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# PROPLYDS AROUND A B1 STAR - 42 ORIONIS IN NGC 1977

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## ABSTRACT

We present the discovery of seven new proplyds (i.e. sources surrounded by cometary H$\alpha$ emission characteristic of offset ionization fronts) in NGC 1977, located about 30' north of the Orion Nebula Cluster at a distance of $\sim 400$ pc. Each of these proplyds are situated at projected distances $0.04 - 0.27$ pc from the B1V star 42 Orionis ($c$ Ori), which is the main source of UV photons in the region. In all cases the ionization fronts of the proplyds are clearly pointing toward the common ionizing source, 42 Ori, and 6 of the 7 proplyds clearly show tails pointing away from it. These are the first proplyds to be found around a B star, with previously known examples instead being located around O stars, including those in the Orion Nebula Cluster around $\theta^1$ Ori C. The radii of the offset ionization fronts in our proplyds are between $\sim 200$ and 550 AU; two objects also contain clearly resolved central sources that we associate with disks of radii $50 - 70$ AU. The estimated strength of the FUV radiation field impinging on the proplyds is around $10 - 30$ times less than that incident on the classic proplyds in the Orion Nebula Cluster. We show that the observed proplyd sizes are however consistent with recent models for FUV photoevaporation in relatively weak FUV radiation fields.

*Keywords:* protoplanetary disks—circumstellar matter—stars: formation—HII regions—ISM: individual objects (NGC 1977)

## 1. INTRODUCTION

The star formation environment is likely to affect the evolution of protostellar and protoplanetary disks. Thermally driven winds, heated by ultraviolet radiation from massive stars, can shorten the lifetime of disks around neighboring low mass stars with potentially important implications for giant and icy planet formation. Observational support for disk destruction in strongly irradiated environments is provided by the reduction of disk fraction in the vicinity of O stars in clusters such as NGC 6611 (Guarcello et al. 2007, 2009, 2010), Pismis24 (Fang et al. 2012) NGC 2244 (Balog et al. 2007), the Arches Cluster (Stolte et al. 2010), and Cygnus OB2 (Guarcello et al. 2016), although other studies (e.g. Roccatagliata et al. (2011) in IC 1795 and Richert et al. (2015) in NGC 6611) have *not* found such a decline. Likewise Mann et al. (2014) (see also Mann & Willimas (2010)) have shown that the dust component of disks tends to be less massive in the immediate vicinity of the dominant O star in the Orion Nebula Cluster (ONC), $\theta^1$Ori C (though Mann et al. (2015) found no such trend in another cluster containing O stars, NGC 2024). Finally, it should be noted that although a decline of disk fraction in crowded areas could in principle be instead attributed to dynamical interactions (e.g. Pfalzner (2004); Protegies Zwart (2016)) it can be shown that for a normal IMF, photoevaporation becomes an important disk destruction mechanism at substantially lower densities than dynamical encounters (Scally & Clarke 2001).

However, the most dramatic evidence of disk destruction is provided by the large number of *proplyds*, cometary objects imaged in H$\alpha$ in the vicinity of $\theta^1$Ori C in the ONC (O'Dell et al. 1993; Bally et al. 2000)[1]. The sizes (few hundred AU) and morphologies of proplyds are well explained by a model in which FUV radiation from $\theta^1$Ori C drives a neutral disk wind; the bright cometary feature then results from the interaction of ionizing radiation (also from $\theta^1$Ori C) with this neutral wind (Johnstone et al. 1998). Radio free-free measurements of the ONC proplyds imply mass loss rates of $\sim 10^{-7} M_\odot$ yr$^{-1}$ (Churchwell et al.

[1] Note that the term was initially applied to any disk rendered visible by its proximity to an HII region but we here adopt the more restricted definition above which has become common usage.

1987), which would result in extremely short disk lifetimes. It is therefore unsurprising that objects experiencing such extreme photoevaporation are observed rather rarely, with relatively small samples being identified in Carina (Smith et al. 2003), Pismis 24 (Fang et al. 2012), NGC3603 (Brandner et al. 2000) and CygOB2 (Wright et al. 2012); in the latter two environments the 'giant' proplyds (on a scale of $10^4 - 10^5$ AU) are not necessarily derived from disk photoevaporation (Sahai et al. 2012a,b), though see also Guarcello et al. (2014) .

To date proplyds have only been detected around stars of spectral type O, where the high mass loss rates both measured and predicted imply that this should be a short-lived evolutionary stage. Investigating the formation potential of proplyds around O stars, Störzer & Hollenbach (1999) also argued that proplyds should only be detectable in the very close vicinity of such objects, where the FUV field exceeds $5 \times 10^4 G_0$ since their calculations implied that at lower $G_0$, neutral wind driving would be too weak to push the ionization front away from the disk, given the strong ionizing flux produced by O stars (here $G_0$ is the local FUV interstellar field ($1.6 \times 10^{-3}$erg cm$^{-2}s^{-1}$). As noted by Störzer & Hollenbach (1999), this lower limit on FUV field strength required for proplyd production is however sensitive to stellar spectral type since this controls the relative strength of the FUV and ionizing radiation fields.

More recent studies have emphasized that significant winds can be driven at considerably lower $G_0$ values (Adams et al. 2004; Facchini et al. 2016). The radius of a proplyd produced by interaction between this neutral wind and the B star's ionizing luminosity could then be used to *measure* the mass loss rates at lower $G_0$, a quantity that is of great importance in assessing the significance of photoevaporation in a wide range of star forming environments. Although the lower ionizing flux of the B star would produce structures of lower surface brightness than in the O star case, it would also imply spatially larger proplyds for a given wind rate, rendering them potentially more detectable than in the O star case. Moreover, the fact that lower wind mass loss rates are expected implies that such structures would be longer-lived than their counterparts around O stars and hence more abundant on those grounds.

Here we present seven proplyds discovered around 42 Ori ($c$ Ori, HD37018, B1V) in NGC 1977, an H II region located at $\sim 30'$ north of ONC at $\sim$414 pc distance (Menten et al. 2007). There is no O star in the region, but NGC 1977 contains three young B stars and at least $\sim$170 young stellar objects (Peterson & Megeath 2008). 42 Ori has the earliest spectral type, and is the major source for ionizing photons in NGC 1977. An irradiated disk near 42 Ori has been detected by Bally et al. (2012) in the *HST* image using H$\alpha$ filter (F658N). They identified a bent protostellar jet HH1064 from Parengo 2042 (the Spindle) in NGC 1977 with numerous bow shock features. They argue that the arc feature in the H$\alpha$ Spindle is centered on the star and its brightened side of the arc is facing toward 42 Ori, suggesting that it may be a proplyd. The seven proplyds that we describe here (Figure 1) were discovered in archival *Spitzer* and *HST* images; we will discuss the implication of finding *proplyds* around a B star and the wider implications for disk clearing in UV environments.

## 2. *Spitzer* & *HST* ARCHIVAL DATA

We used the *Spitzer* Space Telescope/IRAC (3.6, 4.5, 5.8, 8.0$\mu$m) archival data for the detection of a dusty proplyd, KCFF 1. All four IRAC bands show clear detection of the central source and its tail pointing radially away from the B1 star, 42 Ori (Figure 2). The mosaic images were obtained from the *Spitzer* Heritage Archive (SHA)[2]. The images were processed by the pipeline version S18.25.0, and the mosaic images were made using MOPEX version 18.5.4 and super mosaic pipeline version 2.0. The final mosaic image has resolution of $0''.6$. The median exposure times (seconds per pixel) of the images are 52 sec for long exposures and 2 sec for short exposures.

We used a set of archival data of *the Hubble Space Telescope* (HST)/the Advanced Camera for Surveys (ACS) to identify proplyds KCFF 2-7 (Figure 3). The data were obtained from the MAST archive. The *HST* ACS/WFC images was observed on November 12, 2010 and November 14, 2011 (PI: Bally, proposal ID 12250, cycle 18) using H$\alpha$ (F658N) filter with 2460 and 2510 second exposure times. The F658N narrow band filter transmits both H$\alpha$ and and [N II] lines. The observational details were discussed in Bally et al. (2012). The final mosaic images have pixel sizes of $0''.05$[3].

## 3. PROPLYDS AROUND 42 ORI

We present a total of 7 new proplyds in NGC 1977 in Table 1 (also see Figure 1). The KCFF source ID number ($1^{st}$ column) is used when we discuss individual sources here, and we also assign names for the proplyds based on their coordinates ($2^{nd}$ column of Table 1) similar to the designation given for proplyds in the ONC (O'Dell 1998). We use the last three digits in *right as-*

[2] http://sha.ipac.caltech.edu/applications/Spitzer/SHA/

[3] Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

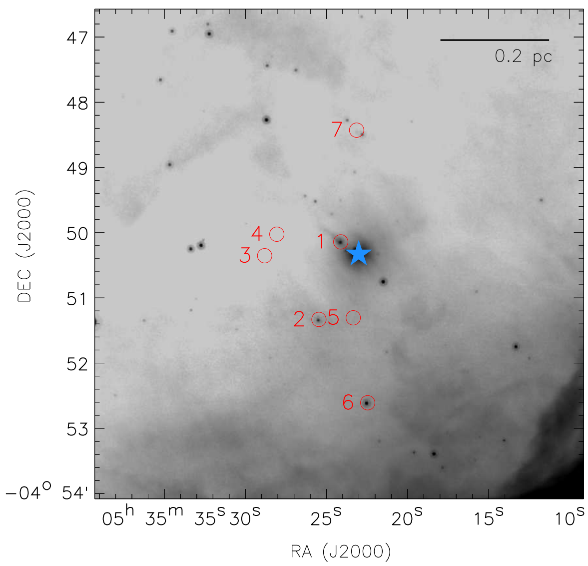


**Figure 1**. *Spitzer* 8$\mu$m image of NGC 1977 centered at 42 Ori (blue filled star at the center). Locations of proplyds are shown as open circles with labels. All 7 proplyds (KCFF 1-7) are within 0.3 *pc* distance from 42 Ori.

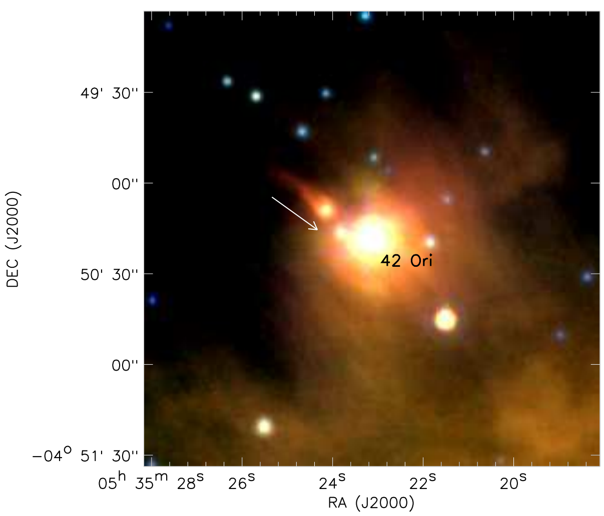


**Figure 2**. Proplyd KCFF 1 identified in the *Spitzer* images using 3.6$\mu$m(blue), 5.8$\mu$m (green), and 8.0$\mu$m (red). The white arrow shows the direction toward the ionizing source, 42 Ori.

*cension* (J2000) ($s.''ss$ after $5^h35^m20^s$) and the last five digits of *declination* (J2000) ($m$:$ss.''ss$) to assign names (Table 1, $2^{nd}$ column) for the coordinate-based names of the 7 proplyds. For example proplyd KCFF 1 with coordinates 5:35:24.142, -4:50:09.21 is named as *414-50092*.

The closest proplyd KCFF 1 (414-50092, Figure 2) is discovered in the *Spitzer* images at a distance of ∼7000 AU from the B1 star with its dusty tail evaporating away from 42 Ori. Sizes and distances from 42 Ori are calculated assuming that the distance to NGC 1977 is 400 *pc* (throughout the paper). This source is detected in all four IRAC bands and in MIPS 24$\mu$m, but not in the *HST* image, because the HST survey area did not cover KCFF-1. The central source is an M3.5-M4 star, and its dusty tail is about 20$''$ (∼8000 AU) long.

Six other proplyds (KCFF 2−7) are identified in the *HST* ACS/WFC image (Figure 3). Bally et al. (2012) presented Parengo 2042, the *Spindle*, residing in a large proplyd. However we do not discuss this source in this paper, since its tail is not clearly visible in the *HST* image alone. We measure the radius of the ionization front ($r_{IF}$) and disk radius ($r_d$) in a manner similar to section 3.2 in Vincente & Alves (2005), where they measure IF chord diameter. For the brightest proplyd, KCFF-2 (551-51201), we fit a circle to ∼30% higher than the background level, and for other fainter sources we fit a circle to ∼10% higher than the background using contour, radial profile, and cross section analyses. The measurement uncertainties in size estimation are about half a pixel to a pixel ($\sim 0.''025 - 0.''05$, ∼10-20 AU); this is introduced when we fit a circle to the 10% or 30% above the average background level, and also because of slight departure from a circular shape of the proplyd's ionization front (IF). The IF radius is estimated as the radius of the circle fitting the IF chord.

All proplyds are found within 0.3 pc distance from 42 Ori with their IF pointing toward 42 Ori and their tails pointing radially away from it (see Fig 2 & 3). KCFF 2 has a bright thick ionization front and a bright central source with $r_{IF} \sim 1.''35$ (540 AU) and a central source with radius$\sim 0.''35$(140 AU). We do not list this central source as a disk source, since the central source does not have clear disk morphology. KCFF 3 (881-50220) has $r_{IF} \sim 0.''4$ (160AU), but the central source is not detected while the ionizing front is very bright.

KCFF 4 & 5 have resolved central sources. The central source of KCFF 4 (808-50020) is an illuminated disk **or quasi spherical material** with $r_d \sim 0.''17$ (∼ 70AU), which is slightly asymmetric with the semi-major axis, located inside the proplyd with $r_{IF} \sim 0.''46$ (184 AU). The central source of KCFF 5 (338-51180) is smaller than KCFF-4 with $r_d \sim 0.''12$ ($48AU$) and $r_{IF} \sim 0.''49$ (196 AU). The size of $r_{IF}$ for these two sources are similar.[4].

KCFF 3, 4, and 5 are undetected in the *Spitzer*

[4] Note that KCFF 4 and KCFF 5 are unique among proplyds in that their disks are observed in H$\alpha$ *emission* as opposed to the dark (silhouette) disks seen in other regions. While this is readily explicable in terms of the fainter background in NGC 1977, it still leaves the open question of how ionizing photons are able to reach these disks.

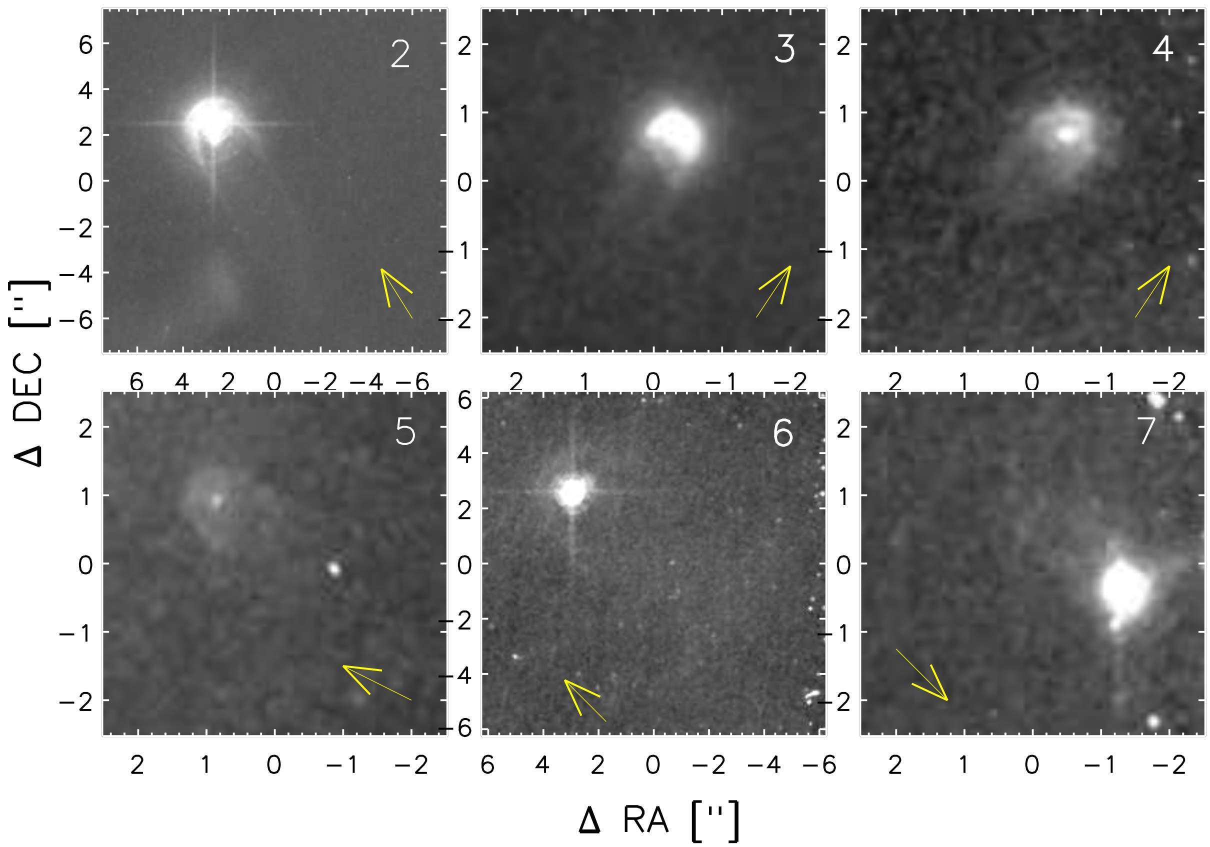


**Figure 3**. Proplyds KCFF 2, 3, 4, 5, 6, & 7 identified in the *HST*/ACS image (F658N). Yellow arrows indicate direction toward the B1 star, 42 Ori.

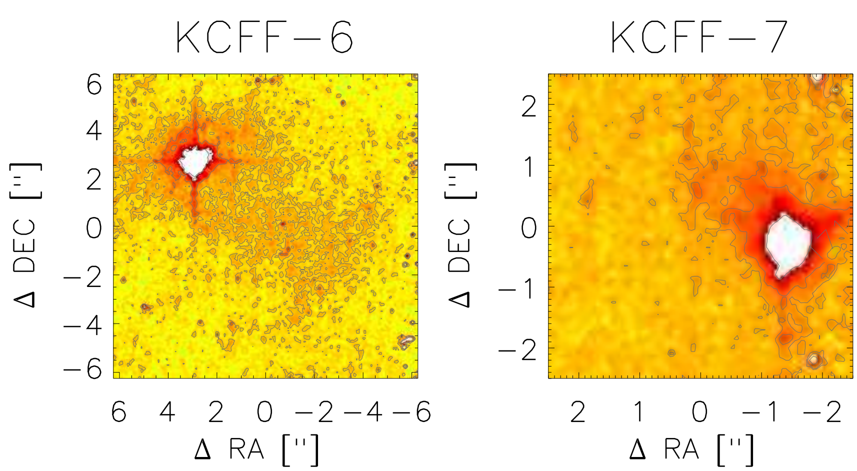


**Figure 4**. The *HST*/ACS images (F658N) of the proplyds KCFF 6, & 7. We show the two faint proplyds, KCFF 6 and 7, in color scale with contours in gray at 60%, 67%, and 90% of the maximum flux level.

photometry catalog from Megeath et al. (2012), which would suggest that these sources are very low mass objects. The *Spitzer* catalog can detect very low mass objects, down to brown dwarfs mass objects, because their *Spitzer* IRAC band 1 (3.6$\mu$m) data go as deep as $\sim$ 16 *mag* with 10$\sigma$ detection in Orion. The non-detection of these sources in the Spitzer IRAC band 1 would equate to an upper mass limit of around 15 Jupiter masses according to the evolutionary models of Baraffe et al. (2015). Partial obscuration of the central object by the disk would, however, imply that the mass was considerably greater than this. We incline towards this explanation on the grounds that the disk masses and consequent disk lifetimes against photoevaporation would otherwise be very short. Note that by invoking obscuration we are requiring some quasi-spherical distribution in the vicinity of the star, or an inclined edge-on disk, which may or may not impact our interpretation of the ~50 AU scale structures within KCFF 4 and 5 as being disks.

KCFF 6 (252-52365) has a bright central object with low surface brightness ionization front with $r_{IF}$ $\sim$ 292 AU. The ionization front size appears to be larger than other proplyds, except KCFF 2. The central source harbors an object with $T_{eff}$ of 3328 K (Da Rio et al. 2016). The ionization front is faint, but clearly shows a half-circular morphology as a proplyd, but we note that its tail is extremely faint (Figure 4) KCFF 7 (313-48277) has a similar $r_{IF}$ size and a faint tail. The central source has the highest $T_{eff}$ (3847 K) among the 7 proplyds in Table 1.

**Table 1**. Properties of proplyds in vicinity of 42 Ori.

| Source ID | Name | RA (J2000.0) | DEC (J2000.0) | T$_{eff}$ | distance to 42 Ori | | $r_{IF}$[d] | | $r_d$[d] | |
|---|---|---|---|---|---|---|---|---|---|---|
| KCFF# | | hh mm ss.sss | ° ′ ″ | (K) | (″) | ($pc$)[a] | (″) | ($AU$)[e] | (″) | ($AU$)[e] |
| 1 | 414-50092 | 5 35 24.142 | -4 50 09.21 | 3243[b] | 17.59 | 0.036 | ··· | ··· | ··· | ··· |
| 2 | 551-51201 | 5 35 25.505 | -4 51 20.11 | 3630[c] | 70.72 | 0.138 | 1.35 | 540 | ··· | ··· |
| 3 | 881-50220 | 5 35 28.812 | -4 50 22.04 | ··· | 84.65 | 0.166 | 0.40 | 160 | ··· | ··· |
| 4 | 808-50020 | 5 35 28.076 | -4 50 02.06 | ··· | 75.45 | 0.148 | 0.46 | 184 | 0.17 | 68 |
| 5 | 338-51180 | 5 35 23.381 | -4 51 18.06 | ··· | 59.42 | 0.116 | 0.49 | 196 | 0.12 | 48 |
| 6 | 252-52365 | 5 35 22.522 | -4 52 36.56 | 3328[b] | 138.14 | 0.268 | 0.73 | 292 | ··· | ··· |
| 7 | 313-48277 | 5 35 23.134 | -4 48 27.69 | 3847[c] | 111.05 | 0.215 | 0.56 | 224 | ··· | ··· |

[a] Projected distances from 42 Ori to proplyds. We use the distance of NGC 1977 to be 400pc in this work.

[b] Da Rio et al. (2016)

[c] Fang et al. 2016, in prep.

[d] Uncertainty of measuring sizes of ionization front and central disk size ranges about $0\farcs025 - 0\farcs05$.

[e] Calculations using $d \sim 400$ $pc$ to NGC 1977.

## 4. MODELING

In order to estimate the expected size of proplyds in this environment (specifically the distance between the center of the proplyd source and the offset ionization front) we need to i) estimate the ionizing flux from the neighboring B star, ii) estimate the expected mass loss rate in the neutral wind from the proplyd and iii) impose a condition of ionization balance in the ionized flow close to the ionization front. This approach can be applied whatever the mechanism driving the neutral wind (Clarke & Owen 2015). Here we follow Johnstone et al. (1998) in assuming that this is driven by the FUV flux from the same neighboring massive star which also provides the ionizing photon source. We however differ from Johnstone et al. (1998) in that we use new calculations of photoevaporative mass loss in regions of relatively low FUV fields (Facchini et al. 2016), noting that the observed proplyds in NGC 1977 are exposed to a FUV field that is less than that irradiating the well studied proplyds in the ONC.

All proplyds here (KCFF 1−7) have structures with tails pointing radially away from 42 Ori. It is thus reasonable to associate the ionization source with this star; indeed the relatively close proximity of these sources to what is the earliest type star in the region strengthens this expectation. We estimate the stellar mass from the B1V spectral type as around $10 M_\odot$ (e.g., Lorenz et al. (2005); Lorenzo et al. (2016)) and obtain ionizing photon outputs and FUV luminosities of $10^{45}$ $\mathrm{s}^{-1}$ and $2 \times 10^{37}$ erg $\mathrm{s}^{-1}$ from Diaz-Miller et al. (1998) and Armitage et al. (2000) respectively. We can then obtain a maximum FUV flux of $\sim 3000\ G_0$ in the vicinity of the proplyds. This maximum is obtained by neglecting dust extinction between the B star and the proplyd and by setting the distance between star and proplyd to be its separation on the sky $\sim 0.2 - 0.3$ pc. Störzer & Hollenbach (1999) showed that the creation of proplyds around O stars requires a minimum FUV flux of $5 \times 10^4\ G_0$. We here re-examine this issue using the lower ionizing fluxes of B stars and more recent models of neutral winds from protoplanetary disks in mild FUV environments by Facchini et al. (2016) (see also the pilot solutions of Adams et al. (2004)). The mass loss rate in this regime is a sensitive function of the disk outer radius and also depends somewhat on the effect of grain growth in modifying the FUV opacity in the wind. As an example, we take the cases of moderate grain growth (maximum grain size of $3.5\mu$m) and disk radii of 40 and 50 AU, for which the mass loss rates for an FUV field of 3000 $G_0$ are $10^{-9}$ and $10^{-8} M_\odot$ $\mathrm{yr}^{-1}$ respectively (see Figure 12 of Facchini et al. (2016)). Combining equations (6) and (10) of Johnstone et al. (1998) in order to remove their dependence on the explicit formula for FUV driven mass loss rate as a function of system parameters) we obtain $r_{IF} = 1200 AU \Phi_{45}^{-1/3} \dot{M}_{-8}^{2/3} d_{pc}^{2/3}$ where $\Phi_{45} = \Phi / 10^{45} s^{-1}$($\Phi$ being the stellar ionizing luminosity taking into account possible absorption by dust and the background nebula), $\dot{M}_{-8} = \dot{M} / 10^{-8} M_\odot \mathrm{yr}^{-1}$ and $d_{pc}$ is the distance to the ionizing source in parsecs. Adopting a distance between the proplyds and the B1 star of $\sim 0.2\ pc$ and the mass loss rates given above, we obtain $r_{IF}$=70 AU and 400 AU for disk radii of 40 and 50 AU respectively; $r_{IF}$ values that are higher by a factor of a few are obtained in the case of dust growth to mm sizes (see right hand panel of Figure 12, Facchini et al. (2016)).

We thus see that ionization fronts with offset distances on the observed scale ($\sim$ 200 AU) are to be expected given the distances of the proplyds from the B1 star in NGC 1977.[5]

## 5. CONCLUSION

We have presented 7 new proplyds around a B1 star, 42 Ori, in NGC 1977, about 30′ north of the Orion Nebula (M42). This is, to our knowledge, the first time that proplyds (i.e. imaged structures showing clear evidence of external photoevaporation) have been detected in the neighborhood of stars of later spectral type than O type. This discovery therefore opens up the possibility of testing theories of FUV photoevaporation in much weaker FUV background fields than has been possible hitherto (the estimated FUV background at the location of these new proplyds is $\sim 3000\ G_0$, more than an order of magnitude less than the estimated fields in the vicinity of the classical proplyds in the ONC).

Two proplyds (KCFF 3 & 4) contain bright interior structure on a scale of $\sim 50 - 70$ AU. We have used the recent models of Facchini et al. (2016) to estimate the mass loss rate from such disks in radiation fields of $\sim 3000\ G_0$ and find values in the range $10^{-9} - 10^{-8}\ M_\odot \mathrm{yr}^{-1}$. Such rates are comparable with typical accretion rates in T Tauri stars, and therefore suggest that external photoevaporation will be a major player in the evolution of such disks. We have already noted that the (lack of) *Spitzer* detection in KCFF 4 and KCFF 5 might imply very low mass central objects in these cases; if so, the low expected mass of associated disks would in turn imply very short disk depletion timescales. Alternatively these masses may be substantially under-estimated if the source is partially obscured by an edge-on disk or quasi-spherical material.

Given estimates for the ionizing flux from 42 Ori that is incident on the proplyds, we use these mass loss estimates to predict the expected radii for offset ionization fronts in these objects and obtain values of order 100 AU (the predicted mass loss rates and the resulting proplyd radii are a sensitive function of disk radii, which can be estimated only in a few cases). These predicted proplyd sizes are in excellent agreement with the scales of structures seen in the proplyds of 42 Ori.

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[5] Note that an ionization front with such an offset is expected from *any* mechanism that drives a neutral wind of this magnitude; such a structure could also thus be explained by wind produced by internal X-ray photoevaporation in the case of an X-ray luminosity $\sim 10^{30}$ erg $\mathrm{s}^{-1}$ (Clarke & Owen 2015); such an explanation is however unnecessary given that externally driven FUV photoe-

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vaporation can produce such a mass loss rate.