The imprint of photoevaporation on edge-on discs

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ABSTRACT
We have performed hydrodynamic and radiative transfer calculations of a photoevaporating disc around a Herbig Ae/Be star to determine the evolution and observational impact of dust entrained in the wind. We find that the wind selectively entrains grains of different sizes at different radii resulting in a dust population that varies spatially and increases with height above the disc at radii > 10 au. This variable grain population results in a ‘wingnut’ morphology to the dust density distribution. We calculate images of this dust distribution at near-infrared wavelengths that also show a ‘wingnut’ morphology at all wavelengths considered. We have also considered the contribution that crystalline dust grains will have in the wind and show that photoevaporative wind can result in a significant crystallinity fraction at all radii, when the disc is edge-on. However, when the disc’s photosphere is unobscured, the photoevaporative wind makes no contribution to the observable crystallinity fraction in the disc. Finally, we conclude that the analysis of extended emission around edge-on discs could provide a new and independent method of testing photoevaporation models.

Key words: accretion, accretion discs – protoplanetary discs – circumstellar matter – stars: pre-main-sequence.

1 INTRODUCTION
Protoplanetary discs are ubiquitous around young stars, an inevitable consequence of angular momentum conservation during star formation. Young stars accrete their mass through discs which then provide the reservoir of material from which planets may form. Any understanding of the processes involved in star and planet formation requires knowledge of how discs evolve and finally dispersed. Observations of disc evolution have typically focused on thermal emission from the dust grains in the disc through the analysis of their continuum spectral energy distribution (SED) at several different wavelengths. While empirical analysis and numerical modelling of the SED of discs around young stars have proved extremely useful to study this important phase of the star and planet formation process, a number of well-known degeneracies conspire to render the interpretation of the data non-unique. To remedy these shortcomings, recent observational efforts are making use of various techniques to obtain spatially resolved information of many sources.

Herbig Ae/Be stars are more luminous than their lower mass T-Tauri counterparts and provide an opportunity to observe large-scale morphology in resolved images. Discs observed at nearly edge-on inclinations are particularly useful in studying the large-scale structure since the star and inner disc, which are much brighter than any extended emission, are obscured along the line of sight. Several edge-on discs around young stars exhibit extended emission above and below their mid-plane at near-infrared (NIR) wavelengths (e.g. Padgett et al. 1999 and Perrin et al. 2006) and some have been further imaged through AO systems providing excellent spatial resolution, as in the case of PDS 144N (Perrin et al. 2006).

Photoevaporation (Hollenbach et al. 1994) is the mechanism by which high-energy photons (ultraviolet (UV)–X-rays) heat the surface layers of the discs to temperatures of order the escape temperature, forming a thermally driven wind from the disc out to large radius. Photoevaporation has been proposed as the dominant disc dispersal mechanism around low-mass stars (e.g. Clarke et al. 2001) and has been successful in explaining much of the observational statistics (Owen et al. 2010b). However, there is only tentative evidence that the photoevaporative wind itself has been detected, through Ne II and O I emission (Hartigan, Edwards & Ghandour 1995; Alexander 2008; Pascucci & Sterzik 2009; Schisano, Ercolano & Güdel 2010; Ercolano & Owen 2010), which probes the wind on a very local scale. In order to test photoevaporation, along with various different heating mechanisms, we need global observational diagnostics to validate the models. Edge-on discs provide the perfect opportunity to detect a disc wind on a global scale through light scattered by the dust grains that will inevitably be entrained by the wind.

The origin of crystalline dust grains detected in protoplanetary discs via IR spectroscopy (e.g. Bouwman et al. 2001) and directly within our own Solar system (e.g. Wooden et al. 1999) is still a
matter of discussion. The source of all dust in star formation – the interstellar medium (ISM) – is inferred to be entirely amorphous (e.g. Kemper, Vriend & Tielens 2005). Spectroscopy of discs (Apan et al. 2005; van Boekel et al. 2005) indicates a non-negligible level of crystalline dust outside the crystalline radius, where grains are hot enough (T > 800 K) to be thermally annealed and converted into crystalline grains. This discovery has lead to the development of disc models with radial mixing to allow crystalline grains that formed in the hot inner disc to be transported to larger radii (e.g. Morfill & Voelk 1984; Gail 2001, 2002; Wehrstedt & Gail 2002; Bockele-Morvan et al. 2002; Dullemond, Apan & Walch 2006; Hughes & Armitage 2010). Another suggestion put forward by Shu, Shang & Lee (1996) is that crystalline grains could be carried outwards by an X-wind. Given that the crystallization radius of <1–2 au is smaller than the minimum launch radius for the photoevaporative wind >2 au around Herbig Ae/Be stars and lower mass stars, the wind cannot be the direct source of the crystalline grains at larger radii, but could work in combination with radial mixing to produce the observed enhancement. Furthermore, crystallinity around edge-on discs can be used to probe the source of the dust in the extended emission, since a disc origin will give rise to crystalline dust grains in the wind while an in-falling envelope will contain only amorphous grains.

In this article, we present a simple model to investigate the imprint of photoevaporation on the extended emission observed around edge-on Herbig Ae/Be stars. We will compare our model to the current observations of edge-on discs along with following the fate of crystalline grains in the wind as they are transported to large radius. In Section 2, we describe the model including the hydrodynamic and radiative transfer methods. In Section 3, we present synthetic images obtained from the models. In Section 4, we describe the results of crystallinity calculations for the wind. We compare our results to observations of edge-on discs in Section 5 and we summarize our main findings in Section 6.

2 MODEL

Considering the force balance on a dust grain, it is easy to show that small dust particles are entrained in the photoevaporative wind, which carries them out to large distances. Takeuchi et al. (2005) showed that the drag force on a grain is approximately:

\[ F_d \approx \frac{m_d \rho_d v_w^2}{\rho_i} \]

where \( m_d \), \( \rho_d \) and \( a \) are, respectively, the mass, the density and the radius of a dust grain (assumed to be spherical); and \( \rho_i \) and \( v_w \) are the density and velocity of the wind. At large radius, \( 1/2 < \rho \) the flow is approximately spherical implying \( \rho_i v_w \) falls off as \( 1/r^2 \).

Since gravity also falls off as \( 1/r^2 \) and \( v_w \) increases monotonically with radius, then if a grain is still entrained several scaleheights above the launching surface, it will be entrained permanently, allowing dust to be carried to very large distance from the star, since the drag force will dominate over gravity.

We build a simplified model to test the possibility of extended emission from dust grains due to photoevaporative wind, and we choose a set of assumptions that allows us to place an upper limit on this expected level of emission. Namely, we assume that the entire dust population is able to reach the launching surface of the wind via some turbulent mechanism and ignore the effects of settling and grain growth. Our simple model ignores the details of the bound regions of the disc\(^2\) and thus ignores any emission produced by this region, including only the wind itself and its contributions to emission. This simplification means our model will not be accurate near the mid-plane, where emission from dust in the disc’s upper atmosphere dominates over the wind emission. Therefore, we are unable to reproduce the observed intensities and optical depths seen at several scaleheight above and below the mid-plane in an edge-on disc; however, here we are interested in the extended emission, which in the absence of an infalling envelope is dominated by the photoevaporative wind.

Our model naturally produces a ‘wingnut’ morphology similar to that seen in several scattered light images (e.g. Perrin et al. 2006), and produces a spatially variable dust distribution due to the different maximum grain size that can be entrained along each streamline. The radial morphology of the streamlines then yields that, at a given cylindrical radius, the maximum grain size increases with height, resulting in a spatial variation of colour in the scattered light images. Furthermore, crystalline grains entrained in the wind are transported outwards from regions of the disc with higher crystallinity fractions resulting in an enhancement of crystalline grains in the wind over the disc’s underlying distribution.

We can split the method for constructing scattered light images into three separate parts: (i) hydrodynamic calculations of the photoevaporative wind; (ii) calculation of the dust profile distribution and crystallinity based on the hydrodynamic solution; and (iii) radiative transfer modelling of the dust distribution.

2.1 Model set

As the mass-loss rates are not well known for Herbig Ae/Be stars, we have left the ionizing luminosity (which sets the mass-loss rates) for an extreme UV (EUV)-driven wind (Hollenbach et al. 1994) as a free parameter and consider the effect of changing mass-loss rates on the morphology, colour of the emission and crystallinity distribution in the winds. We consider an EUV wind from a primordial disc around a 2.5 M\(_\odot\) star with a range in ionizing luminosity from 10\(^{31}\) to 10\(^{35}\) s\(^{-1}\) in steps of 1 dex. These luminosities correspond to mass-loss rates in the range 10\(^{-10}\)–10\(^{-8}\) M\(_\odot\) yr\(^{-1}\) and are similar to the values calculated by Alexander, Clarke & Pringle (2004). In order to calculate images, we compute scattered light images at 1.6, 2.1 and 3.8 μm with band passes corresponding to the H, K\(^*\) and L\(^*\) bands. In order to consider the relative contributions of crystalline to amorphous dust, we take the calculated crystallinity fractions in the disc of Dullemond et al. (2006) for an evolved Herbig Ae/Be star. We assume that this disc crystallinity fraction is the same at the base of our photoevaporative wind, such that the crystallinity fraction along the streamline can be calculated by following the thermal evolution of the dust entrained on that streamline.

2.2 Hydrodynamic photoevaporative wind

The photoevaporative disc wind is a thermally driven hydrodynamic wind occurring when the disc’s surface is heated to temperatures of order the escape temperature, allowing it to launch a freely expanding wind. While the wind-driving source for lower mass (T-Tauri) stars is likely to be X-rays (Owen et al. 2010a; Ercolano & Owen 2010; Ercolano & Clarke 2010; Owen et al. 2010b), the wind-driving source around intermediate-mass stars has not yet been thoroughly investigated. X-ray photoevaporation may still occur to...
some degree; however, the lower \( L_\text{X}/L_\text{bol} \) ratio of Herbig Ae/Be compared to T-Tauri stars and their higher EUV fluxes may reduce the role of X-rays in driving the wind. We adopt, here, the EUV-driven wind of Hollenbach et al. (1994) and hydrodynamic solution of Font et al. (2004), which is a simple and scalable hydrodynamic solution, allowing us to consider a wide range of parameter space, something not possible with more complicated far UV models (Gorti & Hollenbach 2009) or X-ray models (Owen et al. 2010a). The simplified EUV treatment is suitable for the purpose of this work which aims at being the first approach in studying the qualitative aspects of scattered light emission from a disc wind. We have repeated the calculation of Font et al. (2004) and Alexander (2008) and we refer the reader to these articles for a detailed description of the model setup, while the basics are summarized below.

### 2.2.1 Numerical EUV Photoevaporative Wind

In order to determine an accurate kinematic structure of the wind, we must compute a numerical solution to the problem. We use the \texttt{ZEUS2D} code (Stone & Norman 1992); we employ a spherical grid with \( \theta = [0, \pi/2] \), the radial grid cells are logarithmically spaced, such that we have adequate resolution at small radius to resolve the onset of the flow. The calculation is an isothermal wind calculation with the sound speed set to \( c_s = 10 \text{ km s}^{-1} \) and the radius scaled to the length-scale \( r_g = GM_*/c_s^2 \) i.e. the radius at which the internal energy of the gas is enough to unbind the gas from the star. We use a radial range of \( r = [0.05, 40] r_g \) with \( N_r = 240 \) and \( N_{\theta} = 50 \). The number density at the base (i.e. the density along the \( \theta = \pi/2 \) axis) of the wind was calculated semi-analytically by Hollenbach et al. (1994) and scales as \( r^{-3/2} \) for \( r < r_g \) and \( r^{-5/2} \) outside \( r_g \), as in Font et al. (2004) and Alexander (2008) we adopt the smooth base density profile suggested by Font et al. (2004) that varies between the two power laws:

\[
n(R) = n_g \left( \frac{R}{R_g} \right)^{5/2} \left( \frac{R}{R_g} \right)^{3/2} \]

where \( n_g \) is the density at \( R_g \) which was determined through the numerical calculations of Hollenbach et al. (1994) to be:

\[
n_g \approx 2.8 \times 10^4 \left( \frac{\Phi}{10^{43} \text{ s}^{-1}} \right)^{1/2} \left( \frac{M_*/\text{M}_\odot}{43} \right)^{3/2} \text{ cm}^{-3} \]

where \( \Phi \) is the ionizing luminosity. We note that this hydrodynamic calculation does not include a cold bound ‘disc’ component, since the base density structure of the wind is known a priori as discussed above. This base density, along with Keplerian rotation, is reset at every time-step and the model is allowed to evolve to a steady-state launching a wind from the grid’s mid-plane (representing the disc’s surface). As expected, we find excellent agreement with the results of the Font et al. (2004) and Alexander (2008) calculations. In Fig. 1, we show a plot of the converged wind structure showing that the wind is approximately spherical once it has reached several scaleheights, in agreement with our earlier discussion in Section 2.

### 2.3 Dust distribution

In order to calculate the dust distribution in the wind, we must make some assumptions about the underlying dust distribution in the disc. We adopt a dust to gas mass ratio of 0.01, and a power-law grain size distribution of index \( -3.5 \) (Mathis, Rumpl & Nordsieck 1977, hereafter MRN) with grain sizes ranging from \( d_{\text{min}} = 5 \times 10^{-3} \mu\text{m} \) to \( d_{\text{max}} = 1 \text{ mm} \), we assume spherical grains with a density of 1 g cm\(^{-3}\).

We also assume that the dust is fully mixed within the disc up to the transition between the bound cold disc and the hot EUV-heated flow. We then calculate streamlines from the base of the flow to the edge of the grid, then along each streamline, compute the force balance between the drag force (calculated from equation 1), gravity and the centrifugal force. We take the dust grain as entrained if the net force along the streamline is \( > 0 \). We then obtain the maximum grain size entrained along the entire streamline (making sure to check that each grain can be entrained the entire length of the streamline). In Fig. 2, we show the obtained maximum grain size as a function of position in the flow for an ionizing luminosity of \( \Phi = 10^{43} \text{ s}^{-1} \).

We can then compute the dust density from this maximum grain size under the assumption that the dust all comes from the same underlying population described above. In Fig. 3, we show the obtained dust density, noting that the combination of the photoevaporative wind and a selective dust population naturally reproduce a ‘wingnut’ structure.

### 2.4 Radiative transfer

We calculate the radiative transfer as a two step process: first, we calculate the temperature structure of the dust using a three-dimensional (3D) grid calculated from the 2D dust density
grains are launched from a disc that is infinitesimally thin and has the crystalline structure calculated by Dullemond et al. (2006), for a Herbig star with a mass of 2.5 M⊙ after 3.3 Myr of evolution. Any dust that was amorphous and is heated to a temperature of >800 K while entrained in the wind is then assumed to immediately become totally crystalline. Any dust that starts off crystalline or becomes crystalline at any point in the flow is assumed to be crystalline for the remainder of the flow regardless of the temperature it reaches at any other stage (we find that no dust in the flow reaches a temperature exceeding the evaporation temperature, which would destroy crystalline dust grains). In order to calculate a radial profile of the fraction of dust in the wind that is crystalline/amorphous, we must apply some cut-off on the flow since the total mass of the flow is a function of time since it switched on, rather than a converged quantity (it diverges logarithmically). Since much of the information on dust structure comes from the 10 μm silicate feature, a temperature cut-off is most appropriate, thus we calculate the mass-fraction of crystalline grains out to a temperature of 100 K; as such this should provide a reasonable estimate of the observable crystallinity fraction (anything colder is extremely unlikely to make much impact on the 10 μm silicate feature). Furthermore, since each cylindrical radial region will be cut by many streamlines with different crystallinity fractions in order to calculate an average crystallinity fraction, we perform a number density-weighted average out to the temperature cut-off.

### 3 IMAGES

In Fig. 4, we show calculated images of the five different models in the H, K′ and L′ bands, they all show a ‘wingnut’ morphology. The emission is strongest in the bluer bands with the H band being strongest and the L′ being the weakest (luminosities are listed in Table 1). As the mass-loss rate increases, the emission becomes more extended and reaches larger radii, since the density along a streamline falls to a given value at larger radius. We also find that all of the emission is scattered light from the central star and inner disc, many orders of magnitude above any thermal emission from the wind itself, in agreement with our assertion that the wind is optically thin. The fact that the emission is dominated by scattered light allows us to understand the evolution of the colour variation and emission morphology as the mass-loss rates change. For high mass-loss rates, the emission morphology follows the gas density distribution of the wind (i.e. essentially spherical with a gap on axis in a region where the wind is negligible), while more pronounced ‘wingnut’ profiles are clearly visible for lower values of mass-loss rate. This arises from the fact that scattering at a given wavelength is dominated by dust grains of comparable sizes. Given the bands we are interested in are in the range 1–5 μm then when there is large spatial variation in grains of this size then a profile that differs markedly from the gas density would be expected (e.g. the ‘wingnut’). However, for large enough mass-loss rates dust grains with sizes in the 1–5 μm range can be entrained in the flow everywhere and the emission then simply follows the gas density distribution. We find that all of the synthetic images are dominated by blue light; this is somewhat expected since the smallest grains can always be entrained in the flow and outnumber the larger grains, thus dominating the opacity for an MRN size distribution as the one considered here. Furthermore, the negative slope with wavelength of the irradiating field, which in the 1–5 μm range is dominated by emission from the disc, means that short wavelength photons are more abundant, contributing to the blue appearance of the synthetic images.
Figure 4. Synthetic images for disc models with irradiating fluxes $\Phi = 10^{41}, 10^{42}, 10^{43}, 10^{44}, 10^{45} \text{erg s}^{-1}$, the far left-hand column shows the image in the $H$ band, the next column displays the $K$ band and the other next column displays the $L$ band. The far right-hand column displays an red giant branch composite image ($L, K$ and $H$ bands, respectively). The images are individually scaled so that there is a 5 dex spread between the brightest pixel and the darkest. All images assume that the disc is edge-on (i.e. an inclination of 90°), therefore we block out the star assuming it would be blocked out by the presence of an optically thick disc.

Table 1. Model luminosities.

| log ($\Phi$) $\text{s}^{-1}$ | log (Luminosity) $\text{erg s}^{-1} \text{Hz}^{-1}$ |
|-----------------------------|-----------------------------------------------|
| $H$                         | $K'$                                          | $L'$                                       |
| 41                          | 15.8                                         | 15.4                                       | 14.0                                       |
| 42                          | 17.4                                         | 17.2                                       | 16.2                                       |
| 43                          | 18.3                                         | 18.2                                       | 17.5                                       |
| 44                          | 18.9                                         | 18.8                                       | 18.2                                       |
| 45                          | 19.4                                         | 19.3                                       | 18.7                                       |

4 CRYSTALLINITY PROFILE

We have used the wind profiles and dust temperature information from the radiative transfer calculation (Section 2.4) to calculate crystallinity fractions in the wind. We have assessed the impact of the wind on the observable crystallinity fraction for discs, where the inner disc is both obscured (edge-on) and unobscured. In the unobscured case, to observe the disc’s crystallinity fraction the wind will also make a contribution along the line of sight. We compare the disc’s emission to the wind’s emission at 10 $\mu$m and find that at all radii the disc dominates over the wind, meaning that the observed crystallinity fraction for non-edge-on discs is unaffected by the photoevaporative wind. However, when the disc is observed close to edge-on the disc’s contribution will be undetectable and the crystallinity fraction in the wind maybe studied.

It is important to note at this point that the radial distribution of the crystallinity fraction in a wind is likely to differ from the disc’s ‘native’ distribution. In Fig. 5, we show radial profiles of the crystallinity fraction obtained from the photoevaporative wind (solid black line) and compare it to the input crystallinity distribu-

Figure 5. Radial profiles of the wind crystallinity fraction (solid line) calculated as a number density weighted mean in the wind and the underlying disc distribution taken from Dullemond et al. (2006) for an evolved 3.3 Myr 2.5 M$\odot$ Herbig star (dashed line).
crystallinity fraction in the disc has now risen above the level in the wind. The crystallinity fraction in the wind remains the same for all ionizing luminosities and is insensitive to the temperature cut-off described in Section 2.5 in the range 150–50 K.

The observed wind crystallinity profile is a direct consequence of the streamline topology, which implies that the grains in the wind at any given cylindrical radius must have originated in the disc at a smaller radius and hence, in general, with a higher crystallinity fraction. The rise in the disc crystallinity at a radii >100 au is not translated into the wind population, since most of the dust in the wind is entrained inside 5rg ≈ 100 au. The low wind rates at > 100 au, coupled with the geometric dilution of the wind, mean that the crystallinity fraction in the wind continues to fall with radius. The fact that the crystallinity fraction is insensitive to the mass-loss rate is simply a consequence that the number of dust particles at a given point scales approximately as r_dust ∝ ϕ^{1/2} everywhere, the same as the gas, since it is largely unaffected by the change in maximum grain size for the MRN dust distribution chosen.

5 COMPARISONS TO OBSERVED EDGE-ON OBJECTS

There are several objects that show extended emission above and below the dark dust lane indicative of an optically thick disc. All the objects in the sample presented by Padgett et al. (1999), which includes the well-known ‘Butterfly Star’, show extended scattered light emission above and below a dark dust lane. The objects in the Padgett et al. (1999) sample; however, all are relatively low-mass young stars and the high fluxes detected in scattered light indicate that there is much more mass present than would be expected in the photoevaporative wind. Furthermore, the observed structure is much more filamentary than our models predict. These observations clearly indicate that the photoevaporative wind is too weak to have produced the observed extended emission. Padgett et al. (1999) suggested that these objects are young (Class I) objects with the extended emission arising from an infalling envelope. Wolf, Padgett & Stapelfeldt (2003) and Stark et al. (2006) have successfully reproduced these observations using detailed radiative transfer modelling that include the combination of a disc component, an infalling envelope and an outflow cavity.

PDS 144N (Perrin et al. 2006); however, is a more promising candidate for a photoevaporative wind with images showing a morphology very similar to the ‘wingnut’ shapes predicted for the lower mass-loss rates Φ ≤ 10^{33} erg s^{-1}. Furthermore, adopting the Φ = 10^{33} erg s^{-1}, which predicts a surface brightness of 0.01 Jy arcsec^{-2} in H at a radius and height of (R = 100, z = 100) au, we can derive a distance to PDS 144N. By comparing the observed image to our predicted image, we find a distance of 200–400 pc, which is in the range of previous estimates. As discussed in Perrin et al. (2006), it is highly unlikely that the morphology arises from foreground extinction as suggested explanation to the morphology of the Padgett et al. (1999) sample. Perrin et al. (2006) indeed discuss photoevaporation as a possible source for the extended emission. However, they oversimplify the photoevaporation model by just considering the radial scale r_g, ignoring the fact that, as discussed in Section 2, dust grains can be carried to very large distances in the wind, and at several flow scaleheights from the disc the streamlines are spherical. Our models show that the use of r_g in discussing the characteristic scales of the flow in dust is a poor approximation, since, as shown in Fig. 2, dust entrained at ~1r_g can be easily carried to radii and heights of >20r_g producing a dust density that varies on scales different to r_g as shown in Fig. 3. Perrin et al. (2006) predict models of the object in which they construct an infalling envelope with a jet cavity surrounding an extended passive accretion disc. While their model (fig. 6 of Perrin et al. 2006) can also reproduce extended emission, it cannot reproduce the distinctive ‘wingnut’ morphology seen in the observations and in the model presented in this work (see the top panels of Fig. 4).

However both the models presented by Perrin et al. (2006) and the ones presented in this work fail to reproduce one important aspect of the observations. The observed colour of PDS 144N is such that the extended regions of the emission become dominated by the redder scattered light. This is opposite to what is predicted by the Perrin et al. (2006) model which predicts a colour variation of red to blue with height and the blue band dominating the emission at large height. This is due to a dust population whose maximum grain sizes decreases with height, as you move from the disc population to the envelope (ISM like) population. On the contrary, our model can reproduce the sign of the observed colour variation i.e. the relative strength of the red light increases with height. This is demonstrated in Fig. 6 where we plot the change in H−K′ and H−L′ for the Φ = 10^{33} s^{-1} model as a function of height above the mid-plane for the Φ = 10^{33} s^{-1}, where there are variations in the grain population at sizes of a few microns, which dominate the scattering opacity at NIR wavelengths. While our models predict that the colours become redder with height above the disc (due to the fact that larger grains are entrained at greater height, see Fig. 2, and they scatter red light more efficiently), our models predict scattered blue light to remain dominant at large heights (see Fig. 4). As discussed in Section 3, in our model blue light dominates due to the spectral slope of the irradiating SED and the fact that small grains are present in the wind at all heights. We estimate using fig. 3 of Perrin et al. (2006) a change in H−L′ (Δ(H−L)) of >1.5, at least three times larger than our simple model can predict.

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Figure 6. Change in colour (ΔH−X) as a function of height above the midplane, at a cylindrical radius of 100 au. Green line: X = K′ band colour and red line: X = L′ band colour. The model shown is the Φ = 10^{33} s^{-1} calculation.

4 Previous estimates range from 140 to 2000 pc. Perrin et al. (2006) use a nearby A5 Herbig star (PDS 144S) to derive a distance of 1000 pc, taking the system to be a wide binary. However, such a distance places the system 300 pc above the Galactic plane. This would require the ejection of the wide binary system from a dense cluster, or formation in situ, both of which are unlikely.
6 CONCLUSIONS

We have considered the fate of dust grains that can be entrained in the photoevaporative wind from the surface of a disc surrounding a Herbig Ae/Be star. For a median mass-loss rate of \( \sim 10^{-9} \text{M}_\odot \text{yr}^{-1} \), we find that grains up to radii of several microns can be entrained in the wind. We also show that, once entrained in the wind, the dust grains will remain entrained and be carried out to very large radius. We have considered the observational imprint of this wind-entrained dust on edge-on discs, showing that the combination of a photoevaporative wind structure and a variable dust grain population resulting from the variable drag force at the base of the wind, can naturally reproduce a ‘wingnut’ morphology of the dust density distribution in the wind. Using a combination of Monte Carlo and ray tracing radiative transfer techniques, we calculate scattered light images from the density distribution at NIR wavelengths. We find our model is not applicable to the well-known edge-on discs in the Padgett et al. (1999) sample, which are too young and optically thick to be explained with a photoevaporative origin, but are likely to arise from an infalling envelope as shown in Wolf et al. (2003) and Stark et al. (2006). These synthetic images show a ‘wingnut’ morphology inferred from the dust density distributions, similar to observations of the edge-on disc around PDS 144N (Perrin et al. 2006). The synthetic images, however, are dominated by emission from the smallest grains entrained in the flow, hence failing to reproduce the colour gradient of the observations, which show redder emission at larger heights above the disc. Grain growth in the disc is a natural solution to the colour problem, and we estimate severely depleted abundance of grains with radii smaller than 1 \( \mu \text{m} \).

Finally, we consider the crystallinity of dust grains entrained in the flow: by following the thermal evolution of the grains, we find that crystallinity fraction will remain unchanged when the disc’s photosphere can be observed since the observable mass in the wind is much less than the observable mass in the disc. However, when the disc photosphere is obscured (i.e. for edge-on discs), the crystallinity fraction in the wind is significantly enhanced above the discs underlying crystallinity fraction. Finally, we suggest that detection of crystalline grains in extended emission around an edge-on disc is indicative of the photoevaporative wind and argue against an envelope origin for the extended emission.

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