher resolution than is necessary to
determine their structural type so that, for example,
although most of the complex sources appear in the last
histogram (with >14 beam-widths resolution), all of them
were classifiable as complex before they were so highly
resolved. Additionally a few sources have been structurally
classified using more or less reliable LBI information,
though the source resolution in Fig. 5.5.1 has been
calculated using only the synthesis telescope observations,
so that a few of the sources appearing in group 1 with <0.9
beam-widths' resolution are nevertheless structurally
classified in some detail.
The main features of the diagram are i) with limited resolution, (1 to 5 beams across the source), most sources appear to be simple doubles and central components are very difficult to isolate. This indicates that any analysis of component substructures will probably be most misleading unless the sources have been observed with at least 5 beams resolution. ii) single component sources are a reality, and not merely a product of poor resolution, as they are present in both of the last two groups. iii) when viewed with very high resolution, most double sources can be seen to have central components and the majority then have complex outer components. iv) those sources that do not have visible central components tend to have relatively more simple outer-component structures. This is apparent from the last histogram where it is seen that 2 of the 4 sources not observed to have central components are classed as simple doubles (although both have powerful bridges of emission) with little or no structure apparent in the outer components proper.

It should be stressed that the structure distribution in Table 5.5.1 is not necessarily representative of the true distribution in space, because all types listed do not have identical luminosity functions. In Chapter 4 this point was
explored further for the complex sources and it was shown that at least at low luminosities, complex sources are relatively much more common than Table 5.5.1 would indicate.

5.6 Central Components

The incidence of central components in an observationally complete sample is a function of resolution and frequency of observation. Since central components are now known to have flat spectra ($\alpha \approx 0.0$) they are relatively more visible at higher frequencies. So that they may be seen separately from the outer components one also needs a minimum number of beam-widths across the source. To make a better estimate of the proportion of double sources that have central components we have selected a subsample of identified sources all of which have been observed at 5GHz (by the OMT or the 5km Telescope) with at least 5 beam-sizes across the source. There are 57 sources in this subset, of which 2 are single component sources, 12 are complex, 10 are double (plus one DQ type) and 32 are triple. This indicates that a better estimate of the proportion of double sources with central components is 76 per cent. This contrasts sharply with the 35 per cent in the complete sample as a whole and indicates that selection effects preclude the observation of many central components.
Table 5.6.1

Comparison of the average properties of those Double and Triple sources that have been observed at 5GHz with better than 5 beam-widths resolution, and which are identified.

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>DOUBLES, N=10</th>
<th>TRIPLES, N=32</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>LOG. MEAN</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{178} (W Hz^{-1} sr^{-1})</td>
<td>1.2327</td>
<td>1.7826</td>
</tr>
<tr>
<td>D (Rcp)</td>
<td>299</td>
<td>257</td>
</tr>
<tr>
<td>Abs. Magnitude</td>
<td>-23.7</td>
<td>0.79</td>
</tr>
<tr>
<td>d_LF</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>z (redshift)</td>
<td>0.16</td>
<td>0.27</td>
</tr>
<tr>
<td>(angular size)</td>
<td>83.3</td>
<td>122</td>
</tr>
<tr>
<td>log (a/b) (asymmetry)</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>log (f/f0) (Flux ratio)</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Optical Types</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 QS = 10Q</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 H = 10F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 G = 864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Resolution (Rcp)/14.1</td>
<td>10.7</td>
<td></td>
</tr>
</tbody>
</table>

Note that where appropriate we have given the logarithmic deviation denoted by 'σ' (read, 'times divide') instead of the more usual ± (plus or minus).
Fig. 5.6.1 (top): 5GHz luminosity of central component versus total source luminosity at 178MHz for the triple sources in the complete sample (log-log plot)

Fig. 5.6.2 (bottom): Total source luminosity at 178MHz versus redshift for doubles and triples in the complete sample (log-log plot)
tendency of triple sources to be associated with quasars

The Relationship Between Central Activity

And Other Source Properties

All current theories of radio sources assume that the origin of the outer components or their energy source, is the central object which is seen optically. It is therefore important to establish relationships between measurable properties of the central object and of the source as a whole. In general, radio measurements fail to resolve the central radio source and the only measurable parameter is the flux density, or intrinsically, by reference to a distance estimate, the luminosity. Optically we can sometimes measure the angular (and thus physical) diameter, but more generally only the optical luminosity is reliably determined. However, we usually have the more or less subjective 'optical type' of the object as assessed qualitatively by the observer.

If we believe in energy transport source models where the outer components are energised continuously from the central object we might expect that a more powerful radio source would possess a more active (and thus higher luminosity?) central component. Fig. 5.6.1 shows the
relationship between the 5GHz luminosity of the CCC, 'P5C', and the 178 MHz luminosity of the whole source, 'P178', for the triples in the complete sample (note that since the CCC's in general have very flat spectra ($\alpha \simeq 0.0$) the difference between the two frequencies is of little consequence). Superficially this plot appears to show strong correlation between the variables. However, the solid line drawn through the lower edge of the band of plotted points is an approximate selection-effect limit line, below which it is very difficult to observe central components. The position of the line is computed as follows: an approximate lower flux density limit at 178MHz on the KPW scale is 10Jy, for the 3CR sample. For any value of P178 there is a maximum value of $Z$ beyond which a source will not be included in 3CR. Because of the decreasing space density of sources with increasing luminosity, at any particular redshift one observes only a narrow range of P178: i.e. P178 and $Z$ are highly correlated for a flux density limited sample (see Fig. 5.6.2). To detect a central component, the 5Km needs a minimum of 10mJy per beam area, and since most CCC's are unresolved by the 5Km, this means they must have a total flux density of at least 10mJy. Using the tight P178 - $Z$ correlation, we can convert the flux density limit into a $P(5GHz)$ limit for any value of P178 and this produces the approximate limit line on our diagram. Thus we cannot deny the existence of sources below this line; indeed, many
### Table 5.6.2

Sources that may have large low brightness components similar to those of the giant radio source 3C273.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>OPT. TYPE</th>
<th>RADIO TYPE</th>
<th>Z</th>
<th>P^2</th>
<th>\alpha</th>
<th>\delta</th>
<th>D(Mpc)</th>
<th>5Mpc angular size</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C24</td>
<td>Ellipts</td>
<td>SH</td>
<td>0.017</td>
<td>5.8224</td>
<td>-1.02</td>
<td>0.93</td>
<td>4.8</td>
<td>5.4</td>
</tr>
<tr>
<td>3C334.1</td>
<td>Companion</td>
<td>U</td>
<td>0.25</td>
<td>2.7856</td>
<td>0.84</td>
<td>0.63</td>
<td>13.4</td>
<td></td>
</tr>
<tr>
<td>3C330</td>
<td>U</td>
<td>U</td>
<td>0.17</td>
<td>2.7826</td>
<td>0.82</td>
<td>0.52</td>
<td>5.0</td>
<td>12.8</td>
</tr>
<tr>
<td>3C306</td>
<td>D</td>
<td>DIT</td>
<td>0.0616</td>
<td>8.8224</td>
<td>0.68</td>
<td>0.79</td>
<td>3.8</td>
<td>9.3 \times 10^{-5}</td>
</tr>
<tr>
<td>3C334</td>
<td>L2</td>
<td>CHP</td>
<td>0.0041</td>
<td>5.6824</td>
<td>0.80</td>
<td>0.71</td>
<td>7.2</td>
<td>11.9</td>
</tr>
<tr>
<td>3C293</td>
<td>D</td>
<td>D</td>
<td>0.0452</td>
<td>8.8224</td>
<td>0.69</td>
<td>0.54</td>
<td>1.7</td>
<td>85.2 \times 10^{-5}</td>
</tr>
<tr>
<td>3C276</td>
<td>G</td>
<td>EOT</td>
<td>0.0094</td>
<td>3.1625</td>
<td>0.65</td>
<td>0.53</td>
<td>3.5</td>
<td>47.0 \times 10^{-5}</td>
</tr>
</tbody>
</table>

The first four sources (3C24, 3C334.1, 3C330 and 3C306) are unlikely to be candidates for 3C273-like structure. The last three (3C334, 3C293 and 3C276) are more probable candidates. The last column indicates the angular size subtended by a linear distance of 5 Mpc at the distance of each of the sources. The details of 3C276 in the first row refer to the centre portion only, the compact double at the centre mapped by the OTT and the 5M telescope.

---

The line in the top left corner of the diagram has a slope of one and passes through the point of 3C276. In the plane this source was not recognized as a triple by the Cambridge telescopes because of the low brightness distribution. It is therefore not included in the table. This source was not included in the 3C276 catalogue. However, it is unlikely that the source 3C334.1 have been missed. The positions of the sources on the diagram have been corrected for the distance errors in the 3C334 catalogue. The errors are not taken into account in the whole of the 3C catalogue. The errors are only taken into account in the whole of the 3C catalogue. Therefore, it is not possible to draw any conclusions about the 3C334 catalogue. Therefore, it is not possible to draw any conclusions about the 3C334 catalogue.
some certainty that sources with relatively very powerful central components are extremely rare, which is apparent from the emptiness of the upper left region of Fig. 5.6.1. Examination of the correlation coefficients between the pairs of variables indicates that P5C is marginally more correlated with P178 than it is with redshift (r=0.869, r=0.865 respectively) though the difference is so small as to be meaningless. The P178 - z correlation has coefficient 0.975 showing just how strong the selection effects are here.

If we believe sources derive their energy from central component activity we can interpret this fact as follows: 'the more luminous the central component of a source, the more luminous will be the source as a whole'. Notice that most central components contribute less than one per cent of the total 178MHz luminosity of sources, and thus this apparent correlation is not explicable by space-density effects alone. Lastly, it is worth remembering that we have excluded from the diagram sources with no double outer components as they are clearly outside the domain of the model under consideration. Thus we qualify our statement by assuming its applicability only to sources with distinct double outer structure.
Fig. 5.6.3 (top): 5GHz luminosity of central component versus total source size in Kpc for all the triple sources in the complete sample with measured redshift (we have omitted sources smaller than 10Kpc and sources bigger than 2Mpc)

Fig. 5.6.4 (bottom): 5GHz luminosity of central component versus redshift for the triples in the complete sample
In Fig. 5.6.3 we have plotted, for the complete-sample triple sources with measured redshift, the central component 5GHz luminosity against the total linear size (D) in Kpc. We have omitted sources smaller than 10Kpc and larger than 2Mpc. There is a relatively strong correlation (r=0.514 for the best fit curve of the form P5C=a-b.log(D) ) amongst the sample data, which implies a corresponding population correlation coefficient of r=0.12%, significant at the 1% level. As has already been stated, P5C is strongly correlated with redshift (r=0.865 for our sample, or r=0.703 (1% sig.) for the population) and we plot this relationship for our sample in Fig. 5.6.4. It is important to discover if the size D is correlated with the redshift, thus giving rise to a spurious correlation with P5C. Fig. 5.6.5 shows such a plot for our sample giving r=0.414 (r=0.0025 (1%) for the population). If we consider P5C as a function of the two variables D and Z, we can compute approximate partial correlation coefficients between each pair of variables, with the third assumed held constant (see, e.g., Goodman, p.125 (429) and notes in Appendix II) whereupon we find the values in Table 5.6.3 where we summarise all the correlation coefficients. These calculations indicate that P5C and D are indeed correlated and that the small apparent correlation between D and Z may be due to the actual correlation between P5C and D.
Fig. 5.6.5 (top): Total source size (in kpc) versus redshift for the triple sources in the complete sample (we have omitted sources smaller than 10 kpc and sources larger than 20 kpc).

Fig. 5.6.6 (bottom): 5GHz luminosity of central component versus absolute magnitude of optical identification for the triple sources in the complete sample.
The correlation suggests that as sources become larger their central component luminosity falls. In terms of continuous energy supply models this may be interpreted as a decrease in energy supply as the source ages, a necessary condition if the sky is not to be well populated with extremely large triple radio sources. Only one (3C236) is known to exist and this has been omitted from our analysis as it is atypical of the rest of the group. The double structure at its nucleus may be a second event unrelated to the first which generated the large outer components. In some sense, this source may therefore be regarded as two double sources and not one triple source. It seems quite reasonable to suppose that P5C and D would correlate slightly better if projection effects (which only affect D) could be removed. However the average dispersion of points relative to the regression line, which has the form

\[ P5C = 8.33E25 - 3.06E25\times\log(D), \]

is by a factor of approx. 2 whereas the average projection factor is only 1.15 (corresponding to a projection angle of 30 degrees). This indicates that there is quite a large intrinsic dispersion of the sizes of triple sources of a given central component luminosity.
Fig. 5.6.7 (top): Absolute magnitude of optical identification versus redshift for the triple sources in the complete sample.

Fig. 5.6.8 (bottom): Total source size, $D$, (Kpc) versus absolute magnitude of optical identification for the triple sources in the complete sample (we have omitted sources with sizes outside the range 10Kpc to 20Kpc)
One might be led to expect by the above result (and also by the apparent relationship noted earlier between the incidence of central components and the emission of non-thermal optical radiation from the nucleus) that there should be some correlation between PSC and the absolute magnitude $M_v$ (see e.g. Longair 1975 (452)). Fig. 5.6.6 shows the good apparent correlation between these variables. However, in this case selection effects do dominate as Figs. 5.6.7, 4 show: the former indicates the very strong correlation between $M_v$ and $Z$ which is due to a combination of an optical observational flux density lower limit, plus the optical luminosity function of radio sources; the latter fig. shows the already mentioned relationship between PSC and $Z$. The partial correlation coefficients are listed in Table 5.6.4 from which it can be seen that the observational selection effects produce much stronger correlations than the PSC, $M_v$ relationship sought after. The figures do indicate a residual correlation between these variables in the population of $r=0.151$ (1% sig.) but because of the approximate nature of the calculations (the sparsity of data does not warrant a more sophisticated technique) this result must be treated with caution until much more data become available. We have repeated these calculations for the quasars and $N$-galaxies only (leaving a sample of 20
objects), giving the results shown in Table 5.6.5. The residual P5C-Mv correlation has now all but disappeared. Again, we should form no strong conclusions from this because the selection effects are so strong. Thus our results are not in conflict with the conclusions of Longair (459), but neither do they lend them strong support. In this context it is worthy of note that 40% of the 35 optically brightest sources in the complete sample (with measured redshifts) have no detected central component although they do display double structure. Thus, strong non-thermal optical emission is no guarantee of strong non-thermal radio emission. The observational selection effects ensure that when central radio emission is observed in these distant objects, it will be very powerful. The observations are consistent with the statement: "The very brightest central radio components can only exist in the presence of a very bright optical nucleus: a bright optical nucleus can, however, support all ranges of brightness of central radio component.". This then explains the lack of observed central radio components in the unidentified sources, since if the CCC's were visible so too would be the optical nuclei. No correlation, in the normal statistical sense, is implied, only that there exists a lower limit to the optical luminosity to be associated with any given radio luminosity of a CCC. Fig. 5.6.8 which is a scatter diagram of D and Mv displays almost zero correlation (no significant
Fig. 5.6.9 (top): 5GHz luminosity of central component versus ratio of separations of outer components from the nucleus for the triple sources in the complete sample.

Fig. 5.6.10 (bottom): 5GHz luminosity of central component versus ratio of flux densities at 5GHz of the outer components for the triple sources in the complete sample.
Fig. 5.6.9 (top): 5GHz luminosity of central component versus ratio of separations of outer components from the nucleus for the triple sources in the complete sample.

Fig. 5.6.10 (bottom): 5GHz luminosity of central component versus ratio of flux densities at 5GHz of the outer components for the triple sources in the complete sample.
correlation in the population at the 1% level).

We have also investigated the possibility of a correlation between P5C and source asymmetry. Figs. 5.6.9, 10 show scatter diagrams relating P5C with $|\log(S1/S2)|$ and with $|\log(D1/D2)|$ respectively. There are no significant correlations here. There are 22 sources in the complete sample with observed central components, which are not classified as triples because they do not demonstrate linear double structure away from the nucleus. These showed the strong expected correlation between P5C and $z$ (again due to selection effects) but not the P5C - D correlation found for the triple sources.

Additionally, we have computed the parameter $PR = P5C/P178$ for the triple sources, the ratio between the 5GHz central component luminosity and the total luminosity at 178MHz (which ranges from 0.02 to 0.0003) and produced more scatter diagrams by plotting it against various other source parameters, viz: D (linear size), $M_v$ (absolute optical magnitude), component separation ratio, and component flux ratio. None of these produced any significant correlations. The mean value of P5C increases by a factor of approx. 10 between each of the subsets of the triples,
Table 5.7.1.

<table>
<thead>
<tr>
<th>RADIO TYPE</th>
<th>QUASARS (46)</th>
<th>RADIO GALAXIES (98)</th>
<th>UNIDENTIFIED (30)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>T</td>
<td>X</td>
</tr>
<tr>
<td>U</td>
<td>11</td>
<td>23.9</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>8</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>14</td>
<td>30.3</td>
<td></td>
</tr>
<tr>
<td>DS</td>
<td>1</td>
<td>2.2</td>
<td>24.2</td>
</tr>
<tr>
<td>DQ</td>
<td>1</td>
<td>2.2</td>
<td>24.2</td>
</tr>
<tr>
<td>T</td>
<td>7</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>TS</td>
<td>2</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

The distribution of radio structural type amongst the three principal optical identification classes.

We have omitted from the table sources whose identification is uncertain. The bottom two rows show the logarithmic mean angular and linear sizes (respectively) of the three groups and their geometric deviations (in parentheses). The linear sizes for the unidentified sources are estimated using a lower limit to their redshifts consistent with a lower limit to their apparent magnitude, assuming an absolute magnitude of -27.2.

Galaxies (12 out of 54) and quasars (15 out of 53) have been selected by their strong optical properties, but the excess is partly due to observational selection effects. In Chapter 4, we have already noted that the galaxies in each group show strong selection effects, and we have also noted that the data for any optical traces of galaxy structure is poor in Table 5.7.1, where the distribution of galaxy types is shown in detail. In Chapter 4, the optical traces of galaxy structure are not used to classify any such objects, and we should also be able to examine the optical traces of galaxy structure in detail.
complex sources are not highly luminous. All three groups are seen to have about 60% double structures, but it is notable that none of the unidentified sources has an observed central component. This could be a consequence of the great distance of the latter sources (implied by their optical faintness), though ten have been mapped by the 5km Telescope at 5GHz with adequate angular resolution to separately resolve any central components brighter than the background noise. However, if the central components are, say, only as bright (relative to the outer components) as that seen in 3C405, it is unlikely that they would be visible beyond a redshift of 1.0 because of confusion effects. At a redshift of 1.0, 3C405 would have a total angular size of approx. 19.5 arcsec. There are only 3 triple sources in the complete sample with redshifts > 0.5 and with an angular size less than 20 arcsec, viz. 3C205, 3C207 and 3C268.4. The greatest ratio of outer component to central component flux densities for these sources is < 17:1 (for 3C205 preceding component). This contrasts sharply with 3C405's minimum ratio of > 200:1 for the preceding component also. The central component in 3C205 is only just above the confusion level so the probability of seeing a much weaker component is very small. In view of what we noted earlier about the distribution of triple sources amongst optical types, the absence of any central components in the unidentified sources strongly suggests that most if not all
Fig. 5.7.1 (top): the distribution of linear sizes (Kpc) of the quasars in the complete sample.

Fig. 5.7.2 (bottom): the distribution of linear sizes of the galaxies in the complete sample.
of them are galaxies and not quasars, as Longair 1975 (459) has pointed out.

The percentage of unresolved quasars is nearly the same as that of the radio galaxies and unidentified sources. However, the geometric mean linear sizes for the three groups are markedly different, (the sizes for the unidentified sources are lower limits derived by assuming the sources are at distances such that a normal galaxy would have been just too faint to see during the optical observations), that of the quasars being less than half of either of the other two. Figs. 5.7.1, .2, show the linear size distributions for the complete-sample quasars and galaxies respectively and it is clear that there is a very large range of overlap. The quasar size distribution suggests that there may be two populations present: the first having a mean around 150kpc and having a distribution similar to that of the radio galaxies in Fig. 5.7.2, and the second, a collection of much smaller sources with sizes centred around 5kpc and with a roughly normal distribution (on the logarithmic scale used). The 5kpc peak in the distribution may be entirely due to selection effects: in Fig. 5.7.3 we show the same distribution for quasars with all sources removed whose measured angular sizes are known to be upper limits only. The peak is very much reduced. A
Fig. 5.7.3 The distribution of total linear size (Kpc) for the quasars in the complete sample excluding sources whose angular sizes are known to be upper limits.
calculation shows that angular sizes close to the limiting resolution of the 5km (0.5 to 1.0 arcsec) will give rise to computed linear sizes in the range 5 to 10 Kpc when at redshifts centred on 1.25, the minimum for the Einstein-de Sitter 'theta-Z' relation, where the curve is very flat. This suggests that the remaining peak could also be due to sources which are unresolved. This latter still implies two populations of quasars since all the unresolved sources will now lie further down the tail of the distribution, below the 5Kpc region, and there will then be many more sources here than one would expect in a gaussian tail from the main distribution (cf. the distribution for galaxies, Fig. 5.7.2). These sources should probably be identified with the flat spectra types discussed in Chapter 7, in connection with the angular-diameter-redshift test.

The work of Kristian (1973, 375) and of Sandage (1972, 284) has indicated that QSO's are probably normal galaxies undergoing a particularly violent phase in their nuclei, giving rise to their stellar appearance. The optical and radio variability observed in quasars suggests that the nuclear event is relatively unstable and may therefore have only a short lifetime. We can explain our two populations of quasar radio structures by assuming that some of the nuclear events give rise to radio sources which continue to radiate
and separate from the nucleus long after the initial event has subsided, giving rise to large separation radio sources. If the lifetime of the external radio source is at least as long as the period between successive nuclear events, in those galaxies prone to multiple events, then we may observe a radio source with a 'second generation' quasar at its centre, and in general these sources will be large. If we happen to observe the initial event, then the sources will be small as they will have had little time to separate from the nucleus. If when we view the source no nuclear event is taking place then we will see a normal radio galaxy, and if the ratio of nuclear event lifetime to average period of occurrence is small, then the observed space density of quasars will be small compared to that of radio galaxies. Lastly, if we happen to observe a source sometime during or shortly after a 2nd event and if that 2nd event gives rise to radio as well as optical emission then we would see a 'triple' radio source. This latter may explain why we find a large percentage of extended quasars to have compact central components. We then have to hypothesise that the first event destroys the nuclei's ability to eject further pairs of compact components, so as to avoid the possibility of true multiple-double sources, which are not observed (except perhaps for 3C236).

5.37 Subclasses of Double Sources
Fig. 5.8.1 (top): The distribution of the ratio of the minimum component dimensions of the outer components for all the double and triple sources in the complete sample.

Fig. 5.8.2 (bottom): Same as Fig. 5.8.1 except that we have omitted all measurements that are upper limits only.
We have attempted to isolate the class of sources called 'D-C', by Fomalont 1969, which he defines as consisting of 'two spatially separated emission regions which have different diameters', and to qualify as 'different' he suggests a component diameter ratio of 2. It is important to try to verify the existence of this subclass because Fomalont (by assuming that the optical identifications always lay on the source axes) found a "noticeable trend for the galaxy to be near to or coincident with the component of smaller diameter". We doubt the existence of this sub-group as a distinct family of objects for the following reasons:

i) Examination of the ratio of component sizes perpendicular to the source axes shows a smooth distribution centred on a ratio of approximately 1.0 (Fig. 5.8.1). The peak at a ratio of exactly 1.0 is caused by the large number of sources which have both components unresolved perpendicularly to the source axis (and observed with the same limiting resolution). Fig. 5.8.2 shows the distribution for only the sources where the components are thought to be resolved.

ii) Of the 20 sources (out of 145 measured) for which we find this ratio to exceed 2, 3 are unidentified, (and thus do not allow measurement), 7 have the larger-width component further from the optical object and in 8 it is nearer. The data for the remaining 5 are highly unreliable.
It is unlikely that more than 8 of the 20 sources are resolved perpendicular to the source axis.

iii) Since Fomalont could only fit spherical component models to his observations he was unable to distinguish between component widths perpendicular and lengths parallel to the source axes.

We have therefore additionally investigated those sources whose component lengths parallel to the source axis have a ratio of greater than 2 and where we can reliably measure the separation ratios. There are a total of 44 such double sources, of which 22 have the larger component nearer to, and 22 further from the optical object. We feel this is sufficient evidence to dismiss this type of object as an archetype.

We cannot be certain that there is anything fundamentally different about those double sources we have classified as 'DQ', though certain of these appear to have one of the two major components coincident with the optical object (to within the errors of measurement). The archetypal source is 3C273 but this source is not considered statistically here as it is not in the complete sample. In 3C273, one of the components is definitely associated with
the quasar nucleus; the other is identifiable with an optical jet feature. The situation is less well defined for the set of DQ's in the complete sample which we now list with some notes.

**3C254**: structurally a simple double source, the quasar is situated very close to the E-component; D1/D2~7.6. Size =107Kpc.

**3C267**: there is a faint 20 object adjacent to the W-component which if real makes this source a DQ (otherwise a normal simple double). D1/D2>10? Size 227Kpc.

**3C305**: whole source is embedded in a 13.6 galaxy of much larger extent. The more powerful component is very close to the centre of the galaxy. Fairly simple double structure; D1/D2~3.2. Size=3.8Kpc.

**3C356**: a simple double source. Sandage (353) has found a possible galaxy at the position of the W (weaker) component but nothing near the E-component. If the identification is correct the source is a DQ type. D1/D2>3. Size 450Kpc

**3C450**: has the stronger component very close to the optical id. (an E5 galaxy). Probably a bridge of radio emission. D1/D2~0.32. Size 25Kpc
The classification of the largest two DQ's (3C267, 3C356) is in some doubt. Some of the DQ's may represent unusual events where the optical nucleus has failed to eject two components in opposite directions. Alternatively, it may be that components are normally ejected individually but within a reasonably short time of each other, so that the large double sources are approximately symmetric. Only very small sources would then show the asymmetry, as their age would be comparable to the time between the ejection of the separate components. 3C305, being less than 4 kpc, may be an example of this type of process, though it is associated with a spiral galaxy, is very weak, and thus is an atypical double radio source.

Another explanation for the occurrence of the 'DQ' sources is suggested by the few double sources which have very large flux ratios. It is unlikely that sources with component flux ratios much greater than 10 will be completely visible with the Cambridge synthesis telescopes because of the limited dynamic range of the latter, (the discovery of the outer components of 3C236 by the Westerbork array demonstrated this anomaly), and it is therefore possible that some of the DQ sources are in fact triple sources where one of the outer components is much fainter.
than the other. All that would then be visible would be a central component and another, distant from the optical object. One would then expect the average sizes of DQ sources to be approximately one half those of triple sources. In reality, there is such a large variation in size of the DQ types (3 to >450Kpc) that a direct comparison is meaningless. However, of the (three) less doubtful DQ's in our sample, all are smaller than 110Kpc; their log. mean size is 22Kpc which is to be compared with 168Kpc for the rest of the doubles and triples. The spectral information available for most of these sources is insufficient to allow the spectra of individual components to be determined, but if in the future the components closest to or coincident with the optical nuclei are found to have flat spectra (≈0.0) then it will lend strong support to the latter hypothesis. Recently, such has been found to be the case for 3C303; see Chapter 3. However, the spectrum of the component of 3C254 close to the quasar has been determined (Pooley and Henbest 1974 (452)) as α =1.0, (i.e. much larger than that of a typical CCC) and they also find no emission >20mJy to the E of the quasar that might constitute the 'other' component.

5.9 The Distribution of Optical Types.

When Mackay reviewed the 3C complete sample in 1971,
Table 5.9.1.

The distribution of optical types amongst the sources in the complete sample.

<table>
<thead>
<tr>
<th>OPTICAL TYPE</th>
<th>No.</th>
<th>%</th>
<th>%</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>U = Unidentified</td>
<td>29</td>
<td>15.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>?G = Possible Galaxy</td>
<td>21</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G = Unclassified Galaxy</td>
<td>48</td>
<td>24.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR = Irregular Galaxy</td>
<td>1</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S = Spiral Galaxy</td>
<td>2</td>
<td>1.0</td>
<td>60</td>
<td>49</td>
</tr>
<tr>
<td>E = Elliptical Galaxy</td>
<td>13</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D = Giant Elliptical Galaxy</td>
<td>25</td>
<td>13.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N = N-Galaxy</td>
<td>8</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>?QS = Possible Quasar</td>
<td>4</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QS = Quasar</td>
<td>46</td>
<td>23.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td>197</td>
<td>100.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

One of the elliptical galaxies, 3C84 - an ED2, is a Seyfert Galaxy.
36% of its members remained unidentified. This proportion has now been reduced to ~26%, including tentative possible and doubtful identifications, with only 15% being wholly unidentified. Table 5.9.1 shows the distribution of the various optical types amongst the complete sample. It will be seen that 25% of the sources are now identified with quasars, the total number having risen from 39 to 46. Details of the new identifications will be found in Appendix III together with the other data on the complete sample. Some of the previous identifications are now in doubt because of the more accurate structural and positional information available from the higher resolution observations. Most of the new information has come from studies with the 200" Hale Telescope used with Image Tube apparatus and also with deep plates, generally baked IIIAJ emulsions.

Amongst the galaxies identified with sources in the complete sample are two 'spirals', 3C31 and 3C305, and one irregular, 3C231. 3C31 is classified by Sandage 1972, (284) as S03, so it does not actually have any spiral arms, but is at the extreme end of the spiral sequence of classifications. 3C305 is classified as an SaP (Sandage 1966 (129)) and possesses 'definite one-armed spiral structure'. They are both relatively weak sources.
(P178=1.5E24, and 8.1E24 W Hz^-1 sr^-1 for 3C31, 3C305 respectively) although they do have radio luminosities 3 to 4 orders of magnitude greater than those of normal galaxies. The irregular galaxy, (NGC3034 = M82) associated with 3C231, has a luminosity at 178 MHz of 5.1E21 W Hz^-1 sr^-1 which makes it only marginally more powerful than a normal galaxy. It is probably part of the local clustering of the M81 group and will not be considered further here.

The 48 unclassified galaxies are generally very distant and have magnitudes near the limit of the observations from which they were identified, 19 to 20 for identifications from the Palomar Sky Survey prints, but often 2 to 3 magnitudes fainter when detected on deep plates or with image tubes. There seems to be no clear distinction between the E- and the D-galaxies, the classification tending to be observer-dependent, though generally the D-galaxies are larger and dominate any associated galaxies in both size and brightness. Apart from differences caused by the extreme distances of the quasars, there are no observable differences of the average radio properties between any of the optically selected groups in Table 5.9.1, other than those already mentioned.

5.10 Relationships between the properties
of The Components of Double Sources

In this section we reappraise the general findings of Mackay 1971, (014), concerning the relationships between the properties of the outer components of double sources. These were as follows:

i) The component of the pair fainter at 1407 MHz is that further from the optical object.

ii) The spectrum of the brighter component at 1407 MHz tends to be flatter than that of the fainter component.

iii) Perpendicular to the major axis the fainter component is less compact than the brighter component.

iv) In most cases the brighter component at 1407 MHz is the more compact parallel to the source axis.

We shall deal with each of these in turn, and then attempt to explain the discrepancies between our findings, using the latest high resolution data in addition to the original 1400 MHz OMT data, and those of Mackay.

Before looking for the correlations described by Mackay, we first discuss the data now available. It is clear from the 5Km maps that a description of outer components as large unstructured 'blobs' is inadequate, and that in reality they generally consist of one or more compact heads, often with tails inclined to the source axis at angles up to 90 degrees, immersed in a region of more
Fig. 5.10.1 (top): The distribution of minimum dimension of preceding component for all double and triple sources in the complete sample.

Fig. 5.10.2 (bottom): The distribution of maximum dimension of preceding component for all double and triple sources in the complete sample.
diffuse emission. Whereas most of Mackay's data referred to unresolved heads, and thus some indeterminate combination of (possibly) resolved diffuse regions and heads/tails convolved with the much larger beam size, most of the new data allows us to refer to the head dimensions and fluxes alone.

Fig. 5.10.1 shows the distribution of DS1 (component number 1 minimum dimension) for the complete sample. This has two principal peaks, one around 1 arcsec and one close to 10 arcsec; these are the smallest upper-limits that can be placed on dimensions by the 5km at 5GHz and the OMT at 1400MHz and merely reflect the inadequacy of the data. The long tail extending to large values of DS1 is due to a few sources which have no compact heads in their broad, diffuse, components; the largest value on the plot (206 arcsec) refers to 3C236. Approximately 50% of the complete sample lie between declinations 10 and 36 degrees and the limiting North-South resolution of the 5km is then worse than 1.7 arcsec, so we should expect a significant number of upper limits on DS1 to be at least as large as this, indicating that more of the hump than just the peak at 1 arcsec is due to selection effects. Similar remarks apply to the distribution of DS2 (component number 2 minimum dimension). The distributions of DL1 and DL2 (component
Fig. 5.10.3 (top): The distribution of the ratio of the minimum component dimensions of the outer components for all the double and triple sources in the complete sample (same as Fig. 5.8.1)

Fig. 5.10.4 (bottom): The distribution of the ratio of the maximum component dimensions for the double and triple sources in the complete sample.
Fig. 5.10.5 (top): The distribution of the ratio of 5GHz flux densities of the outer components for all the double and triple sources in the complete sample.

Fig. 5.10.6 (bottom): The distribution of the ratio of spectral indices of the outer components of double and triple sources in the complete sample. It is likely that the large ratio measurements are in error (see text).
maximum dimensions) show no peaks around 1 arcsec but still have peaks close to 10 arcsec due to those sources observed only by the OMT. The shape of the distribution, shown in Fig. 5.10.2 for DL1, suggests that many components (and heads) have been resolved in at least one direction, though the hint of a peak close to 2 arcsec is probably due to upper limits placed on sources at low declination. There are fewer very large values of DL1, DL2 than DS1, DS2 which merely reflects the difficulty of defining these parameters for the largest components, which often merge with the bridge structure.

In Figs. 5.10.3 and 5.10.4 we plot the log. ratios, DS1/DS2 and DL1/DL2 respectively. Both can be seen to be approximately gaussianly distributed about a ratio of one, though the former (and to a much lesser extent, the latter) plot is badly distorted by limiting values, which tend to be the same for both components, giving rise to the artificially large peak centred on unity. Fig. 5.10.5 shows the 5GHz flux ratio (S51/S52) distribution while Fig. 5.10.6 illustrates the distribution of spectral index ratios (AL1/AL2): both are approximately gaussian with a mean of one. Later we will question the reality of the more extreme spectral index ratios.
Fig. 5.10.7 (top): A 'quadrant' diagram; log. outer-component separation ratio versus log. outer-component flux density ratio for all identified double and triple sources in the complete sample. The number of sources in each quadrant is noted in the corners. Mackay's effects predict an excess of sources in quadrants 2 and 4 (top-left and bottom-right).

Fig. 5.10.8 (bottom): Same as Fig. 5.10.7 for the double sources only.
Fig. 5.10.7 (top): A 'quadrant' diagram: log. outer-component separation ratio versus log. outer-component flux density ratio for all identified double and triple sources in the complete sample. The number of sources in each quadrant is noted in the corners. Mackay's effects predict an excess of sources in quadrants 2 and 4 (top-left and bottom-right).

Fig. 5.10.8 (bottom): Same as Fig. 5.10.7 for the double sources only.
Since all of Mackay's component relationships (i to iv above) depend on the flux density ratio of the two components, we treat them similarly, and to illustrate the data graphically, we plot ratios of properties on the Y-axis against the component flux ratio, both on log. scales. The properties of component #1 (the preceding) are always used as the numerators in our ratios. It can then be seen that i) to iv) above imply that most sources should fall in quadrants 2 and 4, and few in quadrants 1 and 3. Quadrants are numbered anticlockwise starting from the top right hand quadrant. If there are no effects to be found, the points should be distributed approximately gaussianly about the origin, in 2 dimensions.

In Fig. 5.10.7 we have plotted the log component separation ratio, 'L(D1:D2)', against the log flux ratio, 'L(S1:S2)', for all identified double and triple sources in the complete sample for which these quantities are measured (64 sources). It can be seen that the points are reasonably uniformly distributed between the quadrants; the numbers in each are 18, 18, 12, 12 showing no tendency to cluster in quadrants 2 and 4. However, among the more extreme excursions in flux ratio (|L(S1:S2)|>0.5) there are six points in quadrants 2 and 4 and only 2 in quadrants 1 and
Fig. 5.10.9 (top): Same as Fig. 5.10.7 for the triple sources only.

Fig. 5.10.10 (bottom): Same as Fig. 5.10.7 for the quasars only.
Fig. 5.10.11
Same as Fig. 5.10.7 for the radio galaxies only.
3. For \(|l(S_1:S_2)| < 0.2\), there are 18 in quadrants 1 and 3 and only 13 in quadrants 2 and 4. With no a priori reason to separate the regions in this way it is dangerous to attach significance to these results.

In Figs. 5.10, 8, 9, 10 and 11 we redraw the diagram for subsets of the sources in Fig. 5.10.7, viz: the double sources (9.8), triple sources (9.9), quasars (9.10) and radio galaxies (9.11) to see if any of these show significantly non-random distributions. Fig. 5.10.9 for the triple sources is a little interesting as most of the sources in quadrants 1 and 3 lie near the origin, while most in quadrants 2 and 4 are well away from the origin. This means that when the flux density ratio is small so also is the component separation ratio (and the nearer component is the weaker) but when the flux density ratio is large so also is the separation ratio, and now the further component is the weaker. Once again though, the total number of sources in each quadrant (9, 9, 6, 6) is very close to the mean (7.5) and the separation into two groups is still artificial. None of the other diagrams show any meaningful deviations from randomness. We also drew the diagram for those sources only observed at 1400MHz; it contained only 11 sources and showed no significant nonrandomness, the quadrants containing 3, 4, 4, 0 sources respectively. Lastly we looked for
3. For $|l(S1:S2)| < 0.2$, there are 18 in quadrants 1 and 3 and only 13 in quadrants 2 and 4. With no a priori reason to separate the regions in this way it is dangerous to attach significance to these results.

In Figs. 5.10.8, .9, .10 and .11 we redraw the diagram for subsets of the sources in Fig. 5.10.7, viz: the double sources (.8), triple sources (.9), quasars (.10) and radio galaxies (.11) to see if any of these show significantly non-random distributions. Fig.5.10.9 for the triple sources is a little interesting as most of the sources in quadrants 1 and 3 lie near the origin, while most in quadrants 2 and 4 are well away from the origin. This means that when the flux density ratio is small so also is the component separation ratio (and the nearer component is the weaker) but when the flux density ratio is large so also is the separation ratio, and now the further component is the weaker. Once again though, the total number of sources in each quadrant (9, 9, 6, 6) is very close to the mean (7.5) and the separation into two groups is still artificial. None of the other diagrams show any meaningful deviations from randomness. We also drew the diagram for those sources only observed at 1400MHz; it contained only 11 sources and showed no significant nonrandomness, the quadrants containing 3, 4, 4, 0 sources respectively. Lastly we looked for
Fig. 5.10.12 (top): 5GHz flux density ratio of the outer components of the double and triple sources in the complete sample, versus total linear size of source (Kpc).

Fig. 5.10.13 (bottom): Ratio of separations of the outer components from the nucleus versus total linear size of source (Kpc) for all the doubles and triples in the complete sample.
systematic effects by plotting the flux density ratios and
the component separation ratios against total source linear
size, (see Figs. 5.10.12, .13 respectively), and it can be
seen that both distributions are respectably random. This
indicates that amongst the 'simple' doubles and triples,
there is no tendency for the sources to become more, or
less, asymmetric with age.

Most of the 5GHz observations made by the 5km
telescope have produced flux densities for components of
well resolved sources which, when summed over the source,
are considerably below the 5GHz flux density as measured by
total power instruments. This is because only the more
compact regions contribute to the interferometer
measurements and much emission also takes place from diffuse
regions. This makes calculation of component spectra, using
1407MHz data together with the 5GHz data, difficult and in
many cases impossible, since the much lower resolution OMT
'component' flux density measurements often correspond to
one entire half of the source, and not simply to the compact
head. Thus, there are relatively few new measurements of
component spectra, other than those produced by the OMT by
observing at 2.7 and 5GHz, Branson et al. 1972 (005), and
consequently our re-analysis of Mackay's effect (11) will
necessarily be limited to only a few more sources.
Fig. 5.10.14 (top): Quadrant diagram for component spectral index ratio versus flux density ratio (the extreme spectral index ratios are thought to be due to measurement errors - see text).

Fig. 5.10.15 (bottom): Log. spectral index ratio versus log. component separation ratio. The clustering in quadrants 1 and 3 is predicted by a consequence of Mackay's correlations (i) and (ii). However, this observed effect is probably due to confusion of the closer component to the nucleus with the central component: this preferentially lowers the spectral index of that component.
Fig. 5.10.14 shows the log. ratios of component spectra against the flux density ratio as before, for 28 double and triple sources with measured outer component spectra. Seven sources have a spectral ratio of nominally 1.0, 11 show Mackay's effect, and 9 show the opposite effect. Again the distribution among the quadrants is essentially random, and there appears to be no nett effect despite the fact that for at least 7 of the sources, the spectra were determined at 408/1407MHz on maps where a CCC (revealed by later 5GHz observations) was not resolved separately from the nearer component (see (b) following). In Fig. 5.10.15 we have plotted the spectra ratio against the separation ratio, once more including the doubtful spectra mentioned above. Apart from the six sources which have one of the ratios equal to unity, the diagram indicates a distinct clustering in quadrants 1 and 3. This corresponds to the closer component having the flatter spectrum, an implied consequence of Mackay's correlations (i) and (ii). The numbers in the quadrants are 8, 2, 3, 3, the East-West asymmetry being as significant as the trend favoring quadrants 1 and 3. If we ignore those sources where the (now) known CCC may have perturbed the measurement of one of the spectra at 408/1407MHz, we are left with only 9 sources, and the quadrant counts become 4, 0, 1(+1), 3.
Fig. 5.10.16 (top): Quadrant diagram for component minimum dimension ratio versus flux density ratio.

Fig. 5.10.17 (bottom): Quadrant diagram for component maximum dimension ratio versus flux density ratio.
making any residual effect insignificant. All of the sources where the spectra ratio, measured using 1.4GHz OMT data, was found to be greater than 1:1 have now been shown to possess previously undiscovered central components (except for 3C123 where resolution problems in the lower frequency maps make an accurate determination difficult). This indicates that the spectral indices of the two outer components of powerful sources are usually very nearly equal.

The log ratio of the component minimum dimensions and the maximum dimensions are plotted against flux ratio in Figs. 5.10.16, .17 where it will be seen that all four quadrants are approximately equally populated, indicating no nett correlation between these variables. There does appear to be some curious East-West asymmetry present as inspection of Fig. 5.10.16 shows; the dispersion in Log(DS1/DS2) is much larger for those sources to the left of the flux ratio origin; i.e. for sources whose more powerful component is following on the sky. This is true also in Fig. 5.10.17. It is difficult to postulate any sort of physical explanation for this phenomenon and in the absence of any further information, it is assumed to be a statistical fluctuation from uniformity.
Fig. 5.10.18 (top): component minimum dimension ratio versus component separation (from nucleus) ratio.

Fig. 5.10.19 (bottom): component maximum dimension ratio versus component separation ratio.
Fig. 5.10.20 (top): Ratio of minimum dimensions of outer components versus ratio of maximum dimensions. The correlation (the dashed line is a least squares best fit) is significant at the 1% level (r=0.27).

Fig. 5.10.21 (bottom): Ratio of minimum dimensions of outer components versus ratio of their spectral indices.
Fig. 5.10.22 Ratio of outer component maximum dimensions versus ratio of their spectral indices. The extreme values of spectral index are probably in error (see text).
Fig. 5.10.22 Ratio of outer component maximum dimensions versus ratio of their spectral indices. The extreme values of spectral index are probably in error (see text).
Figs. 5.10.18, .19 show the same ratios plotted against component separation ratio, while Figs. 5.10.20, .21, .22 show the various 'dependent variable' ratios plotted against one another. The only significant correlation ($r=0.27$ in the population, at 1% level) is that between $\log(DS_1/DS_2)$ and $\log(DL_1/DL_2)$ in Fig. 5.10.20: this implies that the component of a double source with the greater minimum dimension, generally has the greater maximum dimension. This in turn implies that the two components tend to have similar aspect ratios, independent of the absolute dimensions or orientation.

To summarise, there appear to be no significant correlations between the properties of the compact component heads ($\omega_1, \omega_2, S$) and their separations from the nuclei of the radio sources. Neither are there any internal correlations between these variables, except for a tendency for both dimensions of one component to exceed those of the other at the same time.

To explain the discrepancy between this result and those of Mackay we suggest the following:
a) Firstly we are considering the compact heads and not some composite of diffuse emission and beam convolved with 'point' source. It is not clear what systematic effects the latter would introduce.

b) Most of our results refer to observations at 5GHz of considerably higher resolution. It is likely that at 1400MHz the component separation measurements, \( \theta_1 \) and \( \theta_2 \), were made to some approximate centroid of compact head + tail + any bridge component, and since the head is generally farthest from the nucleus this will artificially reduce \( \Theta \) and increase the flux density over and above that due solely to the head, giving rise to a type (i) effect. When an outer component is sufficiently close to a CCC for them not to be separately resolved, \( \Theta \) will again be reduced, flux density increased and the spectrum flattened. This is akin to effect number (ii). Effects (iii) and (iv) basically say that the brighter the component the more compact it appears: this is true when what one is measuring is appreciably smaller than the telescope beam width. It is difficult to assess the amount of beam broadening produced by weak components, and possibly due to poor signal to noise ratio, the tendency is to overestimate the size of such components. Certainly, we find that many of the outer components contain regions responsible for appreciable fractions of the total flux density, which are still unresolved by the 5Km beam (which
is nearly 11 times as narrow as that of the OMT at 1.4GHz).

c) Lastly, our statistics are based on a larger sample of data and some part of the effects found by Mackay may have been due to random statistical fluctuations.

5.11 The Brightness of Radio Components

We now investigate the possibility of correlations between the surface brightness of radio components and other properties of sources, since such correlations are clearly of astrophysical interest, and have been reported elsewhere (e.g. Heesch 1966 (261), Pomalont 1969 (262)). Little attention has been paid to selection effects with regard to this parameter (but see Longair & MacDonald 1969 (L13)), so we initially analyse the observed $B - Z$ relationship with this in mind.

We estimate the brightness of the outer components (only considering double and triple sources) by computing the quantity

$$B = kS(1+Z)^{(3+\alpha)}/(\omega_{min} \omega_{max}) \propto P/d^{**2},$$
Fig. 5.11.1 (top): Brightness of preceding outer component versus redshift for the 108 double and triple sources for which measurements are available.

Fig. 5.11.2 (bottom): Same as Fig. 5.11.1; the legend indicates which components are unresolved and which brightnesses are computed using an estimated redshift. The solid line indicates the lower bound of the region of the B-Z plane accessible to the 5Km telescope. The dashed line and its solid extension indicate the expected observational correlation between B and Z.
where $B$ is the brightness in Jy sr$^{-1}$, $k$ is a numerical conversion factor, $S$ is the observed 5GHz component flux density, $\omega_{\text{min}}$ and $\omega_{\text{max}}$ are the component dimensions (in arcsec) as defined in Section 5.10, $Z$ is the object's redshift, $P$ is the intrinsic luminosity, and $d$ is a linear scale size of the object. The factor $(1+Z)^{(3+\alpha)}$ ($\alpha$ is the component spectral index where known, otherwise it is 0.8), gives a brightness measure corrected for the reddening (and thus weakening) of the photons, for the reduction in bandwidth and for the non-uniform spectrum of the object. It gives the result that an observer close to the source would measure if he observed at 5GHz (disregarding resolution effects). Because the relationship between the brightnesses of the outer components of double and triple sources is not known, it cannot be assumed that they are independent. Thus we perform all our correlations for first the preceding (#1) and then the following (#2) components. Only if the two sets of results disagree should we be concerned about this procedure. This also avoids introducing complicated selection effects due to our inability to readily observe sources with component flux ratios of greater than 10:1.

Fig. 5.11.1 is a log. plot of $B$ against redshift (2) for the 108 double and triple sources whose parameters have
been measured. There is an obvious correlation, though much scatter, and the correlation weakens for $Z > 0.6$. We can place one selection-effect line on the diagram immediately.

To observe a component at all, the 5Km, (from which practically all our data on B comes), needs 10 mJy per beam area: this corresponds to $\log B \approx 3.4 \text{ Jy sr}^{-1}$ at the telescope (2 arcsec is the half-power beamwidth, so for the purpose of this calculation we have assumed a 3 arcsec beamwidth). This selection line is drawn on Fig. 5.11.2 (same as 5.11.1) where it is seen to lie below most sources. At low declination where the telescope beam is larger, the 5Km is capable of observing lower surface brightness components. Note that a fixed telescope 'brightness' limit corresponds to an intrinsic brightness limit that varies as $(1+Z)^{-3+\alpha}$ and so the selection effect curve is not a straight line on this plot.

We also know, from the work of Chapter 3, that most sources contain structure in the components on a scale of 5 to 10 Kpc, and at the limiting resolution of the 5Km, this corresponds to a redshift close to 0.5. So for $0 < Z < 0.5$ (i.e. small $Z$), we can expect the observed $\omega_{\text{min}}$, $\omega_{\text{max}}$ to fall roughly as $1/Z$, so that

$$B = \frac{P}{d}^{2+2},$$
Fig. 5.1.3 (top): 5GHz luminosity of preceding outer component versus redshift for the double and triple sources in the complete sample used in our analysis of component brightness.

Fig. 5.1.4 (bottom): 5GHz brightness versus 5GHz luminosity for the preceding components of the double and triple sources in the complete sample. The solid line delineates the lower bound of the region of the B-P plane accessible to the 5km telescope. The dashed line has a slope of unity.
where \(d\) is essentially constant.

Now if we observed sources of constant luminosity \((P)\), \(B\) would remain approx. constant with \(z\). However, we have seen in section 5.6 that because our sample is complete down to a limiting flux density, and also because of the decreasing space density of objects with increasing \(P\), the (observed) \(P\) and \(Z\) are very strongly correlated, and in fact the correlation is of the form \(P \propto Z^{2}\) (see Fig. 5.11.3). Thus, for small \(z\) we expect to observe a correlation of the form

\[
B \propto P \propto Z^{2}
\]

An alternative way of looking at this is that the flux densities \((S)\) of all the objects are nearly the same and the angular sizes for fixed physical size go as

\[
\omega \propto \frac{(1+Z)}{(1-(1+Z)^{1/2})}
\]

for \(Z<0.5\) where we can still resolve the components. Thus,

\[
B \propto kS \frac{\omega}{\omega_{\text{min}}} \propto (1+Z)^{1+\alpha} \left(1-(1+Z)^{1/2}\right)^{-\alpha} \propto (1+Z)^{1+\alpha} \left(1-(1+Z)^{1/2}\right)^{-\alpha}
\]

(for \(\alpha \sim 0.8\), and \(Z<1\) this \(\propto Z^{2}\)). This is the dashed line on
Fig. 5.11.2, where it is seen to fit the data well. For $0.5 < Z < 2$, $\omega_{\min}$ and $\omega_{\max}$ are approximately constant at the telescope beamwidth so that

$$B \propto (1+Z)^{2+\kappa}$$

This second line is also drawn on Fig. 5.11.2 (solid) where it can be seen to deviate only slightly from the $B \propto Z^2$ line. This is because in an Einstein de Sitter model the angular size of an object is only a weak function of redshift in the range $0.6 < Z < 2.0$. The figure shows which points are due to unresolved components, and most of them are clustered around the second of our 'fitted' lines with $Z > 0.5$ as expected. Thus we can explain the shape of Fig. 5.11.1 without recourse to any correlations between the properties of radio source components. Let us now see how this affects our interpretation of the $B-P$ diagram, described by Heeschen (261).

Fig. 5.11.4 shows a plot of component brightness against component luminosity. Again there is a large scatter of points, but there is a distinct positive correlation between $B$ and $P$ right across the diagram. We have sketched in the approximate lower limit to observational $B$, but this line is only as well determined as is the $P-Z$ correlation.
Fig. 5.11.5 5GHz brightness versus luminosity for the preceding outer component of double and triple sources in the complete sample with redshifts less than 0.6.
Our previous analysis indicates that for the region $z<0.5$, $B$ is proportional to the first power of $P$. Fig. 5.11.5 shows the data for $z<0.6$ and the computed best fit equation is $B = 3.48E-14 P^{0.963}$ when the correlation coefficient takes a value of 0.7. Beyond this region ($0.5<z<2$) we have no more resolution but as Fig. 5.11.2 shows, the $B \propto z^{2}$ relationship is still a very good approximation and thus $B$ and $P$ are still well linearly correlated. Fig. 5.11.4 shows a line of slope 1 superimposed on the $B - P$ diagram and it is seen to fit the data well. The form of the relationship is different from that reported by Heeschen (261): he found that the curve turned upwards at $\log B \approx 3.3 (\text{Jy sr}^{-1})$ at 1400 MHz, which corresponds to $\log B \approx 3.9$ at 5 GHz (assuming $\alpha = 0.8$). This turnover is at a considerably lower brightness than that corresponding to $z=0.6$ in our data and in fact lies close to the bottom end of our range of measured $B$.

There are several reasons why our data give a different result. Firstly the angular size data available to Heeschen were limited in accuracy and were very inhomogeneous: much was from 1-D LBI scans where only simple
models were fitted to fringe visibilities; the resolutions with which each of his sources were observed varied over a very wide range (1 to 60 arcsec); often, where distant quasars were concerned, only the most compact components could be seen, due to the shortcomings of LBI observations, though frequently these would be at least partially resolved, giving rise to very large brightness values; many of the radio galaxies were not observed by LBI and consequently the sizes of the components were overestimated. Several of the quasars in his sample are not double/triple sources but are akin to what we have referred to as CCC's, with flat spectra. These in general do not have particularly high luminosity at 1400MHz but the measured brightness is very large because they have very small dimensions. Nor did Heeschen make any corrections for the redshifting of the radiation; he made no allowance for the change in bandwidth between emission and reception, nor for the fact that he was observing $P(\nu_e)$ with different $\nu_e$ (emission frequency) for every source, $\nu_e = \nu_0(1+z)$. Since the sources generally have steep spectra this can produce considerable errors. Lastly it is likely that the figures he quotes for B for all but the distant quasars are for some average brightness of the diffuse, and head-tail emission. This is not a very meaningful parameter as it is unclear what contribution is made by different portions of the source structure, and these contributions will differ from
source to source. We feel it is likely that his turnover occurred because for the more distant quasars, the LBI and VLBI observations more nearly resolved the structures, producing measured brightness values comparable to ours for the same objects. For nearly all other sources, the brightness has been underestimated because of poor resolution and/or poor discrimination between the different structures within the sources. In fact, most brightnesses for these sources are down by a factor of of 100 on ours which corresponds to a factor of 10 in angular resolution which is roughly the same as the difference in resolution of the 5Km (~2 arcsec) and Heeschen's ~20 to ~30 arcsec average, though there is very large scatter in his resolutions.

We stress, once more, that the features in the luminosity brightness diagram for the compact components of double and triple sources are explicable in terms of observational selection effects: no internal, physically meaningful correlations are implied by our data; nor do they provide evidence of evolution of the source population. However, this result lends weight to our earlier finding that the scale size of component head features was approximately constant and of order 10Kpc (see Chapter 3) because we have used this assumption explicitly in order to
explain the shapes of the diagrams. The implication of constancy of this dimension over a wide range of source types, luminosities and redshifts, is an important result in itself.

5.12 Luminosity, Linear Size and Redshift

An important cosmological test is the angular diameter - redshift relation. If we can measure the angular sizes of large numbers of radio sources of the same type at varying values of redshift, and if we can then assume the constancy of linear size of these sources, the \( \theta - z \) relationship will tell us something about the geometry of the universe. Miley (1971, Q41) has claimed that such a test when applied to quasars, indicates that the assumption of a constant size is invalid and that these sources have a smaller average size at high redshifts. Reinhardt (1972, 371) reinterpreted Miley's data and concluded that such evolution was not present; he explained the data in terms of two classes of quasars of different linear sizes and deduced a best fit value of \( \alpha = 0.05 \). We treat this whole subject in greater detail in Chapter 7, and here only investigate one major selection effect that appears to have been neglected until now.
Fig. 5.12.1 (top): 5GHz luminosity versus separation from nucleus for the preceding components of the double and triple sources in the complete sample. The solid line at top-left marks the upper boundary beyond which resolution (with the SKA) is insufficient for classification as double or triple. The dashed lines have no physical significance, but are discussed in the text.

Fig. 5.12.2 (bottom): Separation from nucleus of preceding component versus redshift for doubles and triples in the complete sample. The solid line at bottom-right is a resolution limit as in Fig. 5.12.1. The upper solid line is equivalent to the upper dashed line in Fig. 5.12.1 and marks the expected upper limit of observed linear size at a given redshift.
Fig. 5.12.1 is a log. plot of component (\#1) 5GHz luminosity 'P5C1' versus component (\#1) separation from the nucleus, 'D1' (in Kpc) of the complete sample doubles and triples. As usual in this work, we have assumed an Einstein de Sitter World model with $q_0=0.5$ and $\Lambda=0$. There is a clear trend for the larger separations to be associated with the lower luminosities, with a very wide scatter of the one at any fixed value of the other. The curve in the top left corner indicates that region of the diagram wherein resolution effects generally prevent the classification of the source as a double/triple from the 5Km data. The lower left corner of the diagram is almost unpopulated. There are no selection effects against seeing small sources with low luminosity if their space density is reasonably high since if they are bright enough to exceed our flux limit we will have sufficient resolution to resolve them. Similarly, very large high luminosity sources are not selected against unless their components are also very large, when the surface brightness may be sufficiently low to render them unobservable (we investigate this later). Thus we conclude that the (weak) correlation is real.

Unfortunately, because of the very uneven distribution of points on the diagram, the curve fitting routines are biased towards generating curves through the region of
highest density of points \((D \approx 200 \text{Kpc}, P \approx 1 \text{E}25 \text{W Hz}^{-1} \text{sr}^{-1})\) as this then minimises the least-squares error. Consequently, the computed correlation coefficients are smaller than they might otherwise be. However, for a curve of the form

\[ P = 3.6 \times 10^{26} - 1.4 \times 10^{26} \log D \]

the correlation coefficient is \(r = 0.33\) for the sample \((r = 0.12\) in the population at the 5% level). We have drawn rough boundary lines on the figure indicating the approximate limits on P5C1 (P for short) for sources with any value of \(D_1\). For example, sources with \(D_1 = 400 \text{Kpc}\) are unlikely to have \(\log P > 24.6\), and similarly \(D_1 = 100 \text{Kpc}\) corresponds to \(\log P < 26.0\). When one now considers the already mentioned strong selection effects in the \(P - Z\) relation, it is clear that the \(D - Z\) relation will be distorted by the above. Fig. 5.12.2 is a log plot of \(D_1\) against \(Z\) and the absence of large sources with high \(Z\) is obvious. Using our known \(P - Z\) relationship we have transferred the upper limit line (on \(P\)) from Fig. 5.12.1 to this diagram. It delineates very well the boundary where sizes begin to fall, the few sources above the line being explicable in terms of the few sources sufficiently luminous to lie above the upper line on Fig. 5.12.1. The curve in the lower right hand corner is a resolution selection effect; below this line sources are not well enough resolved by the 5Km to be classified as double/triples.
Fig. 5.12.3 5GHz luminosity versus separation from nucleus of the preceding components of the double and triple sources in the complete sample with redshifts smaller than 0.5. The dashed lines have been transferred from Fig. 5.12.1 to aid comparison.
To check that the P-D correlation is not caused by a combination of evolution of the source population and the observational correlation between P and Z we have looked at the P-D correlation for only those sources in Fig. 5.12.1 with \( Z < 0.5 \) where evolution effects ought to be negligible. The data are presented in Fig. 5.12.3, where it can be seen that the cutoff in Z has largely had the effect of a cut off in P. The remaining sources (42 out of 57) still show the P-D correlation but it is much weakened. We have transferred the boundary lines of Fig. 5.12.1 to Fig. 5.12.3 to aid comparison of the figures. The curve fitting routine now produces as best fit, a relation of the form,

\[
p = 1.4 \times 10^{-5} - 5.6 \times 10^{-5} \log D
\]

with \( r = 0.37 \) (\( r = 0.12 \) in the population at the 5% level). This is similar to that for the whole sample and still shows a tendency for the mean luminosity to be lower for the large sources.

So on our \( D-Z \) diagram we can explain the principal features in terms of selection effects and an intrinsic source property correlation without recourse to invoking
Fig. 5.13.1 (top): Component projected area (Kpc$^2$) versus redshift for the doubles and triples in the complete sample. The lower solid line marks the limit of resolution of the 5Km telescope. Lines 'b' and 'c' are those lines above which the most luminous source expected at a given redshift, and a source at the flux limit of the survey (respectively) will be invisible to the 5Km due to inadequate brightness (~10mJy/beam). Line 'a' is the upper boundary of the region where a source will have sufficiently small d/D ratio to be classified as double or triple.

Fig. 5.13.2 (bottom): Component projected area (Kpc$^2$) versus component separation from nucleus. The solid line again indicates the upper boundary for classification as double or triple. The dashed lines are various loci of constant d/D ratio.
evolution or very small values of g. Similar selection effects will apply to any D - Z diagram when the set of sources studied has been selected to a limiting flux density and observed down to a limiting angular resolution (e.g., as was Miley's sample).

5.13 Component Size and Separation

If we denote by 'd' the linear scale size of component heads, and by 'D' the linear separation of the heads from the nucleus, then \( d/D \) is a measure of the angle subtended by the component at the nucleus. For the development of source theories it would be useful to discover how \( d/D \) varies with age \( \omega \) in any given type of source, and having elucidated one of the major selection effects on \( D \) we now investigate \( d \). We have computed the parameter \( 'A' = d(\omega_{min}) \cdot d(\omega_{max}) \) (in Kpc) i.e. the approximate area of the component heads in Kpc for the doubles and triples, as this gives a more typical scale parameter than either \( d(\omega_{min}) \) or \( d(\omega_{max}) \) alone.

Fig. 5.13.1 shows a log plot of \( A \) against \( Z \) with four selection effect lines -a, -b, -c and -d. Line-d is due to the lower limit of resolution of the 5Km and corresponds to the component subtending an angle of 1 arcsec at the
telescope. We expect to see no sources below this line. Lines-b and -c are due to brightness cut-off. Source components lying above line-b have their luminosity spread over a sufficiently large area that they are below the 10mJy/beam limit of the 5Km. The line has the form $A \propto 1/(1+z)^{(1+\alpha)}$. The position of line-b is chosen such that even the most luminous source we might expect to find at a particular redshift (on the basis of the observed P-D diagram) will not be bright enough to be observed if it lies above this line. Line-c is similar except that it is positioned such that a source at the flux limit of the survey will be visible if it lies below this line. On the basis of the observational D-Z relation (e.g. Fig. 5.6.5) we can construct line-a above which sources will have insufficiently small d/D ratio to be classified as doubles or triples, and thus will be absent from the diagram. The selection lines enclose the observed points reasonably well, and there is little residual tendency for components to be more compact at high redshift (luminosity) as has been previously suggested (Fomalont 1969, (260)).

In Fig. 5.13.2 we show a plot of 'A' versus separation from the nucleus, 'D'. The line in the top left corner is similar to line-a above (d/D>1.3; sources above this are not classified as double/triple). The rest of the diagram is
Fig. 5.13.3 5GHz brightness versus separation from nucleus for the preceding components of double and triple sources in the complete sample. The arrows at 45 degrees to vertical indicate that only an estimated redshift is available. The vertical arrows indicate that the component is unresolved in at least one direction.
relatively uniformly covered and since D seems not to be intrinsically correlated with redshift, there are no other strong selection effects other than those mentioned. We stress that the tendency for the eyes to be guided by the selection effect is no indication that d/D remains constant for any particular source. Sources could just as easily evolve along lines perpendicular to this. Unfortunately, because of the way the sources are distributed, we cannot use arguments based on the relative density of points in different regions of the diagram to deduce facts about their evolution.

We are now in a position to be able to explain the apparently strong correlation in Fig. 5.13.3, between the component brightness at 5GHz, 'B5', and its separation from the nucleus. This correlation is stronger than that between P and D. In view of the strong observational correlation between P and B, this might be thought to be the cause of the P-D correlation. However, whereas the latter was not subject to strong selection effects, the B-D correlation is. We have B \propto P/d^{**2}; since P \propto 1/D, (Fig. 5.12.1) we expect some correlation between B and D but it should be weaker than that between P and D. Although as we have seen, d^{**2} is not demonstrably correlated intrinsically with D, there is a strong selection effect that ensures that on the average
for doubles and triples (Fig. 5.13.2) and this enhances the already present B-D correlation via the luminosity. The actual numbers derived by least squares fit to the selection affected data are as follows:

\[
A \propto D^{0.57} \quad \text{(Fig. 5.13.2)}
\]

\[
P \propto D^{0.69} \quad \text{(Fig. 5.12.1)}
\]

and therefore \( B \propto P/d**2 = P/A \Rightarrow B \propto D^{-1.26} \)

The data in Fig. 5.13.3 give \( B \propto D^{-1.36} \) as a best least squares fit which is very close to the proportionality expected from Figs. 5.12.1 and 5.13.2. We conclude that this correlation is due to a combination of observational selection (of which sources we call double/triple) and the luminosity size correlation seen in Fig. 5.12.1.

There are no significant correlations between component size, \('A'\), and absolute magnitude of the galaxy/quasar identification, or with the component spectral indices.

### 5.14 Conclusions

From a detailed examination of the radio and optical
Fig. 5.14.1 Bar chart showing the distribution of optical types amongst the well resolved double and triple sources in the complete sample.
data on a complete sample of 197 radio sources we have deduced the following facts:

i) ~25% of powerful radio sources in the complete sample are associated with quasars, the remainder with normal and N-galaxies.

ii) nearly 90% of all resolved sources in the complete sample show a basic double structure. Of the rest, approximately two thirds are complex and one third consist of a single compact component embedded in a diffuse envelope. ~30% of the double sources possess a bridge of emission connecting the whole source.

iii) approximately 76% of the double sources in the sky (not in the complete sample) have compact central components. Those without CCC's are about 30% smaller overall than the triples (this result is based on a sample of only 10 doubles). About half of the triples are associated with 'active' optical objects (quasars or N-galaxies), the rest with ordinary galaxies. Of the doubles, only 20% are associated with active optical objects. As many as 90% of quasars and 68% of radio galaxies have compact central components. These facts are presented graphically in Fig. 5.14.1.

iv) very large sources of 3C236-type have a low space density. That is, there are very few likely candidates in the complete sample that could possess undetected structure on a scale of 5Mpc.
v) central component luminosity is correlated with overall source luminosity.

vi) central component luminosity is correlated with overall source size.

vii) there is little evidence for a strong correlation between radio and optical luminosities of the nucleus, though the brightest radio nuclei are associated with the brightest optical nuclei (though not necessarily, vice versa).

viii) very few galaxies have very powerful CCC's (i.e. as powerful as those found in quasars).

ix) a few sources appear to have only one component remote from the nucleus, together with radio emission from the nuclear regions (the 'DQ' sources).

x) there are no significant correlations between the properties of the outer components and their separation from the source nucleus in a double/triple source.

xi) component brightness is not demonstrably correlated with outer component luminosity.

xii) component luminosity tends to fall with increasing component separation.

xiii) amongst all the parameters we have discussed in this chapter, there are no other significant correlations than those mentioned in i) to xii) above.
We shall postpone a discussion of the implications for source theory of these facts until we have investigated the information available from the detailed structures of the ensemble of sources in 3CR. This latter we investigate in Chapter 6. Chapter 8 will discuss source theories in the light of all our findings in this dissertation.
CHAPTER SIX

The Morphology of Powerful Extragalactic Radio Sources

6.1 Introduction

The major achievement of synthesis radio telescopes has been to produce detailed two-dimensional structures for many of the powerful (and thus generally distant) extragalactic radio sources (ERS). In the earlier chapters of this dissertation we have attempted to parameterize these structures so as to obtain numerical data suitable for standard statistical analyses, e.g. correlation diagrams. This facilitates a comparative study of radio sources. It must be emphasised that the parameterization process depends heavily on some preconceived models of the structures of archetypal radio sources. The reliability and applicability of these models (the double, triple, complex, etc. radio sources) is not well justified in view of the huge variety of structure found in any sample of real radio sources, though they are probably the best practical approach at present, in view of our limited understanding of radio source mechanisms.
If we relax the requirement for numerical comparisons, we may utilize much more of the information contained in the 2-D structure data, most of which is exceedingly difficult to represent numerically. We can then use the human visual system to perform the comparison process. The result of such a comparison will not be numerical, but some general notions as to the interactions between radio source structures may become apparent, as the general pattern recognition capabilities of the human brain are recognised still to far exceed those of any artificial processing system. It is possible to construct machines that outperform the human in certain recognition problems, but this is only the case when one knows, a priori, for what one is searching. In the case under consideration, we have few if any guidelines from theory to direct the search for pattern in the ensemble of radio source structures. It is just this sort of open-ended pattern search that the brain performs so well. The success of taxonomical studies in botany and biology should be evidence enough that this type of approach can be useful.

6.2 Technical Considerations

Most of the detailed maps of ERS produced to date have been obtained with the synthesis telescopes, the DMT, the
5Km and the WSRT. Since these have a declination dependent N-S resolution, it has been common practice in the past (at Cambridge) to draw contour maps with the N-S scale compressed by a factor cosec, so that the synthesised beam appears circular on the map. This is done to make apparent those portions of the structure that are unresolved by the telescope. Another common practice has been to draw the maps all about the same size so that each has a unique angular scale (arcsec/mm).

To facilitate the visual comparison of the maps, they should have a common scale and preferably a standard orientation. (It is difficult to read alphabetic characters (with which one is intimately familiar) when they are drawn upside down; this indicates that the recognition of unfamiliar features in arbitrary orientations will be made much harder). Since it is the physical structures (and not the angular structures) that are the subject of our comparison, we require the maps to be converted to a common scale in, say, Kpc/mm.

To this end, we embarked on a major photographic exercise to produce prints of all the available radio maps of sources whose distance was known, all to a common scale
Fig. 6.2.1 A schematic of the camera setup used to decompress the compressed maps and illustrating the quantities discussed in the text.
and not subject to compression in one direction. Some of the older maps made by the UMT and synthesised on the University of Cambridge TITAN computer, no longer exist in numerical form, and thus could not be replotted by computer to a different scale. Similar considerations applied to many of the older maps produced by the 5Km telescope. Tracing using a pantograph would have enabled a uniform change of scale but besides being very time consuming, and inaccurate for large scale changes, would not allow the compressed-scale maps to be decompressed. A photographic approach was the only one practical.

Many of the sources at low declination (~15 degrees) have to be expanded by a factor of 4 or more in one dimension only. This is simply achieved photographically by tilting the map to be photographed out of the plane at right angles to the line of sight (see Fig. 6.2.1). If \( \Theta \) is set to \( \delta_{\text{map}} \) then the E-W scale will appear compressed (as viewed by the camera) by an amount equal to the already present compression of the N-S scale, \( \text{cosec} \delta \). (This assumes that the map is in the normal orientation with N at the top). Unfortunately, unless the camera is at a great distance from the map \( (h \gg 1, \text{ Fig. 6.2.1}) \) the differential distances of parts of the map from the camera produce different image sizes, the rearmost portion of the map suffering extra
Fig. 6.2.2 Illustrating the distortion produced by and the poor depth of focus of a 50mm lens when used to photograph a highly compressed map.
compression due to its greater distance from the camera than
the frontmost portion. Additionally there are related
problems with depth of focus unless the lens is heavily
stopped-down. These effects are illustrated in Fig. 6.2.2
which shows photographs of heavily compressed maps taken
from a short distance away by a camera with a 'standard'
50mm lens.

The work was performed with a standard 35mm single
lens reflex (miniature) camera. For adequate photographic
resolution it is necessary to fill a substantial portion of
such small negatives with map image, and this places severe
constraints on the maximum separation of map and camera for
a given lens focal length \( f \). Using a 50mm lens, an A4 size
map will approximately fill the 35mm frame when the camera
distance is 17 inches: this is only 1.5 times the larger
dimension \( l \) of the map and clearly does not satisfy the
constraint \( h \gg l \) necessary to prevent foreshortening of
highly compressed maps. A more exact constraint is
\[ h - f > 20.1 \cos \delta \]
for better than 5\% differential image magnification, where \( f \) is the focal length of the camera
lens and \( \delta \) is the declination of the mapped object. This
appears to indicate that a short focal length lens would
improve matters. However, when one takes into account film
coverage one arrives at the relation \( f > 40s \cos \delta \) where \( 2s \) is
the frame size produced for 5% foreshortening, with a map compressed by factor cosec. It is now clear that for small $\delta$ we need 'f' large. Happily, the same constraint also ensures adequate depth of field with moderate stopping-down of the lens.

A 300mm 'zoom' lens was available and the above relation indicates that we can adequately cover all angles of projection if we are prepared to accept 5% (or less) foreshortening and an image frame size of 15mm (covering roughly one quarter of the negative). A flash gun was used for illumination of the maps, which were clipped to a vertical board free to rotate about a vertical axis. Because of the long lens used, camera shake was troublesome despite the use of a heavy tripod and short exposure times. This problem was overcome by lifting the mirror of the reflex system 5 seconds prior to opening the shutter: this technique allowed the camera oscillations to damp out before exposure of the film.

Prior to photography, the maps were inscribed with a linear distance scale in kpc computed using redshift (or if lacking, magnitude) information and an assumed Einstein-de Sitter World model with $\Lambda = 0$ and $q_0 = 0.5$, and a value of
Hubble's constant, $H_0 = 50 \text{Km} \text{s}^{-1} \text{Mpc}^{-1}$. Medium resolution film was used (Ilford FP4) as a compromise between adequate speed and resolution, and over-exposed 2-stops to improve contrast. The maps were then printed to a common scale using high contrast (grade 5) paper. The correct sizes were obtained by projecting the distance scale onto a ruler in the plane of the printing paper and adjusting the enlarger until a constant Kpc/inch was obtained.

Choosing the map scale was a compromise between having too many maps too small to see structure in, and too many so large that the whole diagram (composed of the ensemble of scaled maps) was unmanageably large (the dynamic range of the structure data is a factor of several thousand). A final scale of 50Kpc/inch was chosen. The form of presentation used was to 'plot' the scaled maps on a luminosity-linear size diagram. This distributed the maps in 2 dimensions and separated them into size and luminosity classes. To avoid excessive overlapping of the maps a linear size scale and logarithmic luminosity scale were chosen for the diagram with the diagram linear size scale somewhat larger (≈7.3Kpc/inch) than that of the scaled maps. The diagram thus produced is approximately 5 x 12 feet and yet still contains detail too small to see. (it would have to be 36 feet long to accommodate 3C236). It was not thought practical
Fig. 6.2.3 A small portion of the Morphology diagram discussed in the text. The source maps are reduced to a common linear scale (approx. 200Kpc/inch in this reproduction) and are distributed in the P-D plane.
to include either a full-size version or a useful reduction of the whole diagram in this dissertation. Instead we present a reduction of the left portion of the diagram (0 < D < 400 Kpc), Fig. 6.2.3, and several separate sections of the diagram as discussed in the text in the form of prints or sketches.

To construct the diagram we have used maps from the whole set of 3CR sources and not just those from the complete sample. This enabled a fuller coverage of the P-D plane with well resolved structures. The features that we hope to extract from the diagram will necessarily be of a qualitative nature and thus not subject to rigorous statistical analysis, so the incompleteness of the sample used is of no consequence. Thus are findings are complementary to those of Chapter 5 though not, we hope, contradictory.

6.3 Features of the Scaled Diagram

What we shall do is to look for plausible evolutionary tracks on the P-D diagram, and eliminate totally implausible ones. For example, we do not believe that a source such as 3C129 could evolve into one similar to, say, 3C295. The
actual number per unit area (in the P-D plane) of sources is affected by selection effects, particularly in that low brightness objects are selected against. The absence of many large P sources is due to their actual low space density. The absence of any large separation, compact component doubles at low P is also almost certainly a real effect. At small D (<100 Kpc) there are few selection effects to make our map density unrepresentative of the actual space density, at least for log P > 24 or 25.

Basic assumptions we shall use

A1) Sources get bigger with age in all dimensions. All source theories to date have made this assumption. This may be partly due to early dogma, but it is difficult to envision emission mechanisms that gather-up diffuse emission and form tight 'bundles' (compact components), away from large gravitating masses. The puzzling double symmetry of many large sources becomes yet more difficult to explain in a contracting model. Note that there is no direct observational evidence for this assumption.

A2) We make no strong assumptions about the evolution of luminosity P - rather, we will use A1) and the features of the diagram to deduce that P generally diminishes with time (except perhaps for small D (D<50 Kpc, say), and we thus call
A3) all the sources we have observed belong to a single class of objects with well defined evolutionary histories. That they appear to differ so much amongst themselves is simply an accident of the random ages at which individuals have been observed. This assumption is equivalent to saying that one source model - (albeit a smooth function of the initial energy of creation of the source and a few local parameters such as gas density, angular velocity of nucleus, etc.) can explain all the observed structures with a smooth transition from one to another. The occasional 'freaks' such as 3C315, are then explained as due to local external perturbations which have no part in the basic model. We shall not specify any features of the model. We hope to deduce a few from the analysis of our P−D map.

A4) sources are not created with large linear size (>10Kpc, say). This means that the existence of a source of arbitrary structure, total size D (>10Kpc) implies the existence of sources smaller than it (A1) and more powerful than it (when D1 is verified) and with similar structure. If these are not observable then an error is indicated in our assumptions.
Observations

Throughout the next section, where reference to no particular figure is made, reference to Fig. 6.2.3 is implied.

a) General

1) The most powerful sources (log $P > 27.7$) (e.g. 3C123, 3C295, 3C9, 3C196, 3C205) are small (<200Kpc) and have compact components. Also, not on our diagram, are many of the powerful quasars whose radio components are completely within the nuclei of the quasars and are thus very small. All the sources larger than 200Kpc are weaker than these. Assumption A1) then implies that $P$ decreases with age of source since we would otherwise observe larger sources at least as luminous as these. There is no selection effect against seeing large, powerful sources with compact components and which are a smooth structural transition from the most powerful objects. Only low brightness sources would be undetectable at this luminosity and their adjacency to the compact objects would violate the smoothness assumption in A3).

2) The least compact of the smaller sources (<200Kpc) (e.g.
3C402, 3C66.02, 3C31) also have the lowest luminosities. This strengthens our deduction that P decreases with age, as one must assume from A1) that the least compact, small sources are older than the more compact sources of similar and smaller size. That they have the lowest luminosities then indicates that source luminosity falls with age.

3) There are no double sources on any size scale with logP<25.5, having two compact outer components (<15Kpc, in contrast to the high P sources). This seems to indicate that a minimum rate of radio emission is a necessary feature for the maintainance of a stable pair of compact components.

4) For 27>log P>25 there are double sources of all scale sizes up to approximately 1Mpc (and one, 3C236 of 5.7Mpc); of these, the smallest often have the most compact components and beyond D=500Kpc most source components have broadened considerably, an exception being 3C61.1, D=731Kpc. For log P<25.7 we see no sources larger than about 400Kpc but this may be partly due to their low surface brightness. Sources of this size whose structures are smooth transitions from those visible with log P>25.7 would have very extended components in most cases and would be undetectable by our present synthesis telescopes. Sources such as 3C129 and 3C465 whose large scale structure is
3C402, 3C66.02, 3C31) also have the lowest luminosities. This strengthens our deduction that \( P \) decreases with age, as one must assume from A1) that the least compact, small sources are older than the more compact sources of similar and smaller size. That they have the lowest luminosities then indicates that source luminosity falls with age.

3) There are no double sources on any size scale with \( \log P < 25.5 \), having \( \text{two} \) compact outer components (\(<15\,\text{kpc}\), in contrast to the high \( P \) sources). This seems to indicate that a minimum rate of radio emission is a necessary feature for the maintainance of a stable \( \text{pair} \) of compact components.

4) For \( 27 > \log P > 25 \) there are double sources of all scale sizes up to approximately \( 1\,\text{Mpc} \) (and one, 3C236 of \( 5.7\,\text{Mpc} \)); of these, the smallest often have the most compact components and beyond \( D=500\,\text{kpc} \) most source components have broadened considerably, an exception being 3C61.1, \( D=731\,\text{kpc} \). For \( \log P < 25.7 \) we see no sources larger than about \( 400\,\text{kpc} \) but this may be partly due to their low surface brightness. Sources of this size whose structures are smooth transitions from those visible with \( \log P > 25.7 \) would have very extended components in most cases and would be undetectable by our present synthesis telescopes. Sources such as 3C129 and 3C465 whose large scale structure is
principally of low surface brightness ($T_{\text{eff}} \approx 2000$K at 178 MHz) lie right on the edge of the area of detectability of sources for the 3C4 catalogue (Bennett 1962 Fig. 1 (L4)). Thus larger sources of similar luminosity are not likely to be found in our sample.

5) There is a 'cluster' of sources with large component flux density ratio (cfr) roughly centred on $10^\circ$ P=27, D=300 kpc (Fig. 6.1.1). The group includes the two quasars 3C68.1 (cfr=8.9), and 3C351 (cfr=4.8) which are adjacent on the diagram, and also 3C268.1 (cfr=22), 3C263 (cfr=4.9) and 3C437 (cfr=1.72). The significance of this close grouping is not clear, though if they evolved to lower luminosity it is likely that the weaker component would become invisible due to low surface brightness and the sources would then be classified as single, and probably remain unidentified. However, most of the remaining unidentified sources in the complete sample display double structure on a scale characteristic of entire sources, not of single components, so this explanation seems rather unlikely.

6) A few sources display a general 'banana-shaped' structure: i.e., their luminosity is distributed principally along a single curved line on the sky, the curve being but a small fraction ($\approx 1/3$) of a closed loop: e.g., 3C465 (see Fig. 6.3.3). Without exception, these sources are clustered at
the bottom left of the diagram, in the region \( \log P > 24.7 \), 1500-4000Kpc (Fig. 6.3.2). The sources are, in order of increasing size, 3C449, 3C31, 3C66.02, 3C402, 3C382, and 3C465. Interestingly this is also the region of the P-D plane wherein lie the two 'head-tail' or 'radio-trail' sources, 3C83.11 and 3C129, both of which are also banana shaped. There is no other obvious morphological connection between the head-tail and other banana objects. However, all these sources have compact components centred on the galactic nuclei, with the exception of 3C382, which has one compact component well separated from and more powerful than the CCC, they all have their most powerful emission regions close to the galactic nuclei. Thus they might all be the result of relative motions between a galaxy of continuing activity and a surrounding medium, as has been suggested for the radio-trail sources, 3C129 and 3C83.11 (Jaffe & Perola [479]).

b) Specific

We shall now investigate specific plausible evolutionary tracks on our P-D diagram attempting to incorporate not only the assumption of D increasing with age and the deduction that P decreases with age, but also all the structural information inherent in our synthesis maps.
and the specification of a smooth transition of form throughout the history of any individual source. We shall sometimes begin with the largest and weakest structures, working backwards in time, and sometimes reverse the process, as best suits the individual cases.

1) To the left of (smaller D) and slightly higher in luminosity than the banana sources lie the extended, single component sources, 3C264, 3C386, 3C371 and the source 3C293 which is essentially similar to 3C371 though it has a slightly better defined 'component' remote from the nucleus. They are not much bigger than a typical galaxy (\(\sim 100\) Kpc diameter). The structures of these sources are sufficiently ill defined (in the sense that they display no strong double symmetry) that they are possible candidates for later development into banana sources. It is also possible that they represent the end stages of more powerful sources such as tripies, where the outer components have expanded sufficiently that we no longer observe their low brightness structure. These single components could be the expanded remains of compact central components. However, as we note in 3), none of the very large sources has a CCC so it is likely that the outer components persist longer than the central one. Further left still are two weak sources 3C338 and 3C76.1 (the latter is very poorly resolved perpendicular to its longest dimension). 3C338 has been
resolved (by the MSRT at 56GHz (443)) into three weak peaks, the central component being coincident with the optical nucleus. Most interestingly, the three peaks display embryonic banana structure in their overall layout and plausibly could expand to form a structure such as 3C66.02.

The strong non-alignment of its components makes it unlikely that 3C338 can expand to become a normal simple double.

There are just two well defined head-tail sources on our diagram, 3C83.11 and 3C129 as mentioned previously, both close to slightly smaller, slightly more powerful banana sources 3C31 and 3C465. There are also just two sources that display a cross-like structure (i.e. they have two approximately perpendicular axes of symmetry): these are 3C366 and 3C315. It is interesting that there is a diagonal sequence through each triplet of cross-like, banana shaped and head-tail sources. It might be that these represent an evolutionary sequence, though it may just be chance (see Fig. 6.3.3).

2) Next higher in luminosity than the sources discussed in 1) are a set of weak "doubles", generally characterised by large diffuse bridges of emission surrounding the entire source and often, displaying complex component structure. A sequence of these from small-D to large-D is typified by
3C132, 3C288, 3C197, 3C388, 3C277, 3C430, 3C34, 3C98, 3C382, 3C192, 3C285 and 3C310 (see Fig. 6.3.4). Of these, 3C98 and 3C312 come closest to the region of the banana sources, and both, particularly 3C382, have banana shaped bridges, though the principal components are approximately aligned with the optical nuclei. Also, 3C310 lies between 3C315 and 3C465 and possesses a large bulge in its bridge structure, not unlike a half-symmetric version of 3C315 (though even more similar to 3C386, the other, smaller cross shaped source).

The sources in the sequence become more diffuse along the sequence from small to large - in general 'large' is interpreted as 'older'. The roughly cigar shaped bridges seen most clearly in 3C430 and 3C192, may be associated with those predicted by the models of Scheuer 1974 (425). As was noted earlier, none of the sources in this sequence has both components compact. We do not suggest that Fig. 6.3.4 necessarily represents an evolutionary sequence. By this we mean that sources at the left may fall in luminosity more quickly with increase in size than the figure indicates and would then expand and become of sufficiently low brightness to become invisible to current telescopes. Likewise, the sources at the right in Fig. 6.3.4 may have resulted from the smaller, more powerful sources above the illustrated
sequence. It is unlikely, however, that the slope of the P-D evolution is much steeper than that suggested, as will become clear in the next section.

3) For 25<logP<27 we see sources on all scales up to 1Mpc all of which are basically double. The absence of large sources (>200Kpc) with log P>27 indicates that the sources with 25<logP<27 evolve with only slowly changing luminosities. This is because the largest sources (~1Mpc) with 26<logP<27 must have evolved from much smaller sources (~200Kpc) in the same range of P as there are no more-powerful sources that could be plausible ancestors (there are no selection effects against seeing such large powerful sources). This perhaps indicates that in the range 25<logP<27 the emission mechanism and the structural form are very stable. A typical evolutionary sequence might start with a source such as 3C207, expand through something like 3C411, thence to 3C323.1, become much more diffuse like 3C452 and finally expand perhaps adiabatically into a 3C314.1-like structure. It is noteworthy that none of the large sources beyond D=600Kpc have powerful compact central components.

4) There are no large (>200Kpc) sources with log P>28. This indicates that the high luminosity phase is not long-lived and sources lose energy rapidly as they separate from the
nucleus (much more quickly than do the weaker sources). Thereafter they may follow similar evolutionary paths as in 3. However, we note that at the very top end of the observed luminosity range, 3C9 and 3C123 are both assymetric (3C9 in cfr 3.36, only resolution is poor), 3C123 having a most peculiar non-aligned structure with the components (cfr=2.04) 'pointing' in almost tangential directions. This suggests that the usual source mechanisms are no longer stable at such powers. We feel that there could well be a connection between the previously noted 'cluster' of high-cfr sources (a5) and these very powerful events, in that the mechanism may be so unstable that at least one of the components nearly always 'goes out' soon after the formation of the source. It is also relevant that neither 3C9 nor 3C123 has an observed CCC: only one of the high-cfr sources in our cluster has a CCC, viz. 3C263.

6.4 Conclusions

By transforming the available morphological data into a self consistent form, we have:

i) made clearer, the overall distribution of source types and sizes.

ii) strengthened (independently of model predictions) the
conclusion that luminosities generally decrease steadily with increase in size of source.

iii) noted several striking associations amongst source types previously not regarded as related, notably the 'bent' (or 'banana'-shaped) weak sources, the head-tail sources and the cross-shaped structures.

iv) deduced a probable lower limit on the luminosity of a stable double structure.

v) deduced plausible evolutionary sequences for the 'standard' simple double source type.

vi) put forward arguments suggesting that the double source mechanism becomes drastically unstable above log P 28, resulting in the rapid loss of emission and the early 'death' of at least one of the components.

We note that most of the above are speculative and open to criticism on the grounds of poor substantiation. However, we do not believe this is reason enough to ignore the information inherent in such collations of structural data. The above conclusions may be tested statistically as more map information is obtained, and are useful now as
suggestions for facts that source models must explain.
CHAPTER SEVEN

The Angular-Diameter-Redshift Test For Quasi-Stellar Radio Sources With Large Redshifts

Z.1 Introduction

The fact that bright extragalactic radio sources can be readily observed at large redshifts makes them ideal candidates for use in the angular-diameter redshift test (the $\Theta-Z$ test) of World models. Since many quasars have now been observed with redshifts greater than 1, the physical sizes of their radio structures may be employed in this test. Miley 1970 (041) first plotted a $\Theta-Z$ diagram for a large sample of quasars and radio galaxies whose structures were known at that time and demonstrated convincingly that, although there is a large scatter in the physical sizes of the overall radio structure (the largest
linear size of the radio source), there appears to be a well defined upper bound to the plot of angular diameter against redshift which follows closely a line $\theta \propto z$. Since this result extends as far as redshifts 2, it is inconsistent with the predictions of all the classical models of General Relativity which predict a flattening of the relation between $\theta$ and $Z$ at redshifts 1 (see Fig. 7.1.1).

An interpretation of this result is that the physical sizes of the quasars observed at large redshifts are smaller than those observed locally (i.e. at $Z<0.5$). It could not be distinguished from Miley’s data whether this effect could be attributed to a change in the physical sizes of sources with redshift, implying a cosmological change, or to a correlation between radio luminosity and physical size; since the quasars were mostly selected from a catalogue complete to a given flux density, those sources observed at large redshift are the most powerful sources intrinsically, and therefore a correlation between smaller physical size and larger luminosity would result in the same observed $\theta - Z$ diagram.

Further evidence that there must be some change in the physical sizes of radio sources at large redshifts as
Fig. 7.1.1 The angular diameter – redshift relations predicted by the classical World models with $\Omega=0$ and $\Omega=1$. Also shown is the Euclidean prediction, where angular size is inversely proportional to redshift.
Fig. 7.1.1 The angular diameter - redshift relations predicted by the classical World models with $\Omega=0$ and $\Omega=1$. Also shown is the Euclidean prediction, where angular size is inversely proportional to redshift.
compared with the local sample is provided by the angular
diameter flux-density relation discussed by Swarup 1975
(469) and Kapahi 1975 (470). Using occultation data obtained
from Doty observations, they showed that the mean angular
diameters of complete samples of radio sources decrease more
rapidly with decreasing flux density than would be predicted
for a population of radio sources of the same physical size
distribution at all redshifts (even including cosmological
evolution of the comoving space density of the powerful
radio sources). This result may be interpreted in the same
way as Miley's result - that radio sources at large
redshifts have smaller physical sizes.

A further relevant result on the physical sizes of
large redshift quasars is that of Hewish, Readhead &
Duffett-Smith 1975 (471) (HRD-S) who showed that there was
an absence of compact radio components at large redshifts -
if Miley's result also applied to these components, many
more compact radio components should have been observed by
HRD-S. Readhead & Hewish 1976 (472) show that those compact
components detected by the scintillation technique refer to
compact structure on the scale 0.2" - 2.0" within extended
sources. One interpretation of the result was that there
was a minimum in the \( \Phi - z \) relation; alternatively the sizes
of components may be larger at large redshifts. There is not
necessarily any contradiction between these results and those of Miley: their implication is that there must be some differential evolution of the compact features and extended structure of large radio sources.

These separate pieces of evidence contain useful information about the evolution of radio sources with cosmological epoch and/or about the geometry of the World model. In this Chapter we describe further observations relevant to this problem. Since Miley's observations, many more quasars with large redshifts have been discovered. Of particular interest are the complete samples of quasars in the 4C catalogue studied by Lynds & Wills 1970 (473) and Schmidt 1975 (474). In total, 19 quasars with redshifts greater than 1.5 have been found down to a uniform limiting apparent magnitude of about 19.5.

The problems described above have been studied using new observations made with the Cambridge 5Km Telescope of the radio structures of quasars and radio galaxies in the 3CR and 4C catalogues. The samples of sources used in this study are:

(i) A complete sample of 167 3CR radio sources which
includes 41 quasars.

(ii) All 19 quasars in the complete samples of Lynds & Hills and of Schmidt which have redshifts greater than 1.5.

These data enable the following cosmological tests to be made:

a) A re-determination of the angular-diameter redshift plots for bright radio sources using much improved knowledge of the radio structures and with much improved statistics at large redshifts.

b) It is possible to test directly if there is any change in size of radio sources of the same intrinsic luminosity with redshift (or cosmological epoch).

c) It is possible to compare the angular size distributions of radio sources in the 3CR and 4C samples for different cosmological models. This comparison may be made absolute, because the samples of quasars are drawn from complete samples with well defined limits at radio and optical wavelengths. Of particular importance in this comparison is the inclusion of the effects of cosmological evolution upon the comoving space density of quasars at
large redshift.

7.2 The Data

7.2.1 The Complete Sample of 41 3CR Quasars

In order to obtain a complete view of the radio structure of sources, a suitable complete sample of 167 3CR radio sources has been observed with the Cambridge 5Km Telescope. (This is an updated version of the 'complete-sample' used for the studies in the earlier chapters.) These sources fulfil the following selection criteria.

i) all sources have flux densities at 178MHz, $S_{178} > 10$Jy using the flux densities of 3CR sources given by Kellermann, Pauliny-Toth & Williams (KPW) 1969 (34).

ii) all sources have declination $\delta > 10$ degrees and galactic latitude $|b| > 10$ degrees.

The area of sky corresponding to this search area is approximately 4.3 sr. Within this sample there are 41 quasars which are listed in Table 7.2.1. The sample includes two quasars which have recently had redshifts measured, 3C68.1 and 3C212. Redshifts have been measured for 36 of
Table 7.2.1
The observed parameters for the sample of 41 quasars selected from the 3CR Catalogue.

<table>
<thead>
<tr>
<th>SC</th>
<th>(n_v)</th>
<th>Redshift</th>
<th>(S_{0.178})</th>
<th>Angular size (arcsec)</th>
<th>Spectral index</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>18.2</td>
<td>2.012</td>
<td>17.8</td>
<td>10</td>
<td>0.99</td>
<td>D</td>
</tr>
<tr>
<td>43</td>
<td>20.0</td>
<td>-</td>
<td>11.6</td>
<td>&lt;1.3</td>
<td>0.73</td>
<td></td>
</tr>
<tr>
<td>47</td>
<td>18.1</td>
<td>0.425</td>
<td>26.4</td>
<td>69</td>
<td>0.97</td>
<td>DC</td>
</tr>
<tr>
<td>48</td>
<td>16.2</td>
<td>0.367</td>
<td>55</td>
<td>&lt;0.5</td>
<td>0.41</td>
<td>C</td>
</tr>
<tr>
<td>66.01</td>
<td>15.0</td>
<td>-</td>
<td>12.3</td>
<td>&lt;1.2</td>
<td>1.09</td>
<td>C</td>
</tr>
<tr>
<td>68.1</td>
<td>19.8</td>
<td>1.237</td>
<td>12.8</td>
<td>58</td>
<td>0.80</td>
<td>D</td>
</tr>
<tr>
<td>128</td>
<td>17.9</td>
<td>0.759</td>
<td>22.2</td>
<td>&lt;0.9</td>
<td>0.40</td>
<td>C</td>
</tr>
<tr>
<td>147</td>
<td>17.8</td>
<td>0.545</td>
<td>60.5</td>
<td>&lt;0.3</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>175</td>
<td>16.6</td>
<td>0.768</td>
<td>17.6</td>
<td>48</td>
<td>0.96</td>
<td>DC</td>
</tr>
<tr>
<td>181</td>
<td>18.9</td>
<td>1.382</td>
<td>12.7</td>
<td>5.9</td>
<td>0.80</td>
<td>D</td>
</tr>
<tr>
<td>186</td>
<td>17.6</td>
<td>1.063</td>
<td>14.1</td>
<td>2.7</td>
<td>1.02</td>
<td></td>
</tr>
<tr>
<td>191</td>
<td>18.5</td>
<td>1.946</td>
<td>13.0</td>
<td>7</td>
<td>0.92</td>
<td>C</td>
</tr>
<tr>
<td>196</td>
<td>17.6</td>
<td>0.871</td>
<td>68.2</td>
<td>5.4</td>
<td>0.68</td>
<td>D</td>
</tr>
<tr>
<td>204</td>
<td>18.2</td>
<td>1.112</td>
<td>10.3</td>
<td>31.1</td>
<td>1.00</td>
<td>DC</td>
</tr>
<tr>
<td>205</td>
<td>17.6</td>
<td>1.534</td>
<td>12.7</td>
<td>15.9</td>
<td>0.84</td>
<td>DC</td>
</tr>
<tr>
<td>207</td>
<td>18.2</td>
<td>0.684</td>
<td>13.6</td>
<td>8.4</td>
<td>0.80</td>
<td>DC</td>
</tr>
<tr>
<td>208</td>
<td>17.4</td>
<td>1.110</td>
<td>18.3</td>
<td>11.3</td>
<td>0.90</td>
<td>DC</td>
</tr>
<tr>
<td>212</td>
<td>19.1</td>
<td>1.063</td>
<td>15.1</td>
<td>8.6</td>
<td>0.79</td>
<td>DC</td>
</tr>
<tr>
<td>215</td>
<td>18.3</td>
<td>0.411</td>
<td>11.4</td>
<td>28.5</td>
<td>0.94</td>
<td>DC</td>
</tr>
<tr>
<td>216</td>
<td>18.8</td>
<td>-</td>
<td>20.2</td>
<td>&lt;0.7</td>
<td>0.72</td>
<td></td>
</tr>
<tr>
<td>245</td>
<td>17.3</td>
<td>1.029</td>
<td>14.4</td>
<td>4.6</td>
<td>0.72</td>
<td>D/AD</td>
</tr>
<tr>
<td>249.1</td>
<td>15.7</td>
<td>0.311</td>
<td>12.5</td>
<td>23.0</td>
<td>0.82</td>
<td>DC</td>
</tr>
<tr>
<td>254</td>
<td>18.0</td>
<td>0.734</td>
<td>19.9</td>
<td>13.2</td>
<td>0.85</td>
<td>D/AD</td>
</tr>
<tr>
<td>263</td>
<td>16.3</td>
<td>0.652</td>
<td>15.2</td>
<td>44.2</td>
<td>0.76</td>
<td>DC</td>
</tr>
<tr>
<td>268.4</td>
<td>18.4</td>
<td>1.400</td>
<td>10.3</td>
<td>10.2</td>
<td>0.74</td>
<td>DC</td>
</tr>
<tr>
<td>270.1</td>
<td>18.6</td>
<td>1.519</td>
<td>13.6</td>
<td>12.2</td>
<td>0.67</td>
<td>Dp</td>
</tr>
<tr>
<td>275.1</td>
<td>19.0</td>
<td>0.557</td>
<td>18.3</td>
<td>13.6</td>
<td>0.84</td>
<td>Dp</td>
</tr>
<tr>
<td>280.1</td>
<td>19.4</td>
<td>1.659</td>
<td>11.9</td>
<td>22.0</td>
<td>0.88</td>
<td>DC</td>
</tr>
<tr>
<td>286</td>
<td>17.3</td>
<td>0.846</td>
<td>24</td>
<td>&lt;0.5</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>287</td>
<td>17.7</td>
<td>1.054</td>
<td>16.0</td>
<td>&lt;0.6</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>309.1</td>
<td>16.8</td>
<td>0.904</td>
<td>22.7</td>
<td>1.1</td>
<td>0.45</td>
<td>SR</td>
</tr>
<tr>
<td>334</td>
<td>16.4</td>
<td>0.555</td>
<td>10.9</td>
<td>48</td>
<td>0.97</td>
<td>DC</td>
</tr>
<tr>
<td>336</td>
<td>17.5</td>
<td>0.927</td>
<td>11.5</td>
<td>21.7</td>
<td>0.73</td>
<td>D</td>
</tr>
<tr>
<td>343</td>
<td>20.6</td>
<td>0.988</td>
<td>12.4</td>
<td>&lt;0.3</td>
<td>0.34</td>
<td>C</td>
</tr>
<tr>
<td>345</td>
<td>16.0</td>
<td>0.594</td>
<td>10.8</td>
<td>&lt;0.4</td>
<td>0.30</td>
<td>C</td>
</tr>
<tr>
<td>351</td>
<td>15.0</td>
<td>0.371</td>
<td>13.7</td>
<td>58</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>16.8</td>
<td>0.693</td>
<td>59.4</td>
<td>1.2</td>
<td>0.74</td>
<td>AD</td>
</tr>
<tr>
<td>432</td>
<td>17.8</td>
<td>1.804</td>
<td>11.0</td>
<td>13</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>454</td>
<td>18.4</td>
<td>1.756</td>
<td>11.6</td>
<td>&lt;4</td>
<td>0.81</td>
<td>C</td>
</tr>
<tr>
<td>454.3</td>
<td>16.1</td>
<td>0.860</td>
<td>13.0</td>
<td>&lt;0.96</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>455</td>
<td>19.7</td>
<td>0.543</td>
<td>12.8</td>
<td>3.2</td>
<td>0.70</td>
<td>AD</td>
</tr>
</tbody>
</table>

Note: 'SR' in the 'Type' column indicates that the source was slightly resolved only.
this sample, the quasars without redshifts being 3C66.01, 3C43 and 3C216 each of which has a featureless spectrum. The data included in Table 7.21 are as follows:

column (1). The apparent V-magnitude of the quasar taken from Schmidt 1968 (253) or from more recent publications.

column (2). Redshifts from the literature.

column (3). The revised flux density of the source at 178 MHz from KPW.

column (4). The total angular size of the radio source. Most of the quasars are double radio sources, many of them with compact radio components associated with the quasar nucleus. The angular sizes quoted correspond to Miley's 'largest angular size' - i.e. the distance between the outer components of a double. In some cases, the double is asymmetric in the sense that one component is associated with the quasar and the other displaced from it. In these cases the separation of the components is used as the largest angular size. For the purpose of comparison with the results in the 4C sample, compact sources have been given upper limits to their angular sizes as measured by the 5Km telescope. We have not included information on the hyperfine structure determined by trans-continental interferometry.
column (6). The low-frequency spectral index from KPW, as not
reported in the present, will eventually be given in a separate
column (7). The morphological type of the radio source and
comments on the radio structure. We have adopted a simple
description of the radio structure for the purposes of the
investigation.

D  classical double radio source

DC  classical double radio source with compact
central component associated with the quasar

AD  asymmetric double such as 3C273

C  compact - i.e., unresolved by the 5Km

Sources worthy of particular note are 3C186 in which there
is a slightly extended source associated with the
identification and an additional single component at angular
distance 100^\prime arc from the quasar. The distant component is a
factor of ten smaller in flux density than that associated
with the quasar and it is unlikely that it would have been
detected in observations of faint 4C objects. The smaller
physical size has therefore been used in the analysis.
3C68.1 was noted as a double source with large ratio of
component intensities in observations at 1407MHz (Mackay 1969 (011)) but the very faint southern component was not detected in the original 5GHz observations. More recently, from 5km observations at 2.7GHz, it has been confirmed that indeed it is an extended double, with a very large value of S1/S2. It has been included with angular size 58" arc.

7.2.2 The Sample of 19 4C Quasars with Redshifts >1.5

The samples of 4C quasars were selected from lists of Lynds & Wills and Schmidt. Their completeness limits are as follows.

Lynds & Wills (1970) The following areas of sky were studied, RA 8° to 11°, dec 4° to 10°; and RA 8° to 14°, dec 10° to 20°, covering 0.35 sr. Within this area of sky there are 159 4C radio sources with $S_{178} > 2.5$ Jy. Of these, 25 are associated with quasars which are brighter than $V = 19^m5$; of the 25 quasars, 8 have redshifts greater than 1.5, including the 3CR source 3C191. Details of these sources are given in Table 7.2.2 in the same form as Table 7.2.1.

Schmidt (1975) Schmidt's sample of 4C quasars was derived from the survey of Olsen 1970 (425) who sought radio galaxy and quasar identifications in the 20° to 40° degree zone of the 4C catalogue using improved radio positions. Regions
component intensities in observations at 1407MHz (Mackay 1969 (11)) but the very faint southern component was not detected in the original 5GHz observations. More recently, from 5km observations at 2.7GHz it has been confirmed that indeed it is an extended double, with a very large value of S1/S2. It has been included with angular size 58" arc.

7.2.2 The Sample of 19 4C Quasars with Redshifts >1.5

The samples of 4C quasars were selected from lists of Lynds & Wills and Schmidt. Their completeness limits are as follows.

Lynds & Wills (1970) The following areas of sky were studied, RA 8h to 11h, dec 4° to 10°; and RA 8h to 14h, dec 10° to 20°, covering 0.35 sr. Within this area of sky there are 159 4C radio sources with S1 > 2.5Jy. Of these 25 are associated with quasars which are brighter than V = 19.5; of the 25 quasars, 8 have redshifts greater than 1.5, including the 3CR source 3C191. Details of these sources are given in Table 7.2.2 in the same form as Table 7.2.1.

Schmidt (1975) Schmidt's sample of 4C quasars was derived from the survey of Olsen 1970 (475) who sought radio galaxy and quasar identifications in the 20 to 40 degree zone of the 4C catalogue using improved radio positions. Regions
### Table 7.2.2
The observed parameters for the Lynds & Wills sample of high-redshift quasars.

<table>
<thead>
<tr>
<th>3C/4C</th>
<th>m_v</th>
<th>Redshift</th>
<th>S_178</th>
<th>Angular size (arcsec)</th>
<th>Spectral index</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.31</td>
<td>17.7</td>
<td>1.691</td>
<td>2.8</td>
<td>18</td>
<td>0.7</td>
<td>AD</td>
</tr>
<tr>
<td>06.40</td>
<td>18.3</td>
<td>1.699</td>
<td>9.5</td>
<td>20</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>11.32</td>
<td>19.1</td>
<td>1.754</td>
<td>3.0</td>
<td>6.6</td>
<td>0.9</td>
<td>D</td>
</tr>
<tr>
<td>13.39</td>
<td>17.8</td>
<td>1.875</td>
<td>2.8</td>
<td>&lt;9</td>
<td>0.8</td>
<td>C</td>
</tr>
<tr>
<td>191</td>
<td>18.5</td>
<td>1.952</td>
<td>13.0</td>
<td>&lt;7</td>
<td>0.9</td>
<td>C</td>
</tr>
<tr>
<td>12.39</td>
<td>19.3</td>
<td>2.118</td>
<td>4.4</td>
<td>&lt;2.5</td>
<td>-</td>
<td>C</td>
</tr>
<tr>
<td>11.45</td>
<td>19.1</td>
<td>2.171</td>
<td>8.1</td>
<td>6.8</td>
<td>0.8</td>
<td>D</td>
</tr>
<tr>
<td>05.34</td>
<td>18.2</td>
<td>2.877</td>
<td>2.6</td>
<td>20</td>
<td>1.3</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 7.2.3
The observed parameters for Schmidt's sample: the column headings are as for Table 7.2.2

<table>
<thead>
<tr>
<th>270.1</th>
<th>18.6</th>
<th>1.519</th>
<th>13.6</th>
<th>12</th>
<th>0.7</th>
<th>Dp</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.59</td>
<td>1.535</td>
<td>5.3</td>
<td>&lt;1.4</td>
<td>0.8</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>31.38</td>
<td>1.557</td>
<td>7.5</td>
<td>0.2</td>
<td>0.4</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>29.64</td>
<td>1.753</td>
<td>5.1</td>
<td>&lt;1.4</td>
<td>0.8</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>29.01</td>
<td>1.828</td>
<td>2.9</td>
<td>2.9</td>
<td>0.7</td>
<td>AD</td>
<td></td>
</tr>
<tr>
<td>38.37</td>
<td>1.844</td>
<td>2.8</td>
<td>&lt;0.8</td>
<td>0.6</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>29.50</td>
<td>1.927</td>
<td>6.6</td>
<td>4</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.40</td>
<td>1.989</td>
<td>3.5</td>
<td>30</td>
<td>1.0</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>24.61</td>
<td>2.328</td>
<td>2.7</td>
<td>&lt;1.3</td>
<td>0.1</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>25.05</td>
<td>2.353</td>
<td>2.5</td>
<td>&lt;1.3</td>
<td>0.1</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>25.21</td>
<td>2.686</td>
<td>3.3</td>
<td>10</td>
<td>0.5</td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>
with \(|\theta| < 10\) degrees were excluded resulting in a search area of approximately 1.0 sr. Of 490 sources studied with \(9 > S > 2.5 \text{Jy}\), 46 are quasars with measured redshifts and 10 have redshifts greater than 1.5. To make the sample complete for all flux densities greater than 2.5Jy, the 3CR sources in the region should be included, increasing the total sample to 59. The sample of quasars with \(Z > 1.5\) includes the 3CR source 3C270.1. Details of these 11 sources are given in Table 7.2.3 in the same form as Table 7.2.1.

7.3 The Results

7.3.1 The Angular Diameter Redshift Plot

The results are plotted in Fig. 7.3.1 in which the following notation is used: sources with \(\alpha < 0.5\) are plotted with a square; sources with \(\alpha > 0.5\) are plotted with a circle; for 3CR galaxies, the symbols are filled; for 3CR quasars they have diagonal crosses, and the symbols for 4C quasars are open. Arrows have been attached to those angular diameters which are only upper limits. Only quasars and radio galaxies with measured redshifts have been included on the plot. It can be seen that there remains the well defined upper bound noted by Miley.
Fig. 7.3.1 The angular size - redshift diagram for the complete sample of X and 4C sources. Legend: □ <0.5; □ >0.5: filled symbol are X galaxies, crossed symbol 4C quasars and open symbol, 4C quasars. † indicates upper limit only to angular size; ‡ indicates source is possibly larger than shown.
It can be seen that there do indeed exist double sources of moderate angular size at large redshifts; 4C28.40 has \( z=1.989 \) and \( D=387 \text{Kpc} (a=0) \) or \( 246 \text{Kpc} (a=1) \). Interpretation of the diagram depends upon whether one believes one should treat the quasars and galaxies separately or not. If one fixes attention only upon the quasars, the upper bound is more or less independent of \( Z \) and a large value of \( \Omega \) would fit the data well. If one believes one should include the data on radio galaxies together with the quasars, inspection of the diagram suggests that the upper bound is consistent with the line corresponding to \( a=0 \) and that the line \( \Omega \propto Z^{-1} \) is perhaps a poorer fit to the data. We note that three lines of independent evidence also favour a low density universe: (i) the most recent redshift-magnitude relations for brightest cluster galaxies; (ii) measured cosmic deuterium abundance interpreted as of primordial origin and (iii) the similarity of the local and distant value of the Hubble constant. However, because of remaining uncertainties, we will investigate the implications of the results for both the \( a=0 \) and the \( a=1 \) cases. (Notice that strictly the best value of \( \Omega \) is about 0.1 but the dynamics of World models and the space curvature correspond closely to the \( a=0 \) models for \( Z<1/a \). Since all the redshifts considered here have \( Z<10 \) i.e. \( Z<3 \), we may use the \( a=0 \) model to approximate rather precisely the \( a=0.1 \) case).
It is clear that the statistics of sources are still small and definite conclusions are difficult to draw. In particular, the peculiar nature of individual sources modifies the already small statistics. For example, 3C236, the giant radio galaxy, is far beyond the upper bound indicated by Figure 7.3.1.

Despite these individual eccentric sources, Miley's result, that there is a well defined upper bound to the $\Theta$ - $Z$ plot, is substantiated but the present observations for quasars do not contradict the expected relation for the $\mathcal{N}=0$ model.

7.3.2 Variations of the Physical Size of the Radio Structure of Quasars with Redshift

The question of whether double radio sources are physically smaller at large redshifts may be tested using the present data. The answer depends on the assumed World model and so the analysis has been performed for the $\mathcal{N}=0$ and the $\mathcal{N}=1$ World models. The physical parameters - radio luminosity at 178MHz emitted wavelength, $P_{178}$, and physical
The physical parameters of the quasars in the complete sample. The sources are grouped in order of redshift and the parameters have been computed for the classical models with $\alpha = 0$ and with $\alpha = 1$.

<table>
<thead>
<tr>
<th>3C</th>
<th>Redshift</th>
<th>$\omega = 0$</th>
<th>$\omega = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P(175)</td>
<td>D(Kpc)</td>
</tr>
<tr>
<td>249.1</td>
<td>0.311</td>
<td>5.26</td>
<td>140</td>
</tr>
<tr>
<td>48</td>
<td>0.367</td>
<td>24.5</td>
<td>3.4</td>
</tr>
<tr>
<td>351</td>
<td>0.371</td>
<td>8.28</td>
<td>314</td>
</tr>
<tr>
<td>215</td>
<td>0.411</td>
<td>9.38</td>
<td>206</td>
</tr>
<tr>
<td>47</td>
<td>0.425</td>
<td>23.4</td>
<td>509</td>
</tr>
<tr>
<td>455</td>
<td>0.543</td>
<td>18.3</td>
<td>27</td>
</tr>
<tr>
<td>147</td>
<td>0.565</td>
<td>76.4</td>
<td>125</td>
</tr>
<tr>
<td>334</td>
<td>0.555</td>
<td>18.5</td>
<td>409</td>
</tr>
<tr>
<td>275.1</td>
<td>0.557</td>
<td>29.6</td>
<td>116</td>
</tr>
<tr>
<td>345</td>
<td>0.574</td>
<td>15.8</td>
<td>135</td>
</tr>
<tr>
<td>263</td>
<td>0.652</td>
<td>34.5</td>
<td>404</td>
</tr>
<tr>
<td>207</td>
<td>0.664</td>
<td>53.3</td>
<td>79</td>
</tr>
<tr>
<td>380</td>
<td>0.691</td>
<td>153</td>
<td>169</td>
</tr>
<tr>
<td>254</td>
<td>0.754</td>
<td>60.6</td>
<td>128</td>
</tr>
<tr>
<td>138</td>
<td>0.759</td>
<td>59.4</td>
<td>48.9</td>
</tr>
<tr>
<td>175</td>
<td>0.768</td>
<td>66.5</td>
<td>4.44</td>
</tr>
<tr>
<td>256</td>
<td>0.846</td>
<td>92.5</td>
<td>4.51</td>
</tr>
<tr>
<td>454</td>
<td>0.86</td>
<td>58.6</td>
<td>2.94</td>
</tr>
<tr>
<td>146</td>
<td>0.861</td>
<td>50.6</td>
<td>56</td>
</tr>
<tr>
<td>369</td>
<td>0.904</td>
<td>13.9</td>
<td>11.6</td>
</tr>
<tr>
<td>396</td>
<td>0.927</td>
<td>60.4</td>
<td>230</td>
</tr>
<tr>
<td>343</td>
<td>0.988</td>
<td>49.3</td>
<td>233</td>
</tr>
<tr>
<td>66A</td>
<td>(1)</td>
<td>101</td>
<td>13.1</td>
</tr>
<tr>
<td>43</td>
<td>(1)</td>
<td>74.1</td>
<td>142</td>
</tr>
<tr>
<td>216</td>
<td>(1)</td>
<td>128</td>
<td>4.7</td>
</tr>
<tr>
<td>245</td>
<td>1.029</td>
<td>96.1</td>
<td>50.6</td>
</tr>
<tr>
<td>227</td>
<td>1.054</td>
<td>89.5</td>
<td>6.4</td>
</tr>
<tr>
<td>212</td>
<td>1.063</td>
<td>118</td>
<td>95.6</td>
</tr>
<tr>
<td>186</td>
<td>1.063</td>
<td>150</td>
<td>30 (112)</td>
</tr>
<tr>
<td>218</td>
<td>1.11</td>
<td>148</td>
<td>12.4</td>
</tr>
<tr>
<td>204</td>
<td>1.12</td>
<td>108</td>
<td>351</td>
</tr>
<tr>
<td>68.1</td>
<td>1.237</td>
<td>149</td>
<td>6.45</td>
</tr>
<tr>
<td>181</td>
<td>1.382</td>
<td>200</td>
<td>4.0.6</td>
</tr>
<tr>
<td>268.4</td>
<td>1.4</td>
<td>159</td>
<td>123</td>
</tr>
<tr>
<td>274.1</td>
<td>1.519</td>
<td>245</td>
<td>14.9</td>
</tr>
<tr>
<td>205</td>
<td>1.534</td>
<td>27.6</td>
<td>175</td>
</tr>
<tr>
<td>280.1</td>
<td>1.575</td>
<td>33.4</td>
<td>127</td>
</tr>
<tr>
<td>454</td>
<td>1.756</td>
<td>35.3</td>
<td>250.5</td>
</tr>
<tr>
<td>432</td>
<td>1.804</td>
<td>42.1</td>
<td>16.5</td>
</tr>
<tr>
<td>191</td>
<td>1.946</td>
<td>60.2</td>
<td>9.0</td>
</tr>
<tr>
<td>9</td>
<td>2.012</td>
<td>98.2</td>
<td>12.9</td>
</tr>
</tbody>
</table>
Table 7.3.1 (cont.)
The parameters for the 4C complete samples of quasars with $Z > 1.5$.

<table>
<thead>
<tr>
<th>3C / 4C</th>
<th>Redshift</th>
<th>$\Sigma = 0$</th>
<th>$\Sigma = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P(178) D(Kpc)</td>
<td>P(178) D(Kpc)</td>
</tr>
<tr>
<td>29-01</td>
<td>S</td>
<td>1.519 265</td>
<td>149</td>
</tr>
<tr>
<td>21-59</td>
<td>S</td>
<td>1.535 112</td>
<td>&lt; 17.7</td>
</tr>
<tr>
<td>31-38</td>
<td>S</td>
<td>1.557 4.3</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>19-31</td>
<td>LW</td>
<td>1.691 69.9</td>
<td>225</td>
</tr>
<tr>
<td>06-40</td>
<td>LW</td>
<td>1.699 291</td>
<td>231</td>
</tr>
<tr>
<td>29-64</td>
<td>S</td>
<td>1.753 145</td>
<td>&lt; 17.7</td>
</tr>
<tr>
<td>11-32</td>
<td>LW</td>
<td>1.984 96.6</td>
<td>88.3</td>
</tr>
<tr>
<td>29-01</td>
<td>S</td>
<td>1.828 83.9</td>
<td>56.9</td>
</tr>
<tr>
<td>33-37</td>
<td>S</td>
<td>1.844 47.6</td>
<td>&lt; 10.2</td>
</tr>
<tr>
<td>13-39</td>
<td>LW</td>
<td>1.895 102</td>
<td>&lt; 115</td>
</tr>
<tr>
<td>29-50</td>
<td>S</td>
<td>1.925 239</td>
<td>51.3</td>
</tr>
<tr>
<td>191</td>
<td>LW</td>
<td>1.946 60.2</td>
<td>&lt; 90</td>
</tr>
<tr>
<td>28-40</td>
<td>S</td>
<td>1.989 184</td>
<td>184</td>
</tr>
<tr>
<td>12-39</td>
<td>LW</td>
<td>2.118 91.9</td>
<td>&lt; 32.6</td>
</tr>
<tr>
<td>11-45</td>
<td>LW</td>
<td>2.171 426</td>
<td>89.0</td>
</tr>
<tr>
<td>24-41</td>
<td>S</td>
<td>2.328 77.6</td>
<td>&lt; 17.7</td>
</tr>
<tr>
<td>25-05</td>
<td>S</td>
<td>2.353 66.9</td>
<td>&lt; 17.7</td>
</tr>
<tr>
<td>25-21</td>
<td>S</td>
<td>2.666 23.9</td>
<td>135</td>
</tr>
<tr>
<td>05-34</td>
<td>LW</td>
<td>2.847 62.3</td>
<td>&lt; 27.1</td>
</tr>
</tbody>
</table>
size $D$ are tabulated in Table 7.3.1 for both cases. The plots of $P_{178}$ against $D$ are shown in Figs. 7.3.2 and 7.3.3 for the cases $\pi = 0$ and $\pi = 1$ respectively. The range of redshift in which the sources lie is indicated by the different symbols noted in the figure caption.

The test of whether the physical size of the radio structure of quasars varies with redshift is made by inspection of these diagrams. The comparison can only be made meaningfully for sources of the same intrinsic luminosity and therefore the test is feasible in those regions of the diagrams where there is a mixture of large and small redshift sources of the same intrinsic luminosity.

**The case $\pi = 0$ (Figure 7.3.2).**

The comparison is only useful for sources in the luminosity range $P_{178}>6E27$ W Hz$^{-1}$ sr$^{-1}$ and for the area in which the sources are resolved, $D>40Kpc$. It can be seen that in this luminosity range, the 4C quasars with $Z>1.5$ span the same physical size range as 3CR quasars with $1<Z<1.5$. Evidently the significance of this result is not great in view of the very small statistical sample. We note the
Fig. 7.3.2 The luminosity - linear size plot for the complete samples of quasars; $\Omega = 0$

Legend: $\bigcirc$ = 4C sample quasar with $D > 1.5$; $\blacksquare$ = 3CR quasar with $D > 1.5$; $\bullet$ = 3CR quasar with $D < 1.5$. 

$$\Omega = 0$$
Fig. 7.3.3 Same as Fig. 7.3.2 but with $\Omega = 1$.
importance of 4C28.40, \(Z=1.989\) which is almost as large as the most extended sources at small redshifts. At lower luminosities, \(P_{178}<6\times10^7\) W Hz\(^{-1}\) sr\(^{-1}\), most of the high redshift sample are of smaller physical size than the most extended radio quasars but the statistics are poor.

It is noticeable that the most luminous sources in the sample are not the most compact radio sources. The resolved double sources 3C9, 3C432, 3C280.1 and 4C11.45 are about 5 times more luminous than the large group of unresolved sources in the luminosity range \(5\times10^7<P_{178}<2\times10^8\) W Hz\(^{-1}\) sr\(^{-1}\).

The case \(\alpha=1\) (Figure 7.3.3)

The range of luminosities spanned by the sample is much smaller in the case \(\alpha=1\) as can be seen from the diagram. Now useful comparisons can be made for a much larger range of sources with \(P_{178}>2\times10^7\) W Hz\(^{-1}\) sr\(^{-1}\). Inspection of the diagram indicates that sources with \(P_{178}>7\times10^7\) W Hz sr span smaller ranges of physical size but in the range \(2\times10^7<P_{178}<7\times10^7\) W Hz\(^{-1}\) sr\(^{-1}\), the low redshift sources are of larger physical size than those with \(Z>1.5\). Again the numbers are small and the significance of the result is difficult to estimate.
It should be noted that again the most luminous sources have physical size $D \sim 100\text{Kpc}$ rather than $<10\text{Kpc}$.

It can also be seen that for the highest luminosity ranges, for which there is little difference between the low and the high redshift samples, the maximum linear size decreases with increasing luminosity.

Thus, the test is not very conclusive. There is certainly no strong cosmological effect as for the highest luminosity sources the points are well intermixed on the $P_{178-0}$ diagram. At lower luminosities ($\lambda = 0, P_{178} \sim 8\text{E27 W Hz}^{-1}\text{sr}^{-1}, \Omega = 1, P_{178} \sim 4\text{E27 W Hz}^{-1}\text{sr}^{-1}$) there may be a significant difference in that there are fewer extended sources at large redshifts.

7.3.3 The Statistics of Quasars in the 3CR and 4C samples

Because the samples of 4C quasars are drawn from complete samples, it is possible to make a quantitative comparison of the absolute numbers of quasars of different angular sizes and redshifts with what might be expected from the 3CR sample of quasars. This test now involves comparing
the overall distribution of physical size in the 2 samples rather than just their upper bounds in the θ-Z plane or their distribution in the P-D plane.

In performing these computations, the following assumptions are made. The quasar population evolves rapidly with cosmological epoch: in order to obtain the best description of the evolution of the comoving space density of quasars we adopt the evolution laws derived by Jackson 1974 (454) from the combined 3CR sample and the 4C sample of Lynds & Wills. These laws are defined in terms of the total number of sources within a given redshift and are power laws of the comoving volume.

\[ n(<z) \propto V^\beta \]

If there were no evolution, \( \beta = 1 \). We consider the \( \Omega = 0 \) and \( \Omega = 1 \) models for which

\[ (\Omega = 0) \quad V = \frac{4\pi c^3}{H_0^3} \int \frac{z^2 (1 + \frac{1}{2} z)^2}{(1+z)^{1/2}} \frac{dz}{(1+z)} \]

\[ (\Omega = 1) \quad V = \frac{32 \pi c^3}{3 H_0^3} \left(1 - \left(1+z\right)^{\frac{3}{2}}\right)^3 \]
The predictions for the total numbers of quasars at 2.5 Jy are made by working out the number of quasars expected for each quasar observed in the 3CR catalogue. This calculation is made assuming that the 3CR sample is complete and hence the space densities can be derived directly from the limiting redshift at which each 3CR source could be observed and still remain in the 3CR catalogue. Thus for each source in the 3CR catalogue, we expect 'n' 4C sources at S=2.5 where

\[ n = \frac{P(Z(5=2.5))}{P(Z(5=1\pm0))} \tag{1} \]

\( Z(5=2.5) \) means the redshift at which the source would be observed to have flux density 2.5 Jy. In practice we must also take account of the optical limiting apparent magnitude of the sample. If \( Zm \) is the limiting redshift at which the quasar has apparent optical magnitude equal to the limit of the survey, then if \( Zm \) is less than \( Z(5=2.5) \), it should be used rather than \( Z(5=2.5) \) in equation (1). This procedure is exactly the same as the procedure used in the V/Vmax test.

In Table 7.3.2, we compare the observed and predicted numbers of quasars in the 4C samples assuming different
Table 7.3.2
The observed and the predicted angular size - redshift distributions for various optical limiting magnitudes.

<table>
<thead>
<tr>
<th>OBSERVED</th>
<th>PREDICTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m&lt;19.5</td>
</tr>
<tr>
<td></td>
<td>n=0</td>
</tr>
<tr>
<td>Total number of sources in the LW and S areas</td>
<td>84</td>
</tr>
<tr>
<td>Number of sources with z 1.5</td>
<td>19</td>
</tr>
<tr>
<td>Fraction of total</td>
<td>0.26</td>
</tr>
<tr>
<td>Number of sources with z 1.5, 0.5</td>
<td>15</td>
</tr>
<tr>
<td>Fraction of total</td>
<td>0.16</td>
</tr>
</tbody>
</table>

In the case of S, there are contributions from sources on physical sizes of 2.5 (1D) and 2.0 (1D).
either side of the minimum angular diameter which occurs at 
\( Z = 1.25 \). If the redshift interval \( Z_1 \) to \( Z_2 \) lies within the 
redshift range within which the source has \( m < 19.5, > 2.5 \) Jy, 
the number of sources observed in that angular size range is 
just the number of sources in the redshift interval \( Z_1 \) to 
\( Z_2 \).

This procedure may be performed numerically for each 
source in the 3CR sample for the angular diameter range 
1000" - 0.1" arc. Then the predicted angular diameter 
distribution at 2.5 Jy may be found by summing the 
contributions from the 38 quasars of known redshift. In 
practice, the computer works out the number of sources in 
equal logarithmic bins so that for a factor of 10 in angular 
size there are 20 bins.

By using individual sources observed in the 3CR 
catalogue, rather than smoothing the data, the predictions 
are very 'noisy' and to smooth the predictions, they are 
summed to produce integral angular diameter counts at 
2.5 Jy, i.e. \( N(> \theta) \). We are well aware of the dangers of using 
integral counts in the presentation of results of this 
type. In this case, little confusion can occur because we 
use a linear scale on \( N(> \theta) \) and the reader is invited to
Fig. 7.3.4 The predicted angular size distributions for $\alpha=0.1$, all $\psi < 0.5$, all $Z$ and $Z > 1.5$, for an apparent magnitude limit of $19^m.5$. 

\[ \text{LAS/arc} \]
convert the results into differential counts if he wishes a cleaner comparison.

The program predicts the function \( N(>\theta, 2.5) \) for all sources, and also for sources with \( Z>1.5 \) for direct comparison with the observations. Fig. 7.3.4 shows the result of these computations for the following selections of sources:

- \( \alpha=0 \) and \( \alpha=1 \): all ranges of \( Z \) and only \( Z>1.5 \): all ranges of spectral index and only sources with \( \alpha>0.5 \)

All eight curves are shown for a magnitude limit \( V=19.5 \). The predicted number of sources \( N(>\theta, 2.5, Z>1.5) \) is sensitive to the assumed apparent magnitude limit as illustrated in Fig. 7.3.5. The final comparison of our observational results with the predictions of the models are summarised in Figures 7.3.6 and 7.3.7. The observations have been presented as integral counts, assuming that the sources with upper limits to their angular diameters in fact have those diameters. Separate observations and predictions are shown for sources with \( \alpha>0.5 \). The predictions agree very closely with the observational curves.
Fig. 7.3.5 The variability of the angular size distribution predictions with assumed apparent magnitude limit.
Fig. 7.3.6 A comparison of the predicted angular size distributions (thin lines) with the observed distributions (thick lines). The broken line is the prediction for sources of known angular size, excluding those with upper limits only, $\Omega = 0$. 

$$\Omega = 0$$
The excellent agreement of theory and observation indicates that at least to the flux density level $S_{1.4} \leq 2.5\text{Jy}$, the observations are consistent with the hypothesis that the physical sizes of the most powerful quasars are unchanged with cosmological epoch. In the statistical comparison, equally good predictions were made for both the $\Omega = 0$ and the $\Omega = 1$ models, indicating that there is little to choose between these models so far as the angular diameter distribution is concerned.

### 7.4 Comparison with Other Work

This investigation has not found strong evidence for the variation of the physical sizes of the radio structures of quasars with cosmological epoch. This is because (i) the added structural data on large redshift quasars have slightly 'bent round' the $L-Z$ relation and (ii) for those luminosities for which the comparison can be made, the physical size distributions are not greatly different; (iii) the proper statistical comparison of the structural data in the 3CR and 4C catalogues shows that they are consistent with the quasars having the same physical size distribution at all redshifts. We note, however, that these statements are all based upon small statistical samples of quasars.
This result is in marked contrast to the results of Swarup and of Kapahi who found strong evolution of the physical size of radio sources to be essential to account for the observed decrease in the median angular size as a function of flux density.

This problem is the subject of much further study (Riley & Longair, private communication) since complete surveys of the structure of radio sources have been completed in the flux density region where the observational anomaly is found. It appears that much of the effect is due to the presence of many bright, extended radio galaxies in the 3CR sample. The intrinsic luminosities of the sources are small and their relative absence at lower flux densities is surprising because their distribution is 'local' and therefore they should obey closely an $N(S) \propto S^{-1.5}$ law. If this is the source of the anomalous result, the variation may be the result of some incompleteness in the sample of sources considered. It would seem unlikely to be a genuine cosmological effect.

Thus, because the samples of sources considered are of very differing luminosity, there is no contradiction between the present results(points (i) - (iii) above) and the
results of Swarup and Kapahi. Further analysis of the Swarup-Kapahi results is however of great interest and importance.
CHAPTER EIGHT

Theories of Extragalactic Radio Sources

8.1 Introduction

All current theories of radio sources are based on two main assumptions, viz:

i) The synchrotron mechanism is responsible for the observed emission, (or possibly a variant such as 'synchro-Compton' radiation, Rees 1971, [473]).

ii) The two outer components of extended double radio sources (EDRS) originate in the nucleus of the associated galaxy or quasar and are moving away from it.

Most of the other details vary from model to model and account for the differences in predictions between them. It is not inconceivable that even the above two foundations of the theories will survive the test of time, but in the absence of viable alternatives this point will not be pursued further here. The existing theories may be roughly divided into 3 categories: (a) confinement models, in which
the energy in the components is produced in one event in the nucleus of the optical identification and the components are flung out in opposite directions, the individual components being held together (against the disruptive pressure of the internal energy density) by some confinement mechanism: (b) beam models, wherein the components are the regions where a beam of relativistic particles or low frequency electromagnetic waves (LFEMW), emitted by the nucleus, interacts with an external medium. Particles are accelerated at this interface and radiate in the magnetic field presumed to exist there. Because the relativistic particles are continually replenished there are not the same problems of confinement experienced with models of type (a): (c) bubble models, which are slightly different from type (a) models, wherein the components are associated with bubbles of relativistic plasma rising, due to buoyancy forces, from the nucleus because of the existence of a denser surrounding gas sitting in the gravitational potential well around a galaxy, usually at the centre of a cluster.

8.2 The Evolutionary Phases of Radio Sources

Leaving aside, for the moment, all the problems associated with detailed models of radio sources (see, e.g. Longair, Ryle & Scheuer 1973 (404)) (LRS) there are four basic phases associated with sources of the type described
by our assumptions. These are:

i) The initial creation of the source components or the beam forming mechanism in the nucleus of the galaxy, either as the result of some sort of catastrophic event or through some semi-continuous mechanism as postulated for the bubble model by Gull & Northover 1973 (182), and the 'twin-exhaust' model of Blandford & Rees 1974 (472).

ii) The separation of the two components and their subsequent passage through the main body of the galaxy, inside a medium of intragalactic gas.

iii) The eventual appearance of the components outside the galaxy proper and their passage through any external medium be it 'galactic wind', intergalactic gas or intracluster gas.

iv) The death of the radio source when the emission falls to some small value (say, $P < 10^{-24} \text{ W Hz}^{-1} \text{ sr}^{-1}$) associated with the complete deceleration of the components and their subsequent rapid expansion in ram-confinement models, or the switching-off of the beam in beam models.

Most early models either ignored phase i) altogether, or at best appealed to something vague like 'an explosion in the nucleus'. The bubble model treats this stage in some detail but unfortunately requires nuclear structures on the scale of 2Kpc or more whereas VLBI measurements (Cohen et
al 1971 (480)) seem to indicate that the site of source production may be on a scale of less than 10pc.

Recently, Blandford & Rees (472) have put forward their 'twin-exhaust' model for the production of two beams of fast particles (or LFEMN) suitable for Rees' beam model (Rees 1971 (472)) or that of Scheuer 1974 (478), and this may go part of the way to explaining the initial production phase.

Despite their gross differences in some other respects, most models have difficulty in explaining the slow fall in luminosity of the outer components after they have left the nucleus and when the source size has increased to >100Kpc. Just what the relationship between luminosity and source size should be is not clearly predicted by any model, and it is thus difficult to distinguish observationally between models in this way though they all suggest that luminosity falls as the source gets bigger. This implies that when plotted on a luminosity-size (P-D) diagram (see Fig. 8.1.1) a source will (generally) move downwards and to the right as it ages. That the luminosity of the source should fall at the very beginning of its life is not as clear, and there are reasons for believing that
the luminosity might be relatively higher immediately after the nuclear event, since only then will the normal emission mechanisms of powerful double sources be operative. There are no compelling reasons for the formative catastrophic event in the nucleus itself to be a source of powerful radio emission. However, the evidence of central components in many (~75%) of powerful doubles suggests that a mechanism for radio emission does develop in the nucleus at least by the time that the components are well clear of it. The central component luminosities are generally much less than those of the components at frequencies less than 10GHz.

8.3 Variations of Observable Parameters with Source Age.

Since most if not all models account for the bulk of the separated-component emission by some interaction with the medium surrounding the component (be it turbulent mixing in the bubble cap, the interface where the beam (in beam models) pushes back the medium, or the shock front in ram pressure models) it seems reasonable to expect more emission when that interaction is stronger. It is therefore likely that the luminosity of components will be greater whilst they are still inside the parent galaxy (or QSO) stellar system as interstellar gas densities will generally be greater than intergalactic gas densities. As some galactic envelopes extend to huge distances (~300 kpc, de Vaucouleurs
1969 (322): perhaps $\sim 800\text{Kpc}$, Carter, D., private communication) it is not clear where to start looking for a rapid fall in emission, though the sparsity of sources of overall size greater than $600\text{Kpc}$ may be suggestive that here the components of most sources have emerged from the confines of the galaxy. Alternatively, where a radio galaxy is in the core of a cluster of galaxies, X-ray observations show that gas densities of $10^3 \text{cm}^{-3}$ often exist out to a radius of $1\text{Mpc}$ from the cluster centre and this may then be the factor determining the maximum size that a source may attain. For similar reasons, the component luminosity is expected to depend on the velocity with which the component is proceeding through the external medium. For a given pushing force (beam energy density, bubble buoyancy or component kinetic energy) the velocity squared is inversely proportional to the external-medium density and so the two effects tend to cancel for a given source of energy. However, where a component is moving more quickly, all other things being equal, it is expected to be more luminous and this implies a decay of luminosity with age, for non-continuous energy supply models, as the components must continuously decelerate. Beam models are slightly different as there is no a priori reason for the beam power to be
constant, and also it may be that the beam will push back the external medium more rapidly as it becomes less dense away from the optical nucleus. This latter tendency will be partially counteracted by any divergence of the beam because the cross sectional area of the interface will increase as it moves outwards and the beam energy per unit area will consequently decrease.

From the above, it is apparent that models other than the beam models predict a decrease in luminosity, a decrease in velocity, and an increase in size with age, independently of arguments concerning emission losses, expansion losses and fast particle lifetimes. Beam model sources do not suffer from the latter effects per se, and it is not entirely clear just how their component luminosity or velocity will vary with age, though they too should increase in overall size as they become older, but not necessarily at a monotonically decreasing rate. Naively we might then expect a correlation of luminosity with linear size, the smallest sources being the brightest. We should also expect to see relatively fewer small sources since the components spend most time at great distances from the nucleus where they have the smallest velocities.
8.4 The Luminosity - Size Diagram

Unfortunately, from our 'fixed' position in the Universe, we do not see all sources equally well and at great distances we can see only the very powerful sources. That we do not see such sources nearby (Cygnus A, 3C405, is a relatively local exception) indicates that powerful sources have a low space density locally. Resolution limits our seeing of detailed structure to the nearest and/or largest sources, and we have little reliable structural information on the physically small, powerful radio sources (e.g. <30Kpc, >1E27 W Hz sr). Moreover, the distances of many sources (and therefore their intrinsic sizes and luminosities) are only poorly known due to lack of redshift measurements or even of optical identification.

All the above effects combine to produce an observed P-D diagram that bears close resemblance to a random scatter diagram (e.g. Mackay 1971 (94)). We shall attempt to find some order in the diagram as follows: we wish to distinguish between powerful radio sources as a type, and luminous radio sources, luminosity being a description of their appearance to us now, and not necessarily an indication of the initial energy-scale of the source before its evolution began. We thus ascribe to each source a parameter 'E', the quantity of
'available energy' stored in the nucleus at the time that the source was created. By 'available' energy, we mean energy that ultimately will be transferred to the outer components. Large-E sources will at one time have had a high luminosity and a high rate of component separation and thus they will reach a given linear size with larger luminosity than lower-E sources (if we assume that P monotonically decreases with age of source). Clearly then, a source with large E may have a lower luminosity than a source with smaller E, but only if the large-E source is older than the small E source, in which case the former will also be bigger. The rate of fall of luminosity with source age may be greater for high E sources, but we postulate that at a given age 't', \( P(E_1,t) > P(E_2,t) \) for all t, if \( E_1 > E_2 \). By definition, sources must evolve along lines of constant E on the P-D diagram. 'E!', then, is not a directly observable parameter, but one that may be deduced for sources, if enough is known of their physical structure and luminosity history. In fact, \[ E = \frac{1}{\epsilon} \int_{t_0}^{t_e} P \, dt, \] where \( P \) is the radio luminosity at time \( t \), \( t_0 \) is the time of creation of the source, \( t_e \) is the time when the source 'dies', and \( \epsilon \) is an efficiency factor (<1) describing the fraction of the energy in the components of the source that
is converted into radio emission. If we could E-classify a group of sources, then we might expect to find that some other intrinsic source properties would correlate with E, and also it should be possible to form an evolutionary sequence for a set of sources with similar E-values and, say, steadily increasing sizes. Clearly this would be very important as it would give some clues to the detailed history of sources that any viable theory must explain. At present, theories are consistent with observation if they are capable of producing a structure at all similar to one of the extreme examples of observed extended sources, say Cyg A, and a more demanding set of observational data will be useful in weeding out the anomalies within them.

The direct E-classification of sources appears to be impossible with our present observational data and our poor theoretical understanding of the ongoing processes in powerful radio sources. However, we should like to point to the work of Chapter 6 as a possible indirect approach. There, we used arguments based on the morphological continuity of structures to deduce possible 'evolutionary tracks' on the P-D plane. If real, these are clearly associated with the 'lines of constant E described above. Because of the very small numbers of sources in each of our sequences, we have not been able to investigate this matter
further, but as more and more sources become identified and
resolved, and fitted into the morphological pattern, it
seems likely that correlation studies will become possible,
and this approach appears to be the best available for
determining the entire life history of radio sources.

8.5 The Compatibility of a Specific Model
with Observational Evidence

We now consider the relationship between the
observational data described in the earlier chapters of this
dissertation and a specific model of a powerful
extragalactic radio source. For the reasons set out in
detail in LRS we consider a model where energy is
continuously transported to the source components throughout
most of the life of the source. Such models avoid the basic
problems of adiabatic expansion and energy loss, or
confinement and instabilities, inherent in 'one-shot' models
where a single event in the nucleus releases all the energy
which is then somehow supposed contained in the components
throughout the entire life of the source. A model similar to
Model C of Scheuer 1974 (425) will be assumed. This model
has the following principal features: a) a central source of
energy in the nucleus emits a pair of oppositely directed
beams of low frequency electromagnetic waves (LFEMW) and/or
fast particles; b) where the ends of the beam interact with
the surrounding gas (interstellar or intracluster gas) they push back the gas at a rate given by $u \omega \rho v^2$ ('$u$' is the energy density in the beam, '$\rho$' the gas density and '$v$' the velocity of the gas/beam interface). This interaction of the beam with the gas accelerates particles to relativistic velocities which then radiate synchro-Compton radiation in the field of the LFEMW, producing the bright radio component emission; c) the fast particles leaking backwards from the beam/gas interface then 'inflate' a spindle shaped cavity around the entire source by virtue of their pressure $(u_c/3)$ balancing that due to the external surrounding gas, $\rho v_e^2$, where '$v_c$' is the velocity at which the cavity expands. The simple shape of this cavity may be modified if the nucleus is at the centre of a cloud of gas, with appreciable density gradients on the scale of the source. The higher central gas pressure may then be sufficient to 'pinch-off' the cavity in the middle. Indeed, more generally if the source is immersed in any gas density gradient, whether or not centred on the nucleus, the cavity shape is expected to be modified in a similar fashion, and this mechanism could give rise to many of the oddly shaped source envelopes often seen amongst the weaker sources, most of which are in clusters of galaxies; d) the beam is self-focused by the pressure of the fast particles in the cavity surrounding it, and is maintained approximately parallel outside the central nucleus with a width of a few Kpc.
The model has some difficulty in keeping the radio emission from the cavity as low as observations indicate. There are also some theoretical problems with the stability of the beam, and Scheuer suggests no mechanism for the original creation of the beam. Blandford & Rees' model 1974 (AZZ) gives a detailed account of a possible beam producing mechanism but predicts nuclear structure on a scale of 100 - 200pc whereas VLBI and variability observations indicate that the central mechanisms are smaller than \( \sim 10 \)pc.

Our important findings are:

1) Most outer components show structure on a scale of 5 - 10 kpc (Section 3.5 b), which may be associated with the width of the beam where it impinges on the external gas. That this scale size is approximately constant irrespective of overall source size is an indication that some sort of beam focusing mechanism is present.

2) Most (\( \approx 97\% \)) radio sources are in groups or clusters of galaxies (Section 4.5): this coupled with the X-ray evidence of hot gas being a common component of clusters implies the presence of an external gas pressure to; a) contain the
particles diffusing back from the heads and thus produce a spindle shaped cavity or bridge as seen in the weaker doubles or; b) where the external gas pressure gradient is steeper, the cavity will be pinched in the middle where the pressure is higher giving rise to bridge structures similar to that of 3C382, and in extreme cases will close the cavity all the way back to the heads leaving only short tails on the components. (These effects were described by Scheuer (425) - we merely restate them here and stress that the observational evidence is that such gas is probably always present.) We also note that the absence of large tails or complete bridges on the most powerful sources suggests that a large central concentration of gas is a necessary feature for the production of such powerful sources.

3) **All central components of powerful doubles are compact and have flat spectra:** the compactness is probably an order of magnitude smaller than the scale size of the Blandford & Rees 'twin-exhaust' mechanism; there are no compelling reasons yet put forward to explain why the CCC's must have flat spectra.

4) The **hot spots** (Section 3.5 c) seen in many components on scale sizes <10Kpc (perhaps <2Kpc) may be; i) local enhancements in the magnetic field structure thus producing local increased emission or ii) the beams in these sources
may be subject to slightly unstable focusing mechanisms - this would mean that the end of the beam could vary in diameter (and presumably in position too) giving rise to a component on a scale 10 - 20Kpc when focusing was weak and hot spots on scales <2Kpc at times of strong focusing. This type of beam instability would explain why the various hot spots rarely occur at the same distance from the nucleus as successive periods of strong focusing would necessarily occur at different epochs between which the general beam pressure will have advanced the beam/gas interface. The typical separations of hot spots (in radial directions) of 5 - 10Kpc implies beam instability periods of between $2 \times 10^5$ and $2 \times 10^6$ years assuming a beam velocity of between 0.01 and 0.1 c.

5) The non-aligned tails (Section 5.3) are more difficult to explain in the beam model unless the beam focusing mechanism can produce a semi-stable curved beam. Alternatively, there could be a local instability in the cavity wall surrounding the rear of the component. This could conceivably entrain matter and locally wind-up the magnetic field so that 'leaking' fast particles will radiate as they leave the region, producing the tail emission frequently observed. Another alternative is that the cavity surrounding the beam may be deformed by the pressure of 'intergalactic winds' acting obliquely and deflecting it from its canonical
spindle shape.

6) The observed \textit{proportion of double sources} amongst well resolved objects is \textbf{88\%}, of which approximately \textbf{30\% have bridges} and \textbf{34\% compact central components} (Section 5.5). If all radio sources are produced by essentially the same mechanisms, this indicates the stability of beams over other configurations. The high proportion of bridges indicates that it is not essential for stability that the source lies in a very high central gradient of external gas density.

7) Probably \textbf{25\% of doubles have bright nuclear components} (Section 5.6). Thus the beam forming mechanism in the nucleus is also very frequently a source of radio emission which implies the presence of fast particles and fields at the \textit{source centre} and not just in the components and bridges.

8) \textit{Luminosity of central component is only weakly correlated} with luminosity of whole source (Section 5.6). The implication is that the strength of the radio emission from the nucleus is not necessarily a measure of the energy output of the beam, perhaps indicating that the two processes are not directly related.

9) \textit{A few sources seem to have only one external component}.
remote from the nucleus (e.g. 3C273). These may be different phenomena from normal double sources, though we gave reasons in Chapter 6 to suggest that these sources might be the result of catastrophically unstable high powered nuclear events which disrupted the usual mechanisms for stable component formation.

10) There are no significant correlations between the properties of the two outer components of doubles (Section 5.10). In beam model interpretations this is an indication that the two halves of the beam produce components whose characteristics are, at any given time, a complex function of the separate beam stability histories, external gas densities and density gradients and perhaps direction of mean drift of the external gas relative to the galaxy. There is less compulsion to expect roughly equal quantities of energetic material to be ejected by the central object (in opposite directions) when it is not all done at once (the integrated momenta should perhaps be approximately equal but this is not necessary instantaneously).

11) Component brightness is not correlated with component luminosity (Section 5.11). This suggests that although the luminosity of the components may well be a simple function of the beam power, the brightness is subject to much variation due to the widely differing beam focusing
conditions in different sources and thus would not be expected to correlate with luminosity.

12) **Component luminosity falls as source size increases** (Section 5.12). This seems to imply that beam power falls steadily as the source ages, rather than simply cutting off abruptly. One might then expect a gradual collapse of the beam as the external pressure compressed it. The 'jet' structure in 3C219 may be an example of the total collapse of the beam some distance from the outer component, where the particles from the cavity have intruded and closed off the beam, radiating away some of the beam energy in doing so. The compact component on the same side of the nucleus as the 'jet' will not be affected by the beam cut off for a time \( \sim D/c \), where 'D' is the separation of the component from the jet. That the other component is not compact may indicate that the other half of the beam has already collapsed.

### 8.6 Conclusions

We have shown that continuous energy supply models, specifically in a form similar to Scheuer's Model C, are compatible with the majority of the observational data described earlier in this dissertation. In so doing we have put forward several hypotheses concerning the details of the
mechanism. These are: 1) the focused beam diameter is in the region of 5 to 10Kpc, except when there are focusing instabilities, in which case it can vary from <2 to 20Kpc; we deduce a time scale of 2E5 to 2E6 years for the beam focusing periodicity. 2) it is not essential for beam stability that there exists a steep density gradient in the external gas surrounding the source. 3) it is unlikely that the strength of the radio emission from the nucleus is necessarily related to the energy in the beam. 4) the beam forming mechanism probably becomes unstable when the energy output is sufficient to produce sources with luminosities much above 2E28 W Hz sr. 5) The detailed nature of the components is as much a function of the properties of the surrounding medium as it is of the beam power.

There still remain problems with such models, the principal one being the initial formation of a beam. Unless the Blandford & Rees mechanism can be shrunk by a factor of 10 or more and still behave qualitatively in much the same way, we are faced with the prospect of a viable source model with no means of creating it. Studies such as those considered in this dissertation can shed little light on this matter as the scale sizes relevant to the problem are on the order of 1pc, and only VLBI techniques achieve the necessary resolution in the powerful radio sources.
REFERENCES


028 De Young, D. S., Astrophs. J., (1972), 123, L7


053 Schmidt, M., Astrophs. J., (1968), 151, 393


093 Wyndham, J. D., Astr. J., (1965), 70, 394


104 Sandage, A., Q. Jl. astr. Soc., (1972), 13, 282


<table>
<thead>
<tr>
<th>Reference</th>
<th>Authors</th>
<th>Journal</th>
<th>Year</th>
<th>Volume</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>278</td>
<td>Rowan-Robinson, M.</td>
<td>Astr. J.</td>
<td>1972</td>
<td>27</td>
<td>543</td>
</tr>
<tr>
<td>311</td>
<td>Fomalont, E. B.</td>
<td>Astr. J.</td>
<td>1971</td>
<td>76</td>
<td>513</td>
</tr>
</tbody>
</table>


371 Reinhardt, M., Astrophs. Lett., (1972), 12, 135


389 Gull, S. F. & Northover, K. J. E., Nature, (1973), 244, 80


446 Sandage, A., Astrophys. J., 183, 711


458 Wall, J. V., Obs., (1975), 25, 196


471 Hewish, A., Readhead, A. S. & Duffett-Smith, P. J., to be published
472 Readhead, A. S. & Hewish, A., to be published


476 Shklovskii, I. S., Astr. J. USSR., (1960), 37, 256


APPENDIX I

Radio Astronomy Data Analysis (and) Retrieval System
RADARS is an attempt to put at one's fingertips, most of the important data on extragalactic radio astronomy accumulated over the past twenty years or so, and otherwise scattered randomly throughout the literature. Not only is the data available for inspection and reference purposes, it is also readily manipulatable and fast graphic output is available at the touch of a few keys. It is hoped that the inherent power of the system will be made apparent by reading this manual and will be used by others, and that it will help them in their otherwise more tedious research tasks.

HOW TO USE THIS MANUAL

The first parts of the manual are mainly general and explanatory in nature and are intended to be read only once or twice and are not for frequent reference. They discuss the scope and philosophy of the RADARS system and are designed to put the intending user into a useful frame of mind for absorbing the later sections which are mainly tabular and which contain all the essential information necessary to write 'good' RADARS command language. These tables are therefore designed for quick reference purposes and may usefully be detached from the body of the document when the introductory sections have been understood.
CONTENTS

1. Introduction.

2. Scope of the System.

3. The Data.

4. Communication with the Program.

5. The Commands.

6. Adding a FORTRAN Program.

Appendices.
1. INTRODUCTION

This manual is intended for radio astronomers who wish to use the RADARS system for data manipulation only. The system acknowledges two classes of user: the first is made up of lay-users, who have available to them most of the commands, and the ability to perform limited internal filing and naming operations. This class will consist of the bulk of the users. The second class is composed of people with supervisory status who in addition to all the ordinary commands available to lay users, have access to commands controlling updating and bulk input/output operations, and also to those instructions that allow renaming of certain keywords inherent to the system. The system recognises the class of user by a 'password' given somewhere in the command stream. If no password is given, the system may not respond to any of the commands presented by the user. One command in particular, only available to class-2 users is the repeated PASSWORD command which permits changing of passwords.

This division into classes is intended to preserve the integrity of the system files in the face of possible rough handling by inexperienced and casual users. Lay-users have few restrictions placed on them and most will never wish to make use of the supervisor facilities. Those that do should
consult a supervisor-user. Most syntax errors made by users in writing their command language strings are trapped by the system and appropriate action taken - most will cause job termination, though some are skipped over and the next legitimate instruction attempted. It is not possible for lay users to corrupt the system files by writing bad input code so experimentation by beginners is to be encouraged.
2. SCOPe OF THE SYSTEM

It is anticipated that RADARS will be useful to most radio astronomers working on extragalactic topics, and in particular, to those investigating 3CR sources, and to theorists looking for experimental confirmation of their source-models. Data is held on all of the sources in the Revised 3CR Catalogue though some of the sources have been redesignated, either because of inconsistencies in R.A. order of multiple sources in 3CR fields, or because a source in 3CR is now thought to consist of two or more independent sources. Some of these may fall below the $178\text{MHz} > 9$ f.u. limit of the catalogue, and will be excluded. In such cases a second place decimal digit has been appended to the 3CR name to avoid confusion with 3CR decimalisation and therefore in RADARS, 3C66 for example is split into two separate sources, 3C66.01 and 3C66.02, (the lower numbered source always having the smaller R.A.).

The principal purpose of RADARS is to allow selection of samples of sources from 3CR suitable for statistical analyses. Selecting on many properties is very tedious by hand, whereas selection on up to 13 properties is possible
in one pass of a RADARS sampling, further characteristics being checked on multiple passes, though this is seldom necessary. Sample selection is crucially important to any statistical work, since in radio astronomy, selection effects are rife. For a fuller discussion of these effects the reader is referred to Hooley 1976 (Ph.D. dissertation, chapter 5) where their relationship to the sort of work possible with RADARS is investigated. The type of selection possible is best illustrated by an example (see page 43).

Having selected his sample(s) the user may then plot distribution functions for any of the stored or derivable properties, compute means and standard deviations of sample properties, perform significance tests, and also make correlation (scatter) diagrams and compute coefficients of correlation. Tabulated data is available in a useful range of formats in 3CR order, and also sorted in ascending order of its value.

The samples themselves may be stored for future reference or for further sub-sampling, and a source listing for each sample is available. Stored samples may be protected from erasure by using the PROTECT command, but this should only be done if absolutely necessary, as only
supervisor-status users may then write-enable that sample storage space for future use by others.

The PROGRAM command allows a user to run his own FORTRAN program as part of a RADARS job which gives great flexibility of operation. This command virtually lets the user 'into the system' rather than keeping him at arms length protected by the command-language buffer with all its error-trapping mechanisms. Clearly, this exposes the system files to some probability of corruption, so users are asked to read Section 6 carefully before using this command.
3. THE DATA

Most of the radio structural data and associated parameters are derived from Cambridge synthesis maps made with the One Mile Telescope at 408MHz, 1.4GHz, 2.7GHz and 5.0GHz, the 5Km Telescope at 5.0GHz, and the Half Mile Telescope at 1.4GHz. In some cases, where the source is of particularly small angular size, data is drawn from VLBI work, and in others, where the source is of low brightness, highly polarised, or at low declination other observatories' data are used to supplement those from the Cambridge instruments. Optical data is mostly from the literature of the past 20 years, but occasionally, unpublished results appear. Wherever possible, 200-Inch-Telescope plate material is used though in a large number of cases, Palomar Sky Survey Prints are still the best available data source.

The data files are the result of an exhaustive search of the literature and are thought to be very nearly complete, in the sense that they represent the sum total of all published information in the chosen categories on the 3CR sources. Each individual item of data is punched on a separate card which carries both machine codes and literal codes to make it readily identifiable to both the user and the computer, and also easy to update. Each card also carries a reference number, keyed to the source of the
information contained thereon, though in order to conserve space this reference number is not stored on disc in the computer. Lastly, updated cards are punched with their date of entry into the system. There is a cross reference system consisting of a reference book, an author-index card file and a radio source card file which together with the reference numbers on each data card make location of the data source completely straightforward. The procedure is as follows. The reference number on the data card is found in the reference book (references are in numerical order) alongside which will be found the author name and the publication reference if it exists. If the author-name is then located in the author-index card file (filed by alphabetical order) more information about the data may be available, or in the case of unpublished material, the source is generally noted here.

**Data Types**

Three basic types of data are used: numerical, alphabetic-coded, and binary-coded.

a) **Numerical data**

This type of data is the most common and consists of the value of some source parameter in appropriate units. The units used are listed in Appendix IA, together with a list of all source parameters stored in RADARS, and their
code reference numbers to be used when writing Command Language. A value of zero indicates that there is no known available information. Any known real data value that is nominally zero is set to be small and positive (e.g. a spectral index of order 0.0 would be set to, say, 0.001 which would not affect any computations or statistical tests using it, but does allow the system to distinguish it from a null data entry of 0.0).

Most of the source parameters considered by RADARS are defined in such a manner that only positive values are physically meaningful. Use is made of this fact by allowing a negative prefix before data values to occur in any of the following cases:

i) a value is uncertain, usually through practical limitations on its measurement;

ii) a value has been estimated from another property - e.g. a redshift from a magnitude;

iii) a value is an upper or lower limit only.

Which of these three cases is relevant to a particular datum is often apparent from context. Redshifts are generally measurable with some precision, or not at all, so negative values here usually indicate estimates from magnitudes. Negative angular sizes are usually upper limits due to limiting telescope resolution. Fluxes too are usually only upper-limits where no signal is observed above the noise level. A negative value of a derived property (e.g.
luminosity) generally indicates one or more negative values amongst the properties from which it is derived. Visual magnitudes are sometimes set negative when an object is unidentified and (making allowances for galactic obscuration) an upper limit to its brightness has been estimated, whereupon the value stored is set to the negative of the lower-limit to its visual apparent magnitude. Note that none of the 3CR sources is identified with an optical object whose visual magnitude is less than zero. Radio position angles are measured positive only, in the two quadrants East of North and a negative value here indicates uncertainty in the direction of a source axis. The following properties may take physically meaningful negative values and unless the value known is thought to be reliable, it is not entered (value is set to 0.0): U-B, B-V, galactic latitude, spectral indices, declination, absolute magnitude.

Clearly, one wishes to know how much of one's data is estimated and how much reliable, and the system routines allow this distinction to be made. Firstly, for example, if one selects a sample of objects with redshift between 0.01 and 0.1, one will only select those sources with measured redshifts, since a source with estimated redshift in the above range, (with, say, z stored as -0.06) will be rejected by the sampling procedure. One could, however, also select sources with stored z between -0.01 and -0.1. This would
allow consideration of the uncertain data too. If this sample were, for example, to have the linear size plotted against redshift, the system plotting routine would mark those points on the scatter diagram whose axial values were negative as special points, but position them as though the values were positive. The conventions for the plotting routine are as follows:

i) negative input data on the X-axis plots symbol 'X'
ii) negative input data on the Y-axis plots symbol 'Y'
iii) negative input data on both axes plots symbol 'B'
iv) otherwise datum is plotted with symbol '*'
A full description of the preprocessing performed by the graphic-output routines is given in the section on Commands.

b) Alphabetic-coded data

Currently, only two properties are alphabetic-coded, these being the radio and optical morphological types. This is done to make the data more easily user-readable. Internal to the system however, the data is held in real number form and is only converted during input-output operations. This is done in order that the program may treat this data identically to all other data. There are two separate type-coding conventions for radio and optical morphological types because of the totally different types of structure to be described, although both use 3-component alphanumeric
strings to describe the objects. These conventions are set out in Appendix IB and Appendix IC respectively, but a couple of short examples here may be found useful.

Examples.

i) Source has radio type coded as 'DBT' and optical type coded as 'DE3'.

DBT implies that radio wise the source is primarily classified as a Double source, that it has a bridge of emission extending from one component to the other, and that the components are sufficiently well resolved to show tail structure. Optically it is a giant E-galaxy with E3 ellipticity.

ii) Source has radio type 'TS' and optical type '2GR'.

TS means that the source is a Triple source (i.e. double structure with a central component in the vicinity of the optical object, or in the case of an unidentified source, roughly in the middle of the outer components) and is not well enough resolved to show any other features and therefore appears to have simple structure. Optically, the query '2' indicates some doubt about its identification, but in this case it is thought to be a Red Galaxy.

Note that whenever an alphabetic coded value is entered (on a sample selection card, or on a primary data card) the three character code (some of which may be blank) must appear
at the left hand side of the data-field and must contain no embedded blanks.

A useful convention that is applicable to sample selection cards is that one may code (for optical or radio type), for example, 'D*' where the asterisk indicates that only the primary classification (D in this case) is to be considered, further characters being irrelevant. The asterisk may alternatively appear in place of the third component but not in place of the first.

c) Binary-coded data

Certain source properties are best described in a 'yes-no' manner and thus may be considered to be binary data. For example, it is useful to know which telescopes have mapped a source since this gives information on the resolution of observations available (a powerful selection effect when considering morphological factors) and so one of the binary properties coded in RADARS is equivalent to 'source has/has-not been observed by the One Mile Telescope at 408.0MHz'. Certain morphological features are also best described as present or absent and so these too are binary coded.

The way in which this coding operates is that the primary data cards for properties 26 and 27 (BINARY1 and BINARY2 respectively) are each punched with up to 15 2-digit integers in the range 01 to 15. The presence of such an
integer indicates that the source possesses that binary property. For example, '03' is the property, 'observed by the One Mile Telescope at 2.7GHz', and if the BINARY1 card for (say) 3C454.3 carries the set of integers '01, 04, 12, 03, 08' it implies that 3C454.3 has in fact been so observed. The absence of '02' in the string would indicate no observations by that telescope at 1.4GHz. For a complete list of the meanings of the 30 binary codes the reader is referred to Appendix ID.

When using the binary properties for sample selection, they are used in the same way as the other properties and in effect one can ask to sample all sources with property 26 equal to 04 (say). It is as if the binary properties are multivalued constants and are 'equal' to any of the values coded on the data cards. Note that because the data field on the sample selection cards is 10 characters wide, it is necessary to write '04' as '04.0' or '0.4.' and '11' as '11.' unless the two digits are coded in the last two columns of the field. Internally, the set of binary properties are stored in a single real number for each of properties 26 and 27, again to promote simple internal manipulation and to save disc space.
To enable rapid and easy communication, a shorthand Command-Language has been developed which is used to write instructions for the program. A balance has been made between the amount the user has to write and the amount he has to remember of the conventions of the system. Using less conventions would have allowed a beginner to write good code more easily, but would have slowed down a more experienced user. The major part of Sections 4 and 5 are concerned with defining the action and format of these commands.

A 'command-name' is an 8-character alphanumeric string containing no embedded blanks. Most command names are mnemonics for their functions, e.g. 'PRNSAMP' stands for PRINT SAMPLE. A complete list of the command names and their mnemonics will be found in Appendix IE. A 'command-string' consists of a command-name followed by a list of arguments, which may be null. The list of arguments generally specifies in detail what actions are required of the command, upon what it is to act, and sometimes, where it is to place the results. Command-strings are recognised as terminated when another command-name is encountered, except in the case of certain commands, such as 'STOP', which are self-terminating. Command-names, if punched on cards, start in column number 1 (but see the 'free-format' supplement, page 51) and are one to the line. Command arguments, if
any, follow on further cards and most commands are optionally repeatable any number of times, simply by supplying more argument cards.

The commands are executed strictly in the order in which they appear in the input list. The following conventions apply to the commands:

i) For commands dealing with samples, the sample number must lie in the range 00 to 50 (always 2-digits) or an error may occur. Sample numbers 01 to 50 are the samples stored on disc. Sample number 00 is a special sample, known as the 'current sample', and is useful in several ways. When a sample is newly created it is left as the current sample, and may be referred to as sample 00. Until further action is taken there is no permanent disc record of it and it is lost at job termination, or when a new current sample is created. All other samples have to be fetched from disc when required, which involves a relatively slow input/output operation, so it is more efficient when a lot of work is to be performed on a sample, to initially make it the current sample (e.g. by use of the LOADSAMPLE command)

ii) For commands dealing with source properties, the properties are referred to by their code-number and not their code-name. A little practice soon makes this seem quite natural and saves a lot of punching, thus greatly reducing input errors. Users are advised to make a cross reference index (on the back of a computer card for example)
and refer to it while writing the command code. All property code numbers must contain 2-digits and lie in the range 01 to 50. There is no 'current-property'.

iii) Certain commands (marked with an asterisk in Section 5 and Appendix IE) present a hazard to the system files if used carelessly or without full knowledge of their action, and the command system therefore restricts their use to users who have shown evidence of their supervisor-status by giving (one of) the correct password(s). Most users will never need to use these restricted commands since they are mainly concerned with system maintenance. However, users may occasionally wish to make use of the 'PROGRAM' command (see Section 6), in which case they should consult a 'supervisor'. If you wish to input some primary data then you are requested to read thoroughly the appropriate section in the RADARS Supervisor/Maintenance Supplement to this manual before any attempt to do so.

5. THE COMMANDS

Appendix IE gives a list of all the commands, a brief note of their function, and an explanation of the mnemonic where appropriate. Commands only available to supervisors (i.e. password protected) are marked in column 1 with an asterisk. We now give a detailed description of currently
Fig. 5.1 (App. I) A RADARS system standard data card with field definitions.

Tells the system that standard data cards follow in the command stream. System updates file on reception of data input has ceased, and computes derived properties from inputted data before executing next phase of the main program (CURRENTLY EXECUTES A FORTRAN 'STOP' STATEMENT).

Causes the system to cease reading instructions from the command stream and go on to the next phase of the main program. (CURRENTLY EXECUTES A FORTRAN 'CONTINUE' STATEMENT).

Note that once the strict format has been understood, it is easy to write the commands correctly using the 'free-format' conventions described in the last part of this section. We again use an asterisk here to denote password-protected commands, note that all command strings are assumed terminated with a further command keyword is encountered by the system in the command stream.
Format

DATA

3C454.3 etc.
3C 66.01 etc.

PLOT etc. or any other command

*DECK.*

Punches out a full deck of standard data cards for each of the data-types in the list following the keyword 'DECK'. Data type numbers are in I2 format. No sample selection procedures are allowed here.

Format

DECK

05
47
01

PLOT etc.

Note: If there are 300 sources in the system, this
will produce 3 decks of 300 cards, the first carrying magnitude (=#05) information, the second ALPHCENT =(#47) info. and the third, optical types (=#01). All will additionally carry labelling information: source name, source number, data type name and data type number.

DEFSAMP.

This produces a current sample from a list of sources defined in the command stream. The sources may be denoted either by their 3C name (all names in F6.3 format) or by their system file numbers. The system removes duplicate entries and sorts the sample into order of system file numbers (approx. 3C order)

Format

DEFSAMP
3C454.3
3C66.01
272
3C405
HIST etc.

Notes: The current sample now consists of 4 sources, 3C66.01, 3C399.1 (=#272), 3C405, and 3C454.3
DSOVERDL

Computes the ratios $\frac{\omega_{\text{Small}}}{\omega_{\text{Large}}}$ ('D-Small OVER D-Large') for appropriately structured sources and places the computed values in data types as defined in the argument field of the command.

Format

```
DSOVERDL
49 50
DECK etc.
```

**Notes:** future reference to data type #49 will refer to $\frac{\omega_{\text{Small}}}{\omega_{\text{Large}}}$ values.

DUMMYNAME

Allows the system-name of data types to be changed; e.g. in the above example it would have been useful to change the names of data types 49 and 50 to something more suitable, such as 'DSODL1', and 'DSODL2'. All names must be 8 characters or less and must not contain the character '/' . A colon is useful for denoting ratios.

Format
note that names supplied must not be identical to any of the command keywords as they will then be interpreted as commands.

* HERE.

Runs the first section of program supplied in subroutine HERE. For further details see the PROGRAM command and also see section 6, 'Adding a Fortran Program'. The command has no arguments.

Format
HERE ...

HIST.

Draws histograms of the distributions of the
properties specified in the arguments list, for the sources in the selected sample. The first argument is the 2-digit sample number; the second argument consists of three parameters: i) the data type whose distribution function is wanted (two digit integer); ii) the number of bins to use in the histogram (two digit integer): note that if this parameter is set negative, the routine will automatically choose a statistically suitable ($\sqrt{N}$) number of bins for the plot; iii) the desired scale option (one digit in the range 1-5). Scale options are as follows:
1 linear on both axes
2 logarithmic on X-axis, linear on Y-axis
3 linear on X-axis, logarithmic on Y-axis
4 logarithmic on both axes
5 auto selection of scales: the routine chooses log scales on axes where the data is all positive and where the range of the data exceeds a factor of $10^{**2.5}$.

Notes: negative data will force an axis to be plotted on a linear scale. Zero data are ignored. The scale options defined above apply identically to the plotting routine invoked by the PLOT, and the PLOTG commands. The argument list may contain any mixture of sample numbers and plot specifications required, as illustrated in the example below. The format of the 3-component argument is
"I2,1X,I2,1X,I1"

Format HIST
24 20  2
15  20  2
41  -1  1
20  16  1
05  10  5
HERE  etc.

Notes: In this example, the arguments specify that for sample 24, we wish to draw a histogram of radio angular size (#15) with 20 bins on a log. size scale, followed by a second plot for the same sample, of radio linear size (#41) with automatic bin-number selection, on linear scales. Then we wish to do something similar for sample number 20, but this time the angular sizes are plotted on a linear scale with 16 bins, and the magnitudes (#05) are plotted with 10 bins with automatic selection of log. or lin. scales.

HUBBLE.

Changes the system value of the Hubble constant which
is used in computing linear sizes and luminosities (note that because of the way the computations are performed, changing this parameter will not alter the values of absolute magnitude already computed by the system). It is always reset to 50 km s\(^{-1}\) Mpc\(^{-1}\) at the start of any RADARS job. This parameter must not be set by the user prior to the input of data into the system files, as the resulting derived values will then be incompatible with the other data stored on file. The value given to the system should be in F10.6 format, in units of Km s\(^{-1}\) Mpc\(^{-1}\).

Format
HUBBLE
100.0
etc.

Notes: Using this command has no effect unless some \(H\)-dependent calculations are explicitly initiated, e.g. by use of the LUMINOS or KPCSIZE commands. The PROGRAM command must be used to recompute absolute magnitudes.

KPCSIZE.

Computes the linear sizes of features whose angular sizes and redshifts are stored on file, and stores the values in a specified data type (number 48, 49, or 50).
Negative angular sizes and/or redshifts give rise to negative values. The argument consists of a pair of 2-digit integers, the first being the data type of the angular size data, the second the location in which linear size data is to be stored. Useful (particularly) for computing physical sizes of component features. A print-out of the derived values is produced. It is useful to use the DUMMYNAM command first, to name the new data type.

Format

DUMMYNAM
48
DPL1KPC
50
DPL2KPC
KPCSsize
16 48
17 50
PLOT etc.

Notes: Here we have named data types 48 and 50 'DPL1KPC' and 'DPL2KPC' (D-parallel, Kpc etc.) and then KPCSsize has been used to convert angular size data type #16 to Kpc with results placed in data type #48, and ditto with #17, results in #50.

LOADSAMPLE.
Loads a specified sample from disc into main storage for use as current sample.

Format
LOADSAMP
24

LUMINOS.

Similar to KPCSIZE except this computes luminosities (W Hz sr) from flux densities and needs a spectral index as well as redshift information.

Format
LUMINOS.
32 48
33 49

Notes: The program retrieves 1.4GHz component fluxes (type #32) component spectral indices and source redshifts, computes the component luminosities and places the results in data type #48. It then repeats the calculations for component-2 (#33 is S14CMP2).
MERGE.

Forms the logical union or intersection of the two specified samples and leaves the result as the current sample. The type of 'merge' required is chosen by specifying 'AND' or 'OR' as the first argument of the command giving the union or intersection of the two samples respectively. The samples are specified as a pair of two digit integer sample numbers.

Format
MERGE
OR
11 23

Notes: The union of samples 11 and 23 is placed in the current sample (i.e., the current sample now consists of all sources in either sample 11, or 23, or both). Remember that the current sample is known as sample #00. Continuation of arguments is not allowed (this would be pointless as there is only 1 current sample to define!)

NEGHISI.

Same as HIST but actual (not absolute) value of stored
data is plotted so a log-X scale may not be possible if negative data are present. Zero data is still ignored.

Format
NEGHIST
arguments as for HIST

NEG PLOT.

Same as PLOT but actual (not absolute) value of data is plotted on the axes specified by the first argument (an additional argument to those required by PLOT). The options are, ‘X’, ‘Y’, ‘XY’, ‘YX’, the last two being synonymous.

Format
NEG PLOT

arguments as for PLOT

* NEWSORCS.

Enters new sources into the system files, but not any data; that should be done using the DATA command. This command accepts 3C source names as arguments, checks whether
they already exist on file (they are subsequently ignored if they do), gives each new source a file number, and punches out a deck of 50 (blank data field) data cards (one for each data type) for each new source. Format of 3C names is F6.3.

**Format**
**NEWSORCS**
454.3
435.11
83.12
96.

**OMEGA.**

Changes the system value of omega (=2ω₀) to the supplied value. The value is always reset to unity at the start of every RADARS job. This value must not be changed prior to the input of any new data to the system files.

**Format**
**OMEGA**
0.7

**PASSWORD.**
i) allocates a status to the user according to the supplied password, if this is the first occurrence of the command. This then determines whether or not the user will be allowed to initiate the password protected commands (asterisked in this list) in the following command stream.

ii) If an acceptable password of high enough status has already been given to the system, a second use of the password command in the same job will change the user's password to the newly supplied version, which should then be quoted in subsequent jobs.

*Note:* All passwords have 8 or less characters and must not be null.

Format

PASSWORD
PUSSYCAT

PASSWORD
OLDMOGGY

PLOI.
Produces a scatter diagram on the line printer with scale lengths automatically chosen to suit the data to be plotted. Logarithmic or linear plots are possible by means of the scale option, (3rd section of argument, see HIST command for their definition). The data to be plotted are defined by a sample number and by two data-type numbers the first of which is plotted on the Y-axis, and the second on the X-axis. The two data types and the plot option form a single-line 3-component argument, (format is 'I2,IX,I2,IX,II'), initially preceded by a sample number argument. Zero data are ignored.

Format
PLOT
24
04 05 3
40 41 4
11
40 41 4

Notes: Here we want to plot, for sample #24 (the 3CR complete sample), redshift (=#04) against magnitude (=#05) as X-axis using a log scale on the Y-axis which is option 3. Then, for the same sample, we want to plot P178 (=#40)
against linear size (≈41) on a log-log scale (option 4). Lastly for sample 11 we repeat the P-D plot, again on log scales. The MAP option may be used to produce, in addition to the scatter diagram, a similar plot where the data points are plotted from a 52-character set (a-z, and A-Z) with a cross reference table listing the source names against their plotting symbols. This allows individual points on the plot to be related to particular 3C sources.

Format

PLOT

24 MAP

as before

Notes: '24' is the sample number; the 'MAP' tag follows the sample number with one intervening space.

PLOTR:

Same as PLOT command, with all its options, but additionally this command produces 4 least-squares regression fits to the data using the functions: ; \( y=\text{ax}+\text{b} \); \( y=\text{alog}_{\frac{1}{x}} \); \( y=\text{ax}^{\text{b}} \); \( y=\text{ab}^{x} \). The coefficient of correlation along each curve is computed as well as the statistical significance of this value (see Appendix I). The routine also computes the mean, standard deviation, geometric mean
and geometric deviation of the data.

**PRNSAMP.**

Lists the members in a given set of samples, and indicates the number in each.

Format
PRNSAMP
24
05
49

* PROGRAM.

Used for interfacing with user supplied FORTRAN programs. Each program to be run (there may be between 1 and 9) is written as a section of subroutine HERE, which is then linkage-edited to the loadmodule containing the remainder of RADARS, and any other user supplied subroutines. Subroutine HERE is separated into 9 sections by the CONTINUE statements with labels 100, 200, ...900, control being passed to these statements on reception of the commands 'PROGRAM/01, 02, 03...09' in the input stream. Each section
of user supplied program should be terminated by a RETURN or STOP statement, and if the former is used, control is then passed back to the command stream, and the next RADARS command executed. Any program section may be called any number of times in any desired order, giving great flexibility of use.

Format

PROGRAM

03 PlfJT

PLOT


PROGRAM

01

etc.

Notes: see Section 6, 'Adding a Fortran Program'.

PROGRAM

Lists the stored data on the properties requested, for all the sources in the system files.

Format
PROTECT.

Used for making sample files non deletable and protects them from overwriting. Once protected, a sample file can only be modified by prior use of the RELEASE command (a password-protected command) which removes the protected status. Files should therefore only be protected if it is essential to the user that they be preserved at the end of the job. Use of the command produces a listing of all sample names in abbreviated one line form, with their status indicated by the letter 'P' for 'protected' and 'U' for 'unprotected'. On no account must sample number 15 ever be released as this is a system file reserved for the updating procedures.

Format
PROTECT

24
19
Psamnms.

Produce a list of all the names, (in full), assigned to samples stored on disc. There are no arguments to this command.

QO.

Same as 'OMEGA' except that it is the value of q (=OMEGA/2) that is supplied by user. Must not be used prior to input of data into system files. Format is F10.6.

Format
QO
0.4

Ratio.

Given two data types as one compound argument, this command computes the ratios of their values and stores the results as a third data type supplied as a second argument. The third data type must be 48, 49 or 50 so as not to overwrite the system files. Useful for things like $\theta_1/\theta_2$. 
and also for map scaling factors such as arc.secs/kpc.

Format
RATIO
13 16
49
15 41
50

Notes: This computes the ratio DPERPI/DPARLL1 for all sources and places the results in data type #49, then computes (angular size)/(linear size) and leaves the results (arcsec/Kpc) in data type 50.

RELEASE

Releases a sample file from protected status and allows it to be rewritten. NO ATTEMPT to release sample number 15 should be made as this file is reserved for the updating system.
Selects a sample of sources from all those on file, which have the properties defined in the argument list. Up to 13 properties may be supplied as arguments, each of which is a relation between a data type and a constant value. E.g. in words, 'visual magnitude less than 18.5'; in input code, '05 L 18.5'. The allowed relationals are 'L' (less than), 'E' (equals), and 'G' (greater than). In the absence of any other information the program selects only those sources possessing all the supplied properties simultaneously; i.e. the logical intersection (AND) of them. For greater flexibility, the user is optionally allowed to define a logical relationship on the properties, that sources must obey to be included in the sample. E.g. in words, '((NOT property A OR property B) AND property D AND property E, OR property C)'; in input code, '(-A+B).D,E+C'; A, B, C etc. refer to the first, second, third .... properties defined in the argument list. (¬ is the logical 'NOT' symbol). The presence of such a logical relationship is signalled to the command interpreter by inserting the 'RELTN' keyword immediately before the line containing the logical expression and immediately after the 'SAMP' or 'SAMAMP' command.

Format

SAMP | selects all sources with measured redshift
<table>
<thead>
<tr>
<th>Source</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>04 G 0.0</td>
<td>AND with magnitude greater than 17.3</td>
</tr>
<tr>
<td>05 G 17.3</td>
<td></td>
</tr>
<tr>
<td>SAMP</td>
<td></td>
</tr>
<tr>
<td>RELTN</td>
<td>selects all sources more than A+B 10 degs. from galactic plane</td>
</tr>
<tr>
<td>19 G 10.0</td>
<td>(#19 = b)</td>
</tr>
<tr>
<td>19 L -10.0</td>
<td></td>
</tr>
</tbody>
</table>

This more complex example proceeds as follows: sources must have \(0 \lesssim k \lesssim 16\) (properties A and I); \(0.01 \lesssim z \lesssim 0.1\)
(properties B and C); \( P_{178} > 0.0 \) (property D), (i.e. \( P_{178} \) measured); sources must be double or triple radio types (* means any further qualifiers in the radio types are ignored), (properties E and F); must be Quasars or \( N \)-galaxies (properties G and H), and lastly must have been observed at 5GHz by the OMT or 5km telescope (properties J and K). Note the use of 'not-less-than' to provide the 'greater than or equal to' relation.

**SAMPALTR.**

Alters the given sample by the addition and/or deletion of the named or numbered sources in the argument list. Sources may be indicated by their 3C name (with RADARS modifications where necessary, i.e. '3C83.11') or by their system file number (e.g. '017') and are preceded by a '+' or '-' sign to indicate whether they are to be added to or deleted from the sample. The first argument is the number of the sample to be altered (#30 in the example). The old version of the sample stored on disc is then overwritten by the new version.

Format

SAMPALTR

30
Note: Addition of sources already present in the sample has no effect; deletion of absent sources produces a warning but no other action. A listing of the new sample is produced and it is refiled onto disc. Attempts to use sources unknown to the system (e.g. 3C475!) will generally produce a warning but should not cause an error.

SAMPNAME.

Used to give a name to a sample of sources (but not possible with the current sample). The first argument is the sample number, and (up to) the next three cards of text (80 characters per card) may be used to describe the sample. Note that if less than three cards are used the text must be terminated with the underline character, '_'. Sample names are printed on all output associated with particular samples (e.g. plots and histograms).
Format
SAMPNAME
24
THE 200-SAMPLE

SAMPSAMP.

Same as SAMP but selects only from the members of a given sample and not from the whole set of sources on file. Particularly useful when working inside a 'selected environment' such as the '3CR complete sample' (= sample number 24).

Format
SAMPSAMP.
24
RELTN etc.

SMPSRCRN.

For every source in the given sample(s), prints out a one page list of all the stored data. Effectively performs a 'SRCPRN' command for each source in the listed sample(s).
Format
SMPSRCPN
24
01

Note: the above example would produce over 500 pages of output so this command should only be used when absolutely necessary, and anyway with great care.

SORTDPRN.

For the given sample, this will sort into ascending order the stored data (and the absolute values of the stored data) for all the properties in the argument list. A separate list is produced for each property.

Format
SORTDPRN
24
01
40
41

Note: the first argument (in this case '24') is the
sample number, and all the rest are data types.

**SRCCNT.**

Performs a V/Vmax analysis (see e.g. Schmidt, M. 1968 (p53)) for the sample(s) given as an argument. Each sample has a second argument associated with it which is the optical magnitude limit to which the sample is thought to be complete. If this is not set, a value of 18.5 is used as a default. The output is in the form of a logN-logS plot. A maximum likelihood method value of beta(slope of source counts) is computed and a V/Vmax analysis is performed for both Euclidean and Einstein-de Sitter world models.

Format

**SRCCNT**

24 20.5
23 19.0

**SRCPEL.**

Produces a one page listing of all filed data for each source named in its argument list. Sources may be listed either by name (e.g. 3C61) or by system file number.
Format
SRCPRN
3C454.3
172
3C6.1

STOP.

Causes termination of job. This should always be included as last card of command stream, as 'end-of-file' may cause the preceding command to terminate prematurely, whilst it is checking for further arguments. STOP has no arguments.

STORSAMP.

This files the 'current-sample' as sample number given as argument.

Format
STORSAMP
34
Note: This command will not be executed if the file to be written-to is marked 'protected'.

TITLE.

Used for setting a title (up to 80 characters) which will be printed at the top of every fresh page of output to indicate its contents. If no argument is supplied (i.e. if the 'TITLE' command is followed immediately by another command) the title is set null, as it is at the start of every job. The character '/' must not appear in a title.

Format
TITLE
A DEMONSTRATION TITLE
PLOT etc.

Free Format Input

Free format does not here mean Fortran-like free format input. It is simply a way of compacting the input command language onto fewer cards, to reduce deck bulk, increase legibility and typing speed, and to aid duplication of similar commands. The rules are very simple: wherever in
the format examples given above for the commands, a new line was indicated, this may be replaced by a solidus, ('slash', '/'). An arbitrary number of blank spaces may occur anywhere before a slash, but no blank spaces must ever follow immediately after a slash, just as all command input in the above examples always started in column 1 of the input cards. e.g.

```
TITLE
200-SAMPLE PLOTS
PLOT
24
40 41 3
22 21 4
```

becomes,

```
TITLE/200-SAMPLE PLOTS/PLOT/24/40 41 3/22 21 4
```

**Note:** It is wise not to start punching a new command beyond column 70 as there may then be inadequate space to complete an argument. Although an argument may not be split across a card boundary, an argument-list may be.
6. Adding a Fortran Program

In order to give the user maximum flexibility, facilities are provided for interfacing user-supplied Fortran programs and subroutines with the rest of the system programs. Communication takes place through a special purpose subroutine called 'HERE' which is called by the system programs on receipt of the commands 'HERE' or 'PROGRAM/n', where 'n' ranges from 1 to 9. Use of the HERE command is not recommended as it has only been retained for compatibility with old job decks; 'PROGRAM' should always be used in preference.

Subroutine 'HERE' contains a number of declaration statements at the beginning which provide the user with useful internal facilities which are listed below. There then follow a few control statements that access the correct section of program, defined by the argument 'n' (a two digit integer in the range 01 to 09) of the PROGRAM command. This is made simple by dividing the last part of the subroutine into 9 sections, separated by CONTINUE statements with labels 100, 200, ..., 900. If the user's 4th section of program is placed between the statements labelled 400 and 500 then this will be accessed when the 'PROGRAM/04' command is received by the system. It is convenient to use statement
labels in the range 100n+1 to 100n+99 for the n'th section of the program to avoid confusion and illegal duplication.

Facilities built-in to subroutine 'HERE'

1. Useful constants: PI (=3.14159); H (=Hubble constant); C (=velocity of light);

2. Conversion constants: LYTOPC (=light years to parsecs); LYTOM (=light years to metres); MTOPC (=metres to parsecs); MTOLY (=metres to light years); YTOS (=years to seconds); PCTOLY (=parsecs to light years); PCTOM (=parsecs to metres);

3. Arrays: integer type - SAMP(400), holds the source numbers of the current sample in the first 'NSAMP' elements; NSAMP is also available through common; real type - A1(400), A2(400), ..., A6(400) are 6 400-element real arrays available as workspace inside the routine. Note however that these are mostly equivalenced into common-areas and the values may be overwritten by other RADARS programs.

ROW(20,50) is an array of correct size for reading one block from the row-filed DA file. After a read instruction it will contain all 50 properties for 20 sources. PLOT(3, 400) is a real array useful for submitting to 'XYPLOT', the system's plotting routine. Up to 400 points may be plotted on one diagram using this array. Users unfamiliar with this routine are referred to Appendix IF for a full description of the
plotting routine.

Note that the arrays A6(400) and SAMP(400) are equivalenced to each other and should not, therefore, be used simultaneously. This consideration also applies to the pairs A4(400), ROW(20,50); A1(400), COL(400); A3(400), row(20,50); a5(400), plot(3, 400).

**Facilities Available from Subroutine HERE**

These take the form of subprograms which may usefully be called either by statements within subroutine HERE or by statements in user supplied programs, themselves called from HERE. Because of the overlay structure inherent to the system programs, not all subroutines in the library may be called via HERE, though all those likely to be useful are overlaid in such a manner that an invalid exclusive call will not be generated.

A list of the most useful routines, with a brief discussion of their function and arguments, is given in Appendix IG. Users are referred to the supervisor manual for a more thorough and complete discussion of the system routines. Appendix IF describes the graphic output
routines, 'XYPLOT' and 'HIST'.

An example will clarify the use of the Fortran interface facilities.

Example

Suppose we wish to draw a map of the sky, in galactic co-ordinates, plotting the sources in the 3CR complete sample and marking each point with a measure of the position angle of the source on the sky. This would be useful if one wished to re-investigate the phenomena reported by Willson 1972 ([56]) wherein sources adjacent on the sky appeared to have a tendency for their position angles to be aligned.

The program might be written as follows: comment cards have been freely inserted in the example to explain the various operations.

SUBROUTINE HERE

100 CONTINUE

C READ IN POSN. ANGLES, AND GALAC. COORDS
CALL PROPRD(A1, 9)
CALL PROPRD(A2, 18)
CALL PROPRD(A3, 19)
C READ SAMPLE NO. 24
CALL SAMPRD(NINSAM, SAMP, 24)
C NINSAM IS THE NUMBER IN THE SAMPLE
C FAC CONVERTS DEGS. TO RADS.
   FAC=PI/180.
   K=0
   DO 110 I=1, NINSAM
C MAKE J THE SOURCE NUMBER
   J=SAMP(I)
C CHECK FOR ZERO INFORMATION
   IF(A1(J),EQ.0.0) GO TO 110
C INCREMENT TOTAL OF SOURCES TO BE PLOTTED
   K=K+1
C COMPUTE A SUITABLE SET OF X, Y COORDS
C FIRST THE X-COORD PLOT(1, -)
   PLOT(1, K)=90.0-(90.0-A3(J))*SIN(A2(J)*FAC)
C NOW THE Y-COORD PLOT(2, -)
   PLOT(2, K)=90.0+(90.0-A3(J))*COS(A2(J)*FAC)
C SET THE PLOTTING CHARACTERS TO CHANGE EVERY 18 DEGS
C IN P.A.: PLOT(3, -) MUST BE IN RANGE 1 TO 10
   PLOT(3, K)=INT(ABS(A1(J))/18.0)+1
110   CONTINUE
C PLOT THE 'K' DERIVED VALUES NOW IN ARRAY 'PLOT'
C WITH LINEAR SCALES (OPTION 1) AND USING THE SECOND
C CHARACTER-SET (DIGITS 1, 2, ..., 9, 0)
CALL XPLG(PLG, K, 1, 20)
RETURN
200 CONTINUE

END

The output of the program is shown in Fig.6.1 where it
can be seen that a polar plot has been produced, viewed from
above the Galactic N-pole. The band between ±10 degrees
galactic latitude is empty because we chose the complete
sample. The outer perimeter of the extent of the sources is
approximately bounded by the line declination ±10 degrees.
The commands (in the command stream) would be very simple:
PROGRAM/01

Note that we could have loaded sample number 24 by use
of the 'LOADSAMP/24' command in the command stream, prior to
the program command, and this would have avoided using
subroutine 'SAMPRED' inside the program. We should then have
used the variable 'NSAMP' to denote the number of objects in
the sample as that is the value passed to the subroutine
through COMMON. In particular, had we wished to repeat the
plot for several different samples, this latter method would
have been a much simpler way of organising the task.

The job deck required to run an interfaced Fortran program is different from the usual deck in several ways. Firstly a compilation step is necessary, and so is a sub-deck holding subroutine HERE. The Linkage Editor must also be invoked to couple the compiled program into the rest of the RADARS loadmodule. Finally, it may also contain separate data streams from those in use by RADARS proper. The following streams are already in use by the program and must not be used in the user's subprograms. 1, 2, 3, 8, 9.

**Note** however that stream 5 is the command stream, and data may be read in from that stream if it is carefully organised so as not to interrupt the flow of commands after a 'PROGRAM' command (i.e. when the supplied program returns control to the command system, stream 5 should be 'pointing' to the next command and not some stray data). Stream 7 is coupled to the card output punch whilst stream 6 is as usual used for line printer output.

**APPENDIX IA**

<table>
<thead>
<tr>
<th>CODE</th>
<th>NAME</th>
<th>DESCRIPTION and (UNITS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>OPT.TYPE</td>
<td>Optical morphological type (alpha coded)</td>
</tr>
<tr>
<td>02</td>
<td>U-B</td>
<td>U-B Colour (magnitudes)</td>
</tr>
<tr>
<td>03</td>
<td>B-V</td>
<td>B-V Colour (magnitudes)</td>
</tr>
</tbody>
</table>
04 Z Redshift (dimensionless)
05 M(V) Apparent magnitude (magnitudes)
06 OPT.SIZE Optical object angular size (arc sec) (largest angular size down to limiting isophote of observations)
07 CLSTRCH Cluster richness (see notes)
08 RAD.TYPE Morphological radio structural type (alpha coded)
09 RAD.PA Radio position angle (degs. measured E from N)

Note that in the following, references to components 1 and 2 are only applicable to sources with well-defined double outer structure. Component 1 is always the preceding component.

10 L(D1:D2) Log. of ratio of CMPSEP1 to CMPSEP2 (dimensionless)
11 CMPSEP1 Angular separation of component 1 from opt. object (arc sec)
12 CMPSEP2 Angular separation of component 2 from opt. object (arc sec)
13 DPERP1 Size of component 1 perpendicular to source axis (arc sec)
14 DPERP2 Size of component 2 perpendicular to source axis (arc sec)
15 RAD.SIZE Largest angular size of radio structure (arc sec)
16 DPARLL1 Size of comp. 1 // to source axis (arc sec)
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>DPARLL2 Size of comp. 2 // to source axis (arc sec)</td>
</tr>
<tr>
<td>18</td>
<td>GAL.LII Galactic longitude (degree)</td>
</tr>
<tr>
<td>19</td>
<td>GAL.BII Galactic latitude (degree)</td>
</tr>
<tr>
<td>20</td>
<td>S178 Flux density at 178MHz (flux unit)</td>
</tr>
<tr>
<td>21</td>
<td>HF.SPECI High frequency spectral index, 750 to 5000MHz (S=k0^x)</td>
</tr>
<tr>
<td>22</td>
<td>LF.SPECI Low frequency spectral index, 38 to 750 MHz (S=k0^{-x})</td>
</tr>
<tr>
<td>23</td>
<td>DECLNATN Declination (degree)</td>
</tr>
<tr>
<td>24</td>
<td>P-5CENT Luminosity of central component at 5GHz (W Hz^{-1}sr^{-1})</td>
</tr>
<tr>
<td>25</td>
<td>SRC.NAME Source name (numerical part of 3CR name)</td>
</tr>
<tr>
<td>26</td>
<td>BINARY1 Binary valued data (binary coded)</td>
</tr>
<tr>
<td>27</td>
<td>BINARY2 Binary valued data (binary coded)</td>
</tr>
<tr>
<td>28</td>
<td>S5GCMP1 5GHz flux of compact part of comp. 1 (flux unit)</td>
</tr>
<tr>
<td>29</td>
<td>S5GCMP2 5GHz flux of compact part of comp. 2 (flux unit)</td>
</tr>
<tr>
<td>30</td>
<td>ALPHCMP1 High frequency spectral index of comp. 1 (dimensionless)</td>
</tr>
<tr>
<td>31</td>
<td>ALPHCMP2 High frequency spectral index of comp. 2 (dimensionless)</td>
</tr>
<tr>
<td>32</td>
<td>S14CMP1 1400MHz flux of comp. 1 (flux unit)</td>
</tr>
<tr>
<td>33</td>
<td>S14CMP2 1400MHz flux of comp. 2 (flux unit)</td>
</tr>
<tr>
<td>34</td>
<td>S14CENT 1400MHz flux of central component (flux unit)</td>
</tr>
</tbody>
</table>
35 S5GCENT 5GHz flux of central component (flux unit)
36 S5GC1EXT 5GHz flux of extended part of comp. 1 (flux unit)
37 S408 408MHz flux of whole source (computed from S178 and LF·SPECI)
38 ABS,M(V) Absolute optical magnitude (magnitudes)
39 S5GC2EXT 5GHz flux of extended part of comp. 2 (flux unit)
40 P-178MHZ Luminosity of whole source at 178 MHz (W Hz⁻¹sr⁻¹)
41 RADLNSIZ Largest linear size of radio structure (kpc)
42 S51TOT S5GCMP1+S5GC1EXT (flux unit)
43 S52TOT S5GCMP2+S5GC2EXT (flux unit)
44 L(S1:S2) Logarithm of S51TOT/S52TOT (or S14CMP1/S14CMP2 if former are not available) (dimensionless)
45 LINRESLN Minimum kpc/beamwidth for best synthesis observations of this source (kpc)
46 R.A. Right Ascension (degrees)
47 ALPHCENT Central component HF spectral index (dimensionless)
48 DUMMY1 Spare
49 DUMMY2 Spare
50 DUMMY3 Spare
Notes:

i) The following data types are either necessarily derived from others, or in the case of redshift, type #04, may be estimated from another in the absence of a direct measurement.

04, 24, 37, 38, 40, 41, 45.

ii) The definition of the optical and radio type-codes for types 01 and 08 are given in Appendices IC and IB respectively.

iii) Where a measured value of redshift is not available, a value has generally been estimated from the visual magnitude of the associated object, assuming for galaxies, an absolute V magnitude of -23.2 (416).

iv) Where a source is unidentified, a lower limit to the magnitude has often been estimated by inspection of the available observational data, including allowance for Galactic obscuration.

v) Cluster richness is measured using an extended Abell classification. Where a scan of the literature indicates that an object has not been assigned an Abell
richness class (in the range 0 to 5) by an observer, it is given a richness class -2 if there is no evidence for it lying in a group or cluster, and a richness class -1 if it lies in some form of group or cluster.

vi) All position angles are measured positive E from N in the range $0 < \text{p.a.} < 180^\circ$.

vii) $L(D1:D2)$, type #10, is defined in such a way that when plotted in absolute value (i.e. normally) ratios of e.g. 1/3 and 3/1 plot on the same line (with scale value 0.4771) regardless of their sense. When comparisons with other ratios such as $L(S1:S2)$ (=type #44) are to be made, use of 'NEG PLOT' will separate them for comparison of 'absolute' ratio. These considerations also apply to $L(S1:S2)$.

viii) $\text{RAD.SIZE}$, type #15, is the separation between outer component peaks in well defined double and triple sources, but may be the largest angular size observed for less aligned and more complex structured sources (e.g. 3C264).

ix) $P50CENT$ is computed from the measured 5GHz flux density using either the measured central component spectral index ($\text{ALPHCENT}$) where available, or a typical value of 0.0
in other cases.
Appendix 1B

Radio-Type Coding Conventions

We list here only the definition of the abbreviations used. For a fuller description and examples, the reader is referred to Hooley 1976 (Ph.D. dissertation), Chapter 3, page 3.12.

First Character

C - Complex  S - Single
D - Double  T - Triple
E - Extended  U - Unresolved

Note that 'DQ' is a special type of double (asymmetrically disposed about the optical object). First characters are primary source classifications.

Second Character/Third Character

B - Bridge  H - Halo
C - Compact  M - Multiple
D - Double  P - Peculiar
E - Extended  S - Simple

These are secondary characteristics which generally refer to
the component sub-structure. Any doubtful classification may be truncated to two characters and preceded by '?' A very sparse description such as 'D' is indicative of little information available and generally implies that the information comes from a VLBI model fit. (slightly resolved doubles seen on synthesis maps are generally classified as DS).
Appendix IC

Optical-Type Coding Conventions

Where possible, the classifications have been taken from the literature and follow the normal conventions closely (e.g. E, D, N, QS). Where a source is identified as a galaxy but otherwise unclassified, it is here designated type 'G', and the following characters then give more details where possible.

Primary Types

D  D-galaxy (giant)
DB  Dumb-bell galaxy
E  Elliptical
G  Galaxy (unclassified)
IR  Irregular
N  N-galaxy
GS  Quasar
S  Spiral
T  Triplet of galaxies
U  Unidentified
Secondary Classifications additional to conventional designations
(2nd and 3rd characters)

B  Blue
C  (possesses) Companion(s)
CP Compact
D  Double
GG Group of galaxies, no one of which seems most likely associated with the radio source
R  Red
Y  Seyfert

Any doubtful identification is truncated to two characters and preceded by a '??'.

Appendix ID

Binary-Coded Data Types

RINARY = data type #26

01 Observed by OMT at 408MHz
02 Observed by OMT at 1407MHz
03 Observed by OMT at 2700MHz
04 Observed by OMT at 5000MHz
05 Observed by 5km at 5000MHz
06 Observed by 5km at 15000MHz
07 VLBI or lunar occultation measurements
08 Observed by 200" telescope or with 48" Schmidt using IIIaJ deep plates or an image tube
09
10
11
12
13
14 Radio variability
15 Optical variability
Compact central component

Bridge of emission linking whole source

3 compact components other than central component

4 compact components other than central component

5 compact components other than central component

Source axis bent (>5 degs.)

Major components 'both' have tails

Only one major component has a tail

One component compact, opposite component diffuse

Tails on components well aligned with centre line of source (<5 degs.)
## APPENDIX IF

<table>
<thead>
<tr>
<th>P2 COMMAND</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>* COMMAND</td>
<td>(Not yet available)</td>
</tr>
<tr>
<td>* COMNDNAM</td>
<td>(Not yet available)</td>
</tr>
<tr>
<td>* CONTINUE</td>
<td>Proceed to next phase of job</td>
</tr>
<tr>
<td>* COPYFILE</td>
<td>(Inoperative).</td>
</tr>
<tr>
<td>* DATA</td>
<td>Updates source files with following data cards</td>
</tr>
<tr>
<td>* DECK</td>
<td>Punches a deck of data cards for property types supplied</td>
</tr>
<tr>
<td>DEFSAMP</td>
<td>Creates current sample from source names &amp;/or numbers supplied (DEFINE SAMPLE)</td>
</tr>
<tr>
<td>DIFMEANS</td>
<td>(Not yet available) (DIFFERENCE OF MEANS)</td>
</tr>
<tr>
<td>DSOVERDL</td>
<td>Computes ratio of component size ($w_{m,s}$) to separation from optical object (D-Small OVER D-Large)</td>
</tr>
<tr>
<td>DUMMYNAM</td>
<td>Assigns to data type supplied, data type name supplied</td>
</tr>
<tr>
<td>* HERE</td>
<td>Calls supplied Fortran program (see PROGRAM command) (HERE is some Fortran!)</td>
</tr>
</tbody>
</table>
HIST  Plots histogram(s) for sample(s) supplied, for supplied data type(s) with options

(HISTogram)

HUBBLE Changes the system value of Hubble constant to the supplied value

(HUBBLE constant)

KPCSIZE Computes the size in Kpc of the supplied angular data-type

(KiloParseC SIZE)

LOADSAMP Makes the supplied sample the current sample

(LOAD SAMPLE into the current sample)

LUMINOS Computes the luminosity of the flux data-type supplied

(LUMINOSity)

MEANS (Not yet available)

MERGE Merges the two supplied samples to form a new current sample

NEGHIST Same as HIST but plot actual (not absolute) value of data

(NEGative data HISTogram)

NEG PLOT Same as PLOT but plot actual (not absolute) value of data

(NEGative x-y PLOT)

NEWSORCS Creates file space for the supplied new source(s)

(NEW SOURCeS for files)
NNEGHIST  (Not yet available)
NNEG PLOT  (Not yet available)

OMEGA  Changes the system value of the density parameter to supplied value
        (OMEGA = cosmological density parameter =200)

PASSWORD  i) Allocates appropriate status to user on basis of supplied password
        ii) If not first occurrence, changes password to supplied text if sufficient status

* PLOT  Produces an x-y plot for supplied sample(s),
        of supplied data types, with options

PLOTR  As for PLOT, but computes least squares regression fits to data
        (PLOT with Regression analysis)

PRNSAMP  Prints out members of supplied sample(s)
        (PRinT SAMPlE members)

PROGRAM  Runs the section of Fortran program (in subroutine HERE) as indicated by supplied section number

PROJECT  (Not yet available)

PROPRN  Prints the data on the supplied property(s) for all sources
        (PROPerty (P)RiNt-out)

PROTECT  Change the status of supplied sample(s) to 'protected'
PSAMPNMS: Prints out all the sample-names in full
(Print all SAMPLE Names)

QQ: Changes system value of deceleration parameter to supplied value
(QQ = cosmological deceleration parameter = \(Q_0 = \Omega_{\text{DE}}/2\))

RATIO: Computes values of ratios of two supplied data types, and stores in third supplied data type

* RELEASE: Changes status of supplied sample(s) to 'unprotected'

* REGENXXX: (Inoperative)

SAMP: Selects a sample with supplied properties
(SAMPLE selection)

SAMPALTR: Alters the supplied sample in way indicated by supplied sources &/or source numbers
(SAMPLE ALTER)

SAMPNAM: Renames the supplied sample(s) with supplied name(s)
(SAMPLE NAMES)

SAMPSAMP: Selects a sample from the supplied sample with the supplied properties
(SAMPLE from a SAMPLE)

SMPSRCPN: Prints out all the data for each of the sources in the supplied sample(s)
(SAMPLE Source Print)
SORTDPRN  For the supplied sample, sorts into order the supplied data type(s)
(SORTed Data PRINT-out)

SRCCNT  Performs a V/Vm analysis for the supplied sample(s)
(Source Counts)

SRCPRN  For the supplied source(s), prints out all stored data
(Source data PRINT-out)

STOP  Ceases reading commands and terminates

STORSAMP  Stores the current sample as supplied sample no.
(Store SAMPLE)

STUDSTEE  (Not yet available)

TITLE  Sets current title to supplied text (<81 characters)
Use of XYPLOT and HISI

XYPLOT(ARRAY, N, IOPT, MULTI): Produces a scatter diagram on the line printer, given up to 500 co-ordinate pairs as inputs. The size of the plot is 100 printer rows by 100 printer columns. The scale lengths are chosen automatically and a choice of log. or linear scales is available on both axes. Up to 10 different symbols (from 3 different sets) may be used to label the plotted points and least-squares regression analysis along 4 different simple functions is available as an option. ARRAY is a (3, N) array where 'N' is the number of points to be plotted. ARRAY(1, n) are the X-data, ARRAY(2, n) the Y-data and ARRAY(3, n) are given values 1.0, 2.0, 3.0, ..., 10.0 to choose which of the 10 different plotting symbols are to be used. IOPT is the scale option number and takes values 1, 2, 3, 4 or 5. These options are as follows:

1 linear scales
2 log X, linear Y
3 linear X, log Y
4 log scales
5 automatic choice of above (range of data >10**2.5 on an axis causes choice of log. scale on that axis unless zero or negative data are present)
'MULTI' is used to denote how many different plotting symbols are required, and also which character set to choose from. E.g. if up to 7 different symbols are wanted, MULTI=7. However, to choose seven characters from the second character set, 10 is added to MULTI, and from the third set, 20 is added. The character sets are:

1. *, X, Y, B, C, O, D, H, J, K
2. 1, 2, 3, 4, 5, 6, 7, 8, 9, 0
3. A, B, C, D, E, F, G, H, I, J

The graticule of the plot is normally printed with vertical and horizontal lines every ten points. However, when only a few points are to be plotted, or when it is important that none should be easily overlooked by being close to or embedded in the graticule lines, the graticule is optionally printable in dots by setting 'MULTI' = (minus desired value). Alternatively, only the outside edge of the graticule may be printed (this is the option used for all RADARS plots initiated from the command stream). This is done by setting DYM(B)(6)=' ' (=blank), where DYM(B) is an array in labelled common block /LAB2/. When called from within RADARS this option will over-ride any other chosen by the user unless DYM(B)(6) is first set to some other character than 'blank'. The size of the labelled common block is as follows:

COMMON /LAB2/ XLINE(101), DYM(B)(6)
No use may be made of the space reserved for XLINE in this block as this will interfere with the operation of the plotting program.

The axes of the plot may be labelled, each with an 8-character name. These names are passed over through labelled common block '/TITLES/XTITLE, YTITLE, ITITES', where 'XTITLE', 'YTITLE' are each REAL*8 holding the alphanumeric strings for the X and Y axes respectively. If the titles set are to be used by the plotting routine, then ITITES (INTEGER*4) must be set equal to unity to initiate the regression analysis, IOPT is set to the negative of the desired value. The four functions that the program attempts to fit to the supplied data are: \( y = ax + b; \) \( y = a \log x + b; \) \( y = ax^b; \) \( y = a x^x \). Correlation coefficients and their confidence limits are computed. The mean and standard deviation, and the geometric mean and deviation of the X and the Y data are also computed with this option.

**HIST(ARRAY, N, IOPT, NBOX):** Produces a histogram inside a 100 x 100 grid, with up to 100 bins and with up to 500 input data points. The scale lengths are chosen automatically and the scale options are the same as for XYPLOT, where IOPT is the scale option input. The input data are in the first N elements of 'ARRAY' which is a singly subscripted array of
any size greater than or equal to \( N \). 'N' however, must be positive and less than 501. The number of bins used for the plot is chosen by setting 'NBOX' appropriately; however, if NBOX is set negative then a statistically suitable choice is automatically made (NBOX~\( N \)). The internal graticule lines may be removed by the procedure described above for XYPLOT but the 'dots' option is not available. This routine also computes the mean and standard deviation as well as the geometric mean and deviation of the input data.
Appendix IC

Functions and Subroutines Available from System Libraries

Functions:

ABSMVG(Z, VISMV): given a redshift Z and a visual magnitude VISMV, returns the corresponding value of absolute magnitude 'ABSMVG', k-corrected for elliptical galaxies.

ABSMVG(Z, VISMV): ditto for quasars, without k-correction. Quasars have an optical spectral index of approximately unity which effectively compensates for the reddening due to the redshift.

FTAB(X, VALS, NVAL): evaluates an interpolated value of function 'FTAB' at abscissa 'X', where FTAB is defined by the NVAL samples passed over in array VALS(NVAL, 2), where the VALS(n, 1) are the X-values and the VALS(n, 2) are the FTAB-values. Linear interpolation is used.

ISNUMB(RN3CR): given a 3CR source number (RN3CR) as argument, returns the system-file number of the source. Returns value '400' for unknown sources.

PSALZ(S, ALPHA, Z): given a flux-density, 'S', a spectral
index, 'ALPHA' and a redshift 'Z', returns the corresponding value of luminosity, 'PSALZ' (in W Hz sr).

SAROAR(Z): given a redshift, returns the value of SinAr/A(Z), 'SAROAR', using the currently set system value of q0 or omega. Units are metres.

SFRAZ(THETA, Z): returns the linear size in kpc, 'SFRAZ' (Size From Angle and Z) corresponding to angular size 'THETA' in arc.sec at a redshift 'Z'. Uses SAROAR.

TEE(NU, LEVEL): given the number of degrees of freedom 'NU', returns the value of 't', 'TEE', for Student's t-test for the 5% confidence level if 'LEVEL =5', or the 1% confidence level if 'LEVEL=1'. No other values of LEVEL are allowed.

ZFRMVG(MV): given a value of visual magnitude, 'MV', returns an estimated redshift (approximately correct for elliptical galaxies).

Subroutines

DATCRD(NSORC, ITYP, VAL, REF): for source number NSORC,
punches out a standard format data card for data-type ITYP, with data value VAL and reference number REF (integer)

**HIST(ARRAY, NP, IOPT, NBOX):** see Appendix IF

**OPTDCO(DIGIN, CHARSO):** given an encoded alphanumerical value from system files DIGIN (real), returns decoded characters as the 3 elements of array CHARSO(3). (for data types 01 and 08 in particular)

**OPTYPC(CHARS, VAL):** given a three character argument in the form of the 3 elements of array CHARSO(3), returns an encoded value VAL (real) suitable for writing to the system files.

**SAMTIT(NSAM):** given a sample number NSAM, writes the name of the sample to unit 6 (normally to the printer) on the next 3 lines of output.

**TIMTIT:** when called, throws to the top of a new page on unit 6, prints the real time and date at top r.h. side of page, and the current title if one is set. Prints 2 lines in all; useful for page headings.

**UPDCOL:** when called, copies the data stored in the DAF filed by source, into the DAF filed by data type.
UPDROW: does the reverse of UPDCOL.

Additionally, a set of special routines exists to allow the user to read from and write to the system files without endangering them by program errors.

**For Reading and Writing Sample Files**

SAMPRD(NINSAM, SAMP, NOFSAM): for a given sample NOFSAM this routine reads into SAMP(400) (integer array) the system source numbers of the sample members and also returns the number of sources in the sample, NINSAM. The remaining (400-NINSAM) elements of SAMP are unset.

SAMPWR(NINSAM, SAMP, NOFSAM): writes to sample number NOFSAM the number in the sample, NINSAM, and the file numbers of the sample members contained in the first NINSAM elements of the integer array SAMP(400).

**For Reading and Writing Property Files**

PROPRD(A, N): reads into the real array A(400) the values of property number N, for all sources. The number of sources in the system is NDAIAC, a number held in common and read
from disc at the start of a job. NDATAC is not allowed to exceed 399 and at present (28/11/74) there are 329 sources on file. After a read operation (with PROPRD) the last (400-NDATAC) elements of A are undefined, though generally they will be found to be zero.

PROPWR(A, N): writes the data in A(400) into data type N, where 47<N<51.

**For Reading and Writing 'Source' files:**

For each source, there are stored 50 properties and to facilitate access of all the data for one or more sources, these data are stored in source order on a DA file. The block size is such that one must read data for 20 sources simultaneously, in an array (20, 50): i.e. 20 (sources) rows of 50 data types. To read the data for any one particular source, one must compute the block number in which the source's data are held, and then read the entire block, selecting the required row from the array as follows: e.g. we require data for source number 'n' ("n" is the system file number, and may be obtained from the 3CR number by means of function ISNUMB). Block number NBLOCK = (n-1)/20+1 (integer arithmetic). If we read from disc the NBLOCK'th block into ROW(20, 50), the data we require are contained in ROW(r, 1 to 50), where \( r = n-20 \times (\text{NBLOCK}-1) \).
SORCD(ROW, NBLOCK): reads the NBLOCK'TH block of the appropriate disc file into ROW(20, 50).

SORCWR(ROW, NBLOCK): writes the data contained in ROW(20, 50) into the NBLOCK'TH block of the DA file. Note that to avoid overwriting system-file data, NBLOCK must be greater than the block number holding the last of the NDATAC sources on file. A test is performed to check that this requirement is met and the write request is rejected if it is violated.
APPENDIX III

Scatter Diagrams, Correlation Coefficients, and Confidence Limits

When the 'R' option is used with the 'PLOT' command (i.e., 'PLOTR'), in addition to data plotting the system performs least-squares fitting to the data of four simple 2-parameter curves, viz: i) \( Y = aX + b \); ii) \( Y = a \log X + b \); iii) \( Y = aX^b \); iv) \( Y = aX \). We shall only consider case i) in detail. Cases ii), iii) and iv) are dealt with by first transforming the data into a frame where the curves have the form \( Y' = aX' + b \) and then performing the linear analysis.

We require the program to compute the form of the best-fit curve to our data and to also allow us to estimate the statistical significance of the fit. Thus, simply computing a correlation coefficient is insufficient as we are dealing with small samples and it is the properties of the entire population of radio sources that we are trying to deduce. The simple analysis outlined below (for further details, see e.g. "Statistics", Chapter 14, Spiegel, M.R. (1966)) derives confidence limits for the correlation coefficients of the population. We can then make statements such as: "We may be 95% (99%) confident that we would not
have measured a correlation coefficient for our sample data as large as \( 'r' \), unless the population correlation coefficient is at least as large as \( 's'. \)

We compute the equations of the least-square regression line of \( Y \) on \( X \) (always) where \( a \) and \( b \) are determined from the equations

\[
\sum y = a \sum x + b \sum x^2
\]

\[
\sum xy = a \sum x^2 + b \sum x^3
\] (1)

where the summations are performed over the \( N \) data samples \((x,y)\) to be fitted. Using the equations of the least-square regression line, we may compute the estimated value of \( Y \), \( \hat{Y}_{\text{est}} \), at any given value of \( X \). Having computed the mean value of \( Y \), \( \hat{Y} \), we may then compute the correlation coefficient \( 'r' \) by setting \( X \) to each of the \( x \)-data values and forming the following sum,

\[
R = \frac{\sum (Y_{\text{est}}^\wedge - \hat{Y})^2}{\sum (y^2)}
\]

whence \( r = \sqrt{R} \) (2)

We now regard the \( N \) pairs of values \((x,y)\) of the two
variables as a sample from all possible such pairs taken from a population assumed to be a bivariate normal distribution. We can think of 'r' as an estimate of the population correlation coefficient 's'. It can be shown that if \( s=0 \) the sampling distribution of \( r \) is symmetric and the statistic

\[
t = \frac{r \sqrt{N-2}}{\sqrt{1-r^2}}
\]  

has Student's distribution with \( N-2 \) degrees of freedom. This statistic can thus be used to determine confidence limits for the hypothesis, \('s=0'\). If \( s=s_0 \) (non-zero) a transformation due to Fisher produces the statistic

\[
z = 0.5 \log_e \left( \frac{1+r}{1-r} \right)
\]  

which is approximately normally distributed with mean and standard deviation given by

\[
\bar{z} = 0.5 \log_e \left( \frac{1+s_0}{1-s_0} \right)
\]

\[
\sigma_z = \frac{1}{\sqrt{N-3}}
\]

and we can use these parameters to compute confidence limits for the hypothesis \( s=s_0 \).
The program takes the following action; a) Using equation (3) it calculates if the hypothesis $s=0$ is valid at the 95% confidence level. If this is so, it prints out a warning to this effect and returns control to the system. If the population correlation coefficient is significantly non-zero at the 95% level, it repeats the calculation at the 99% level and also uses equations (4), (5) and (6) to deduce the lowest value of $s_0$ for which the hypothesis $s=s_0$ is just true at the 95% and the 99% confidence levels. E.g. for the 95% confidence limit, we wish to find that value of $s_0$ such that

$$\frac{(z-Z)}{O_z} = 1.65$$  \hspace{1cm} (7)

(1.65 is the 95% abscissa of the standard normal curve). We then solve (4), (5), (6) and (7) for $s$ which is trivial since (4) and (6) are immediately expressable in terms of knowns, giving $\hat{s}_1$ from (7) whence (5) may be solved.

**Partial Correlation Coefficients**

Where our analyses of correlations involve several related variables (e.g. redshift, brightness, luminosity) it is sometimes useful to attempt to isolate the correlation between one pair of variables, unaffected by the others. In practice this is impossible because of severe observational restraints, but we can perform an approximate analysis to at
least partially isolate the desired correlation. The following is derived from Goodman, R. "Statistics", p.125 (664).

Consider three variates \( x_1, x_2, x_3 \) with regression equations

\[
x_1 = b_{12.3} x_2 + b_{13.2} x_3
\]
\[
x_2 = b_{23.1} x_3 + b_{21.3} x_1
\]
\[
x_3 = b_{31.2} x_1 + b_{32.1} x_2
\]

where the \( b \)'s have been determined by the method of Least Squares. Let \( x_3 \) be held constant. At this value of \( x_3 \), the two partial regression lines of \( x_1 \) on \( x_2 \) and of \( x_2 \) on \( x_1 \) will have regression coefficients \( b_{12.3} \) and \( b_{21.3} \). In line with one of the usual ways of defining the correlation coefficient (as the square root of the product of the regression coefficients of \( X \) on \( Y \) and of \( Y \) on \( X \)) we define the partial correlation coefficient, \( r_{12.3} \), of \( x_1 \) and \( x_2 \) to be given by

\[
r_{12.3}^2 = b_{12.3} b_{13.2} b_{21.3} \quad (8)
\]
It can then be shown that (for fixed \( x_3 \)),

\[
\rho_{12:5} = \frac{(\rho_{12} - \rho_{13})}{\sqrt{(1 - \rho_{23}^2)(1 - \rho_{13}^2)}}
\]

(9)

which gives the partial correlation coefficient of \( x_1 \) and \( x_2 \) in terms of the total correlations between the variates which are computed for any two by ignoring the effect of the third. In practice, the values of \( \rho_{12:3} \) and \( \rho_{21:3} \) (and thus the value of \( \rho_{12:3} \) from (8)) are rarely independent of \( x_3 \); whereupon the value of \( \rho_{12:3} \) from (9) is to be regarded as a rough average of the partial correlation coefficient over the varying values of \( x_3 \). This type of analysis is extendable to \( n \)-variates but we use it for no more than 3 at once.
APPENDIX II

HPP_User_Manual
This short document describes the operation and use of the Hooley Paginating Program (HPP). HPP accepts a string of characters as an input stream (normally on cards) and paginates and right-justifies this into pages of text, 60 characters to the line, and with optional single, double or triple line spacing. Page numbers and section numbers are also provided, and the starting numbers may be specified as input options. The default options are single line spacing, starting from page 1, with no section numbers.

HPP also provides certain special text-processing facilities which are initiated by typing 'special characters'. These special characters are normally interpreted as controls, and not printed, though they may be treated as part of the text if they are preceded by the correct special character. A description of their functions follows.

'>' throws a new page and increments the page number, which is printed on the top right hand side of the page. The section number is never incremented.

' #' is normally auto-punched on the input cards in column 63, due to the action of the program card that should be used when typing input (these program cards are available
from the author). It is used as a delimiter and causes the program to cease reading the card on which it appears, and to skip to the following card. However, when convenient it may be manually punched anywhere on an input card (except columns 1 and 2 which are not read, and not to be punched, due to the possibility of '//' appearing which will cause HASP to perform undesirable and unpredictable operations, and almost certainly to terminate the job), to terminate reading of that card.

'/' is a bulk erase character and all characters following it, until the next occurrence of '/*' are ignored. The '/*' characters are not printed. M.N. The use of '/*/*' or '/*-/*' to erase 2 or 3 characters is not permitted. At least 4 characters must be erased using this technique (see '0.8.2' for small erasures).

'/' causes the program to skip to a new line and begin printing in column 1 of the output page.

'$$' moves the printer into capital shift (only effective for alphabetic characters) for the next character only, though '$$$' will keep the printer in capital shift until the next occurrence of '$$'.

'/' denotes that the following text-string (terminated either by the second occurrence of '-' or by '/') is to be underlined. ('/' now works as a terminator)

'@' (for '£' read 'cent' throughout this document) throws
to a new line and then causes the following text string to be automatically centred on the page. This is useful for headings. The string is terminated by '/' and must be less than 55 characters in length. Centred text strings are assumed to be in '"$"' (double' capital) shift unless brought down by the appearance of a '"$' in the string. Occurrences of '"#' and '>}' inside the centred text-string are ignored.

'@' is a labour-saving feature. Its action is to print one period, one blank space and move into capital shift for the next character only. It is used at the end of sentences inside paragraphs instead of a period.

'!!' is a dummy-blank character. It is treated as any other non-blank character and type-set accordingly. However, on printing it is converted to a blank symbol, although it may of course be made to appear literally by punching '"<!!"'. Note however that '!!' does not function as a dummy-blank inside a centred piece of text, controlled by a '"#' character.

'<' causes the immediately following character to be printed literally, and not to be interpreted as a control.

'-' may be used at the beginning of paragraphs to indent. Its action is to print three blanks.

'%' is a feature that aids card punching. It causes the immediately preceding character on the input stream to be ignored unless that character is '"<". It is similar to the
'ERASE' feature on TITAN flexowriter input. However, only one character may be erased by the use of this character.

',,' is printed as ',,,' (i.e. comma followed by one space). However, if this control character is not wanted, the option stream may be used to turn it off in which case it will be printed literally (i.e. as a single comma only).

'+,' is another labour-saving feature and has the action of ',\---\---\$' where the number of slashes and the number of indents are optional (use the 'PARA' option card): default is one slash and one indent. This control is intended for paragraphing.

'|' denotes the end of input text and should appear at least once on the input stream. Anything following it will be ignored.

By typing the code produced by the key bearing the legend '0,8,2' unwanted spaces on the cards may be filled as this character is skipped altogether.

Notes:-

i) '++' and ',,' do not work as controls inside a centred piece of text.

ii) If the '||' is left out at the end of the input text, the input stream is terminated at either the first occurrence of '##' on the last card or at the end of the last card, whichever occurs first.

iii) A word-count is now produced at the end of the
output. What is actually counted is the number of blanks (not counting indents at the beginning of lines) in each line, before the justification routine inserts extra blanks.

iv) Page guillotine marks (period at each corner) are now printed, leaving approximately a half-inch right-margin and a one and a half inch left-margin (= A4 width).

v) The number of lines (including spacing lines) per page is now optional, but must be less than 56.

OPTIONS

The format for all options is as follows:-

NAME ****, where the option name begins in column 1 on option cards and **** represents a 4-digit integer (in I4 format), which for some options is irrelevant. The available options are:

i) 'SECT'=section number. Section number and page number are printed as a pair of I2 format integers at top R.H. corner of page, with the section and page numbers separated by a period. If the 'SECT' option is not used, no section numbers are printed, nor is the period. Page numbers are not allowed to be greater than 99 when the 'SECT' option is used.

ii) 'PAGE'=starting page number. The default value is
1. Page numbers are 4-digit integers (but see above) which are incremented on each output page-throw. If PAGE is set at 0000 and the SECT option not used, nothing at all is printed in the page number/section number location.

iiii) 'DOUB' and 'TRIP' are used to indicate double and triple line-spacing respectively. Default is single line spacing. Neither have integer arguments.

iv) 'LINE' is the number of lines /page desired. This must be less than 56; default is 49.

v) 'GOFF' (no integer argument) turns off the guillotine marks.

vi) 'COFF' (no integer argument) turns off the action of ',' as a control.

vii) 'POFF' (no integer argument) turns off the action of '+' as a control.

viii) 'PARA' has a normal 4-digit integer argument and is used to control the action of '+' as a paragraph-throw control character. The 3rd digit is the number of lines thrown/paragraph skip and the 4th digit the number of 3-space indents used on the next line. The first and second digits must be 0. Default is 'PARA=0011'.

Note that only the last option card of any one type is implemented so they may be stacked and shuffled just like HASP job parameter cards.

The text is read from input stream 5 ('SYSIN'), the options on stream 2 and the program uses stream 3 to obtain
its character sets.

The comma is used as a control character for the following reason. Spaces are frequently omitted after a comma, by mistake, because of the way one tends to break the text into chunks when initially punching it on cards. However, one might have punched many comma-space pairs correctly. For this reason it is advisable to use EDIT to globally exchange all comma-space pairs for single commas before running the deck. The EDIT command needed is 'G/ ,/ '.

EDIT may also be used to insert text in place of dummy strings to save repeated typing of the same phrases, e.g. 'The One Mile Telescope ', or 'W/Hz/sr', etc. This may be done quite simply and the EDIT cards needed are described below. Suppose 3 different strings were wanted, and also that the 2nd string was 'string'. Then on the text cards, one would punch '%2' wherever the string 'string' was required. The EDIT cards needed would be:-

G.%1,------etc.
G.%2,% string#%
G.%3,------etc.
0(L.% E.%2.% SL.% E.% SL.% E.%)

Note that in the above '.' was used as the edit-string delimiter, and that the '%2' was exchanged for the desired string 'string' preceeded by '% ' and followed by '#%'. This, together with the multiply repeatable command ensures
that no input lines become longer than 80 characters after the EDIT step. The 'EDITS TO DD name' can be made a temporary data set, then named on the '/GD.SYSIN DD' card. Note that the above set of edits can be combined with the comma editing and any other desired.

The program is filed as a set of pre-compiled load-modules residing in a library named 'RASP.TAH1.SUBLIB' and is now available for use.

This document was prepared with the Hooley Paginating Program, HPP.

Addenda. '&&' (upper case 'A') now prints as '↑'. 
Attention is drawn to the fact that the copyright of this thesis rests with its author.

This copy of the thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with its author and that no operation based on the thesis and no information derived from it may be published without the author's written consent.