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The Dusty Accretion of Polluted White Dwarfs

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Abstract. Infrared observations of polluted white dwarfs provide key insights into the accretion processes in action. The standard model for the observed infrared excesses is a flat, opaque, dust disc. The infrared observations are inconsistent with the presence of such a disc around all polluted white dwarfs. We discuss potential explanations for the absence of an infrared excess for many polluted white dwarfs.

1. Introduction

Infrared emission around white dwarfs has been associated with accretion of dusty planetary material. The standard model most commonly used in the literature (Farihi 2016) suggests that the infrared emission results from dusty material in a flat, opaque disc, similar to Saturn's rings (Jura 2003). This model provides a good fit to the observations *e.g.* Xu & Jura (2012); Jura (2003), however, Farihi et al. (2009) note that the observations are, in general, consistent with a single temperature black-body, and some authors have modelled the emission as optically thin rings or halos (Reach et al. 2005, 2009).

Pollution from elements heavier than helium, whose presence can only be explained by the accretion of external material, are observed for at least 30% of white dwarfs (Zuckerman et al. 2003, 2010; Koester et al. 2014). There is good evidence to suggest that the observed metals originate in an outer planetary system orbiting the white dwarf (Farihi et al. 2010; Debes & Sigurdsson 2002). Asteroids (or comets) scattered onto star-grazing orbits are thought to be tidally disrupted and accreted onto the white dwarf (Jura 2008; Debes & Sigurdsson 2002). The presence of dusty material, alongside gas in a handful of systems, close to the white dwarf provides evidence of the accretion in progress (Gänsicke et al. 2006, 2007, 2008; Melis et al. 2010). Transits obscuring the polluted white dwarf, WD 1145+017, provide further key evidence that the pollution originates from the accretion of disrupted planetesimals (Vanderburg et al. 2015; Croll et al. 2015; Rappaport et al. 2016; Gänsicke et al. 2016).

The aim of this work is to use infrared observations of white dwarfs to investigate the link between emission in the infrared, linked to dusty material accreting onto the star and pollution.

2. Can All Polluted White Dwarfs Have an Opaque, Flat Dust Disc?

The standard model used in the literature to explain the infrared emission around polluted white dwarfs is a flat, opaque dust disc, situated interior to the Roche limit. We refer the reader to Jura (2003) for further details of this model. The emission from such an opaque dust disc is given by:

$$F_{\mathrm{thick},\lambda} = 12\pi^{1/3}\frac{\cos(i)\,R_*^2}{d^2}\left(\frac{2k_BT_{\mathrm{eff}}}{3h\nu}\right)^{8/3}\frac{hc}{\lambda^3}\int_{x_{\mathrm{min}}}^{x_{\mathrm{max}}}\frac{x^{5/3}}{e^x-1}dx$$

where T_{eff} is the stellar temperature, R_* is the stellar radius, d is the distance to the disc, i is the inclination of the disc and

$$x = \frac{hc}{\lambda k_B T_{\mathrm{disc}}},$$

T_{disc} is the disc temperature, which varies as :

$$T_{\mathrm{disc}} = \left(\frac{2}{3\pi}\right)^{1/4}\left(\frac{R}{R_*}\right)^{-3/4} T_{\mathrm{eff}}, \quad (1)$$

between

$$x_{\mathrm{min}} = \frac{hc}{\lambda k_B T_{\mathrm{out}}}$$

and

$$x_{\mathrm{max}} = \frac{hc}{\lambda k_B T_{\mathrm{in}}},$$

where T_{in} is the temperature at the inner edge of the disc and T_{out} is the temperature at the outer edge. We consider that the maximum plausible extent of the disc runs from, T_{in}, which is determined by the temperature at which grains sublimate rapidly, to an outer edge that lies at the Roche limit, whose temperature is

$$T_{\mathrm{out}} = \left(\frac{2}{3\pi}\right)^{1/4}\left(\frac{R_{\mathrm{roche}}}{R_*}\right)^{-3/4} T_{\mathrm{eff}},$$

where the Roche radius is given by:

$$R_{\mathrm{roche}} = C\left(\frac{M_*}{0.6M_\odot}\right)^{1/3}\left(\frac{\rho}{3\ \mathrm{g\ cm^{-3}}}\right)^{-1/3} R_\odot, \quad (2)$$

where ρ is the density of the planetesimal and C is a constant that varies between 0.85 and 1.89 (Veras et al. 2014). We use $C = 1$, and assume a planetesimal density of $\rho = 3$ g cm^{-3}.

Opaque, flat dust discs are bright in the near-infrared. Only those discs that are highly inclined to the line of sight escape detection.

We compile an unbiased sample of white dwarfs with infrared observations from *WISE* or *Spitzer*, collating data from Rocchetto et al. (2015); Mullally et al. (2007) and Debes et al. (2011). This sample is unbiased towards the detection of pollution. In

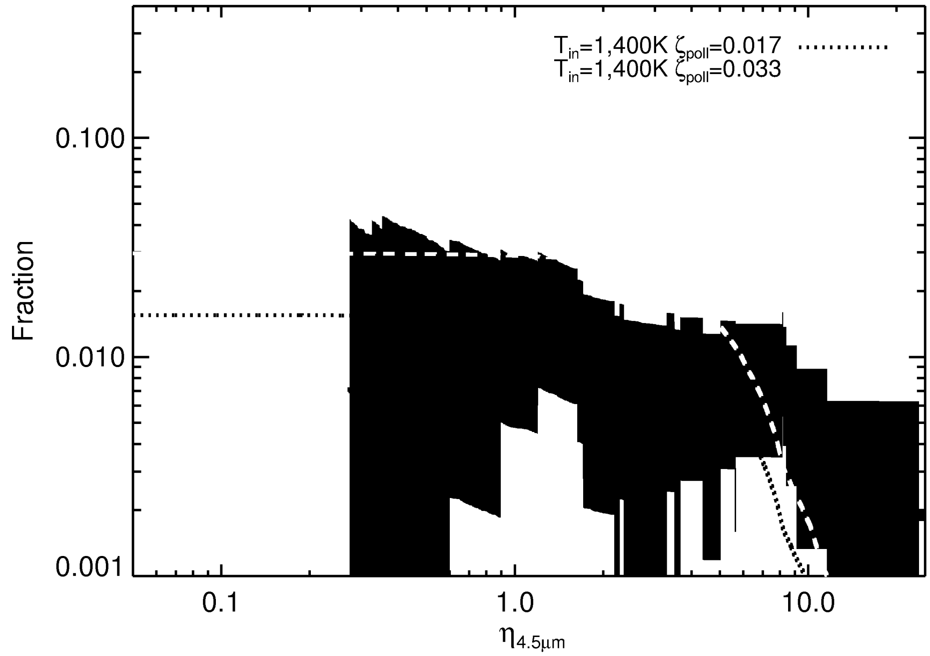

Figure 1. The cumulative distribution of infrared excesses at 4.5μm is shown by the thick black line, with black squares for the detected excesses, and errors indicated by the grey shaded region. This is compared to a model, purple dotted line (blue dashed line), in which all stars in the sample have an equal probability to have a flat, opaque dust disc, based on our fiducial model, but only 1.7% (3.3%) of the sample are polluted (have a dust disc). The cumulative distribution of infrared excesses is matched to the observed distribution at $\eta_{4.5\mu m}$ (or the upper error on the observed distribution).

Fig. 1, we plot the cumulative distribution of infrared excesses; that is the number of white dwarfs that have an infrared excess above a given level, divided by the number of white dwarfs where such an excess could have been detected. An infrared excess is defined as:

$$\eta_\lambda = \left(\frac{F_{\mathrm{dust},\lambda}}{F_{*,\lambda}}\right) = \frac{F_{\mathrm{obs},\lambda} - F_{*,\lambda}}{F_{*,\lambda}}. \tag{3}$$

This is compared to a model in which 1.7% (ζ_{poll}) of the sample have an opaque, flat dust disc that extends from $T_{\mathrm{in}} = 1,400$K to the Roche limit, shown by purple dotted line on Fig. 1. The observations are consistent with the presence of such a disc for a maximum of 3.3% of the observed sample (blue dashed line). This is in stark contrast to the typical rate of pollution of 30%. The only way to reconcile opaque, dust discs with the observations is to consider very narrow discs. Fig. 2 shows the cumulative distribution of infrared excesses if 30% of the sample have a narrow, opaque, flat disc with $T_{\mathrm{in}} = 1,400$K and $\delta r = 0.01R_{\mathrm{in}}$, a disc width of 1% the disc radius. This is consistent with the observed cumulative distribution of infrared excesses. However, it is difficult a higher proportion of stars than those with observed infrared excesses to have discs that are significantly wider. Any distribution of disc widths must be strongly peaked towards narrower discs, whilst including some wide discs to explain the detected infrared excesses. The orange dot-dashed line of Fig. 2 shows that the observed cumulative dis-

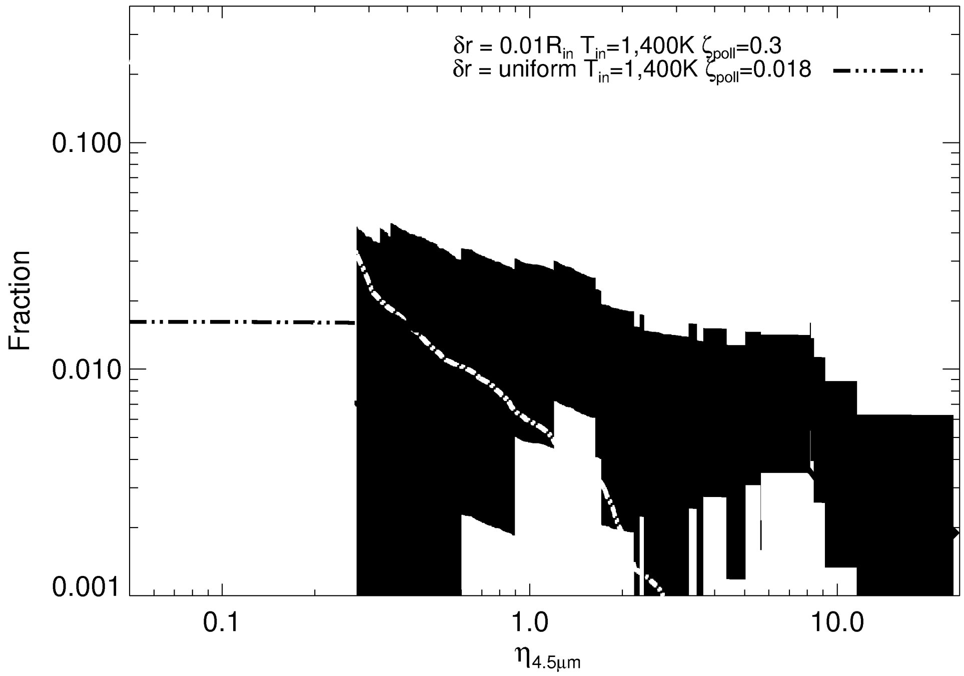

Figure 2. The cumulative distribution of infrared excesses at 4.5μm is shown by the thick black line, with black squares for the detected excesses, and errors indicated by the grey shaded region. This is compared to a model, green dot-dashed line (orange dot-double-dashed line), in which all stars in the sample have an equal probability to have a narrow flat, opaque dust disc, based on our fiducial model, but with a width $\delta r = 0.33 R_{\rm in}$ or a uniform distribution of disc widths from $\frac{\delta r}{R_{\rm in}} = 0.01$ to $\frac{\delta r}{R_{\rm in}} = (\frac{R_{\rm roche}}{R_{\rm in}} - 1)$. The former model cannot explain the largest observed infrared excesses, whilst the latter model only predicts a pollution rate of 1.8%, significantly less than the 30% observed.

tribution of infrared excesses is consistent with that from a model in which the discs have a uniform distribution of widths, if 1.8% of stars have a dust disc. Again, this is starkly in contrast to the expected fraction of 30% from the observed pollution.

3. What Supplies the Accretion when no Infrared Excess is Detected?

This leaves open the question of what supplies the accretion in those polluted white dwarfs where no infrared excess is detected. We have shown that the infrared observations are consistent with the presence of a narrow, opaque dust disc around 30% of the sample, if that belt is as narrow as 1% of the disc radius. Depending on the white dwarf's temperature and the total accretion rate, we present four further potential explanations. Fig. 3 indicates the parameter space in which each explanation provides the best solution, alongside the inferred accretion rates from Ca or Si for those white dwarfs in our sample where observations exist, assuming a composition of bulk Earth. We note here the large potential discrepancies in the accretion rates inferred from different species depending on the bulk composition of the accreting material.

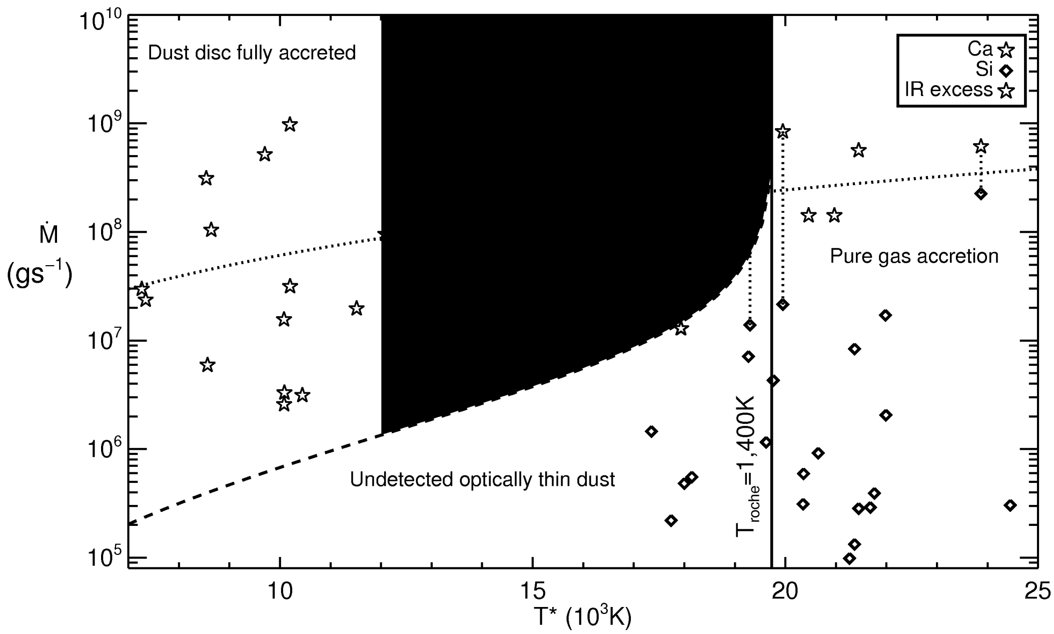

Figure 3. The inferred accretion rates, from Ca or Si, assuming a composition of bulk Earth, as a function of the stellar effective temperature for those polluted white dwarfs in the sample. The dashed line shows the accretion rate due to Poynting-Robertson of undetected optically thin ($\eta_{4.5\mu m} = 0.3$), which can be compared to the accretion rate for opaque, flat dust disc (dotted line). The absence of an infrared excess can be explained by pure gas accretion, as dust sublimates directly (brown), optically thin dust (blue), enhanced accretion of optically thin dust due to gas drag, or pure gas accretion (red) or short dust disc lifetimes compared to sinking timescales (green).

1. For those white dwarfs with long settling timescales and no infrared excess, an opaque, flat dust disc could have been fully accreted, whilst pollution remains detectable in the white dwarf's atmosphere. For those white dwarfs with sinking timescales longer than a year, this requires a disc lifetime of less than $\sim 10^4$yr, in order to explain the statistics of those polluted white dwarfs with and without infrared excesses.

2. For low to moderate accretion rates (up to $< 10^7$ g s^{-1}), sparse, optically thin dust, that escapes detection in the near-infrared, could supply the observed accretion via PR-drag alone. In order to sustain the accretion on decadal timescales or longer, this optically thin dust must be replenished. Variability in the metal abundances may be expected on similar timescales, modulated by the white dwarf sinking timescale.

3. For the hottest white dwarfs ($T_{\rm eff} > 20,000$ K), dust interior to the Roche limit directly heated by the stellar radiation, sublimates. For these hot white dwarfs, the absence of an infrared excess could be explained by pure gas accretion. Pure gas accretion may proceed on short timescales and, therefore, require a continuous supply of material to sustain the high incidence, and the lack of variability, of metals in hot white dwarfs.

4. The hardest to explain are warm polluted white dwarfs (12,000K < $T_{\rm eff}$ < 20,000K) without an infrared excess, but with high accretion rates (> 10^7g s^{-1}). The accretion must be enhanced, for example via gas drag on optically thin dust, or gas accretion.

Future observations that target larger unbiased samples of white dwarfs with *Spitzer* IRAC or MIRI on *JWST* and are sensitive to faint infrared excesses will constrain whether there is a sharp increase in the cumulative distribution of infrared excesses below $R_{4.5\mu m} < 1$ that would indicate the importance of either optically thin dust, or narrow, opaque dust discs. The detection of gas for white dwarfs without an infrared excess would provide strong constraints on the importance of gas accretion as opposed to dust accretion. Variability in metal abundances would point towards accretion processes with shorter lifetimes, for example optically thin dust or gas accretion.

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