Using Intermediate-Luminosity Optical Transients (ILOTs) to reveal extended extra-solar Kuiper belt objects

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Abstract We suggest that in the rare case of an Intermediate-Luminosity Optical Transient (ILOT) event, evaporation of extra-solar Kuiper belt objects (ExtraKBOs) at distances of $d \approx 500 - 10\,000$ AU from the ILOT can be detected. If the ILOT lasts for 1 month to a few years, enough dust might be ejected from the ExtraKBOs for the infrared (IR) emission to be detected. Because of the large distance of the ExtraKBOs, tens of years will pass before the ILOT wind disperses the dust. We suggest that after an ILOT outburst, there is a period of months to several years during which IR excess emission might hint at the existence of a Kuiper belt analog (ExtraK-Belt).

Key words: (stars:) binaries: general — (stars:) planetary systems — stars: variables: other

1 INTRODUCTION

The Kuiper belt in our solar system contains icy bodies (Kuiper belt objects - KBOs) from Neptune to about 50 AU (e.g., Petit et al. 1999). These icy bodies are in fact cometary nuclei. Short period comets have orbital parameters suggesting that their formation is from the Kuiper belt (e.g., Melnick et al. 2001; Stern et al. 1990). The total mass of the belt in the annulus $30 < a < 50$ AU is estimated to be in the range of $0.1 - 0.26$ $M_\oplus$ (e.g., Jewitt et al. 1998; Chen 2006). Around 10^5 KBOs possess a diameter larger than 100 km, with the biggest being Pluto with $D_{\mathrm{Pluto}} \approx 2400$ km. There are more objects with a diameter smaller than 100 km (e.g., Melnick et al. 2001). The small icy bodies in the solar system motivate observations and theoretical studies of such bodies orbiting other stars (see, e.g., Wyatt 2008 for a review). For that, we first note the rich variety of properties that KBOs exhibit in the solar system.

The Kuiper belt in the solar system contains different subgroups of icy bodies, such as the cold population (having an inclination of less than 4 degrees with respect to the ecliptic plane) and the hot population (having an inclination of more than 4 degrees with respect to the ecliptic plane). The hot population was formed closer to the Sun and was transported into the Kuiper belt. The formation of the cold population is still under debate. The two main scenarios are local formation and transportation to its current position (e.g., Gomes 2003; Levison & Morbidelli 2003; Levison et al. 2008; Morbidelli et al. 2014 and earlier references therein). The belt is usually divided into an inner belt ($a < 40$ AU) and an outer belt ($a > 41$ AU); the

area of $40 < a < 42$ AU is dynamically unstable due to secular resonances (e.g., Petit et al. 1999). As noted by Brown & Pan (2004), the plane of the Kuiper belt is affected by many parameters such as the total angular momentum of the solar system, recent stellar encounters, and unseen distant masses in the outer solar system. Therefore, it is quite possible that some stars have a very extended Kuiper-like belt. For example, a massive ≈ 10 $M_\odot$ disk extending to ≈ 1000 AU was detected recently around the young O-type star AFGL 4176 (Johnston et al. 2015). The rich variety of icy bodies in the solar system and the different phases of late stellar evolution raise the possibility of detecting icy bodies, or an outcome related to them, during some particular stages of stellar evolution.

Belts similar to the Kuiper belt exist in extra-solar planetary systems (e.g., Wyatt 2008), like HR 8799 (e.g., Sadakane & Nishida 1986; Su et al. 2009; Matthews et al. 2014; Contro et al. 2015). They are detected through dusty debris resulting from collisions (Greaves et al. 2005). The first discovery was due to excess emission towards Vega, an A0V star (Aumann et al. 1984) whose spectral energy distribution corresponds to cold dust grains at 80 AU from the star (Wyatt et al. 2003). Wyatt et al. (2003) studied stars (and binary systems) within 6 pc from the Sun and found that ϵ Eri and τ Cet have debris disks of 0.01 $M_\odot$ at 60 AU and 5×10^{-4} $M_\odot$ at 55 AU, respectively. Other detections include ζ^2 Ret (Eiroa et al. 2010) and the G stars HD 38858 and HD 20794 (Kennedy et al. 2015).

The subject of KBO analogs (extra-solar Kuiper belt objects or ExtraKBOs) around post-main sequence (MS) stars has been investigated before by Jura (2004). They discuss the ice sublimation of ExtraKBOs when the star

reaches the red giant branch (RGB) phase. This rapid sublimation leads to a detectable infrared (IR) excess at 25 μm, depending on the mass of the ExtraKBOs.

In the present study, we investigate the evaporation of ExtraKBOs during a transient brightening event called an intermediate-luminosity optical transient (ILOT). ILOTs are eruptive outbursts with a total kinetic energy of $10^{46} - 10^{49}$ erg that last weeks to several years (Kashi & Soker 2015 and references therein). Their peak bolometric luminosity can be of the order of 10^{40} erg s^{-1} (e.g., ILOT NGC 300 OT had $L_{\rm bol} = 1.6 \times 10^{40}$ erg s^{-1}, Bond et al. 2009).

ILOTs that arise from asymptotic giant branch (AGB) or extreme-AGB (ExAGB) pre-outburst stars have been modeled with single stars (e.g., Thompson et al. 2009) and binary systems (e.g., Kashi & Soker 2010; Soker & Kashi 2011, 2012). The progenitor masses of the AGB ILOTs M85 OT2006-1 and NGC 300 OT2008-1 were estimated as $M_1 < 7 M_\odot$ and $6 < M_1 < 10 M_\odot$, respectively (Ofek et al. 2008; Prieto et al. 2009). Mcley & Soker (2014) concluded that such ILOTs are most likely powered by a binary interaction. More generally, ILOTs are thought to be powered by gravitational energy released in a high-accretion rate event in binary stars (Kashi & Soker 2015), even possibly during a grazing envelope evolution (Soker 2016). The required orbital separation is about 1-3 times the giant's radius, at least during periastron passages. So, the general binary separation at periastron passages (which is the orbital radius for circular orbits) for these systems is in the general range of $0.5 - 5$ AU. Relevant to the binary model is the suggestion made by Humphreys et al. (2011) that the ILOT NGC 300 2008OT-1 had a bipolar outflow; see however the claim by Adams et al. (2015) that NGC 300 2008OT-1 might have been a supernova explosion rather than an ILOT event.

ILOTs powered by merging stars can occur in MS stars, such as V838 Mon (Soker & Tylenda 2003; Tylenda & Soker 2006). Since the luminosity, mass-loss rate and dust production in winds from MS stars are several orders of magnitude below those of AGB stars, the IR excess due to the ExtraKBO evaporation will be much more prominent. This holds true despite ILOT events of MS stars being generally shorter than those expected from AGB stars. The merger product itself becomes very red and forms dust, but this dust is hotter and concentrated in the center (e.g., Munari et al. 2002; Bond & Siegel 2006; Kamiński & Tylenda 2013; Chesneau et al. 2014; Kamiński et al. 2015).

In the present study, we estimate the IR excess due to sublimation of ExtraKBOs near an ILOT event. The sublimated gas from the ExtraKBOs carries dust which might be detected, we claim, throughout an IR excess. Such observations will reveal the properties of Kuiper belt analogs (extra-solar Kuiper Belts or ExtraK-Belts) around systems that experience ILOT events (that might hint at a binary merger). We start our study by calculating the sublimation of ExtraKBOs when the star experiences an ILOT event (Sect. 2), and then in Section 3 we address the emission and

possible ways to detect this type of evaporation. A short summary of our main conclusions is given in Section 4.

2 ILOT SUBLIMATION OF EXTRA-SOLAR KUIPER BELTS

2.1 Sublimation Rate

ExtraKBOs/comets have not been directly observed around post-MS stars. Observations around subgiants have been made, and although no ExtraKBOs have been found, the large amount of dust indicates that dusty material can survive the MS phase (for more details, see Bonsor et al. 2013, 2014). Stern et al. (1990) and Saavik Ford & Neufeld (2001) model the ice sublimated from comets with orbital separation of more than 100 AU from stars that evolved along the AGB. Stern et al. (1990) study the detectability of comet clouds during the post-MS phase of stellar evolution and show that the change in luminosity in the post-MS stage has a dramatic effect on the reservoirs of comets. They calculate the temperature (see, Stern et al. 1990, eq. (2)) at different orbital separations from the post-MS star and find out that KBOs will go through intensive mass-loss of water and more volatile species. Objects in the Oort cloud will sublimate volatile species, and depending on the eccentricity of their orbit might go through intensive water sublimation as well. Comets on circular orbits will sublimate mostly volatile species such as CO_2, CO and NH_3, while comets on eccentric orbits that come closer to the star will go through significant water sublimation. Their model takes into account a star which evolves from the MS to the red giant phase over $\approx 10^8$ yr. In the RGB phase, its luminosity is $\approx 300 L_\odot$, a change that increases the water sublimation radius from 2.5 AU at $L = L_\odot$ to ≈ 40 AU at $L \approx 300 L_\odot$.

Once the hydrogen has been exhausted and the core contracts, a core-helium flash starts the horizontal branch (HB) phase (the helium flash is inside the core and is too short to influence sublimation). The AGB phase that follows the HB phase lasts for $\approx 10^7$ yr with a luminosity of several thousand solar luminosities. At this stage the water sublimation radius increases to the Kuiper belt and the inner Oort cloud as well. Melnick et al. (2001) agree that the AGB stage affects the Kuiper belt but argue that the Oort cloud is not affected from an increase in luminosity in the range of $100 - 3000 L_\odot$ when the star evolves along the AGB.

Saavik Ford & Neufeld (2001), who studied IRC + 10216, and Maercker et al. (2008), who studied M-type AGB stars, argued that the presence of water vapor in carbon rich AGB stars possibly suggests the existence of extra-solar cometary systems.

There is a direct connection between the sublimation rate and the chance of detecting ExtraKBOs (Jura 2004). We calculate the sublimation rate per unit area per object from the kinetic theory model as is customary (e.g., Delsemme & Miller 1971, eq. (7); Cowan & Ahearn 1979, eq. (2); Fanale & Salvail 1984, eq. (8); Prialnik & Bar-Nun

Table 1 The Relevant Constants for Three Different Molecules

Molecule	A [dyn cm^{-2}]	B [K]
CO	1.75×10^{11}	946.91
H_2O	3.69×10^{13}	6151.7
CO_2	1.14×10^{13}	3157.7

1990, eq. (17); van Lieshout et al. 2014, eq. (12); and references therein)

$$\dot{z} = P_{\text{vap}}(T_{\text{ExtraKBO}})\sqrt{\frac{m}{2\pi R_g T_{\text{ExtraKBO}}}} \text{ g s}^{-1} \text{ cm}^{-2},$$
(1)

where m is the molecular weight in g mol^{-1}, R_g is the gas constant, $P_{\text{vap}}(T_{\text{ExtraKBO}})$ is the vapor pressure in dyn cm^{-2} and T_{ExtraKBO} is the temperature of the ExtraKBO. Note that the sublimation rate per object is a function of the ExtraKBO area. We define the sublimation rate for a single ExtraKBO

$$\dot{Z}_S = \dot{z}\pi R_{\text{ExtraKBO}}^2,$$
(2)

where $\pi R_{\text{ExtraKBO}}^2$ is the area of the ExtraKBO facing the ILOT. Asteroids and comets are subject to a size distribution, e.g., like the one used by Jura (2004), but the mass is probably concentrated in the most massive bodies. For asteroid disruptions near a white dwarf (WD), it is customary to take radii in the range of $R_{\text{ast}} \approx 1-1000$ km (e.g., Jura 2003; Farihi et al. 2014; Veras et al. 2014). In this paper we scale the expression with $R_{\text{ExtraKBO}} = 5$ km. In order to calculate the sublimation rate per object, we must know the vapor pressure which is derived from the temperature of the ExtraKBO and its composition. We address three molecules below, H_2O, CO and CO_2, and assume that the ExtraKBO is composed entirely of one type of molecule.

2.2 Vapor Pressure

The vapor pressure of volatile species such as CO (e.g., Bujarrabal et al. 2013; Hillen et al. 2015) and H_2O can be described by the $Clausius-Clapeyron$ relation for sublimation (e.g., Prialnik 2006; Rosenberg & Prialnik 2009)

$$\frac{d\ln P_{\text{vap}}}{dT_{\text{ExtraKBO}}} = \frac{H}{R_g T_{\text{ExtraKBO}}},$$
(3)

where H is the latent heat (enthalpy) of sublimation (calculated from Table 1). We integrate Equation (3) and derive (e.g., Gombosi et al. 1985; Lichtenegger & Komle 1991; Prialnik 2006; Rosenberg & Prialnik 2009; Gronkowski 2009b)

$$P_{\text{vap}} = A\exp(-B/T_{\text{ExtraKBO}}),$$
(4)

where the relevant constants for three different molecules are given in Table 1 and are derived from the CRC Handbook of Chemistry and Physics (where tables of P_{vap} and T are given for each molecule; Lide 2002).

2.3 ExtraKBO Temperature

The temperature of ExtraKBOs can be calculated from the energy equation, similar to that used for comets (e.g., Beer et al. 2006; Gronkowski 2009a; Prialnik & Rosenberg 2009)

$$E_{\text{ILOT}} = E_{\text{thermal}} + E_{\text{sub}} + E_{\text{con}},$$
(5)

where

$$E_{\text{ILOT}} = \frac{(1 - A_{\text{ExtraKBO}})L_{\text{ILOT}}}{4\pi d^2},$$
(6)

is the heating flux from the ILOT outburst that is absorbed by the body, A_{ExtraKBO} is the albedo of the ExtraKBO, L_{ILOT} is the luminosity during the ILOT and d is the orbital separation. The terms on the right hand side of Equation (5) are as follows.

$$E_{\text{thermal}} = \epsilon\sigma T_{\text{ExtraKBO}}^4,$$
(7)

is the cooling by thermal radiation per unit area of the object where ϵ is the emissivity and σ is the Stefan-Boltzmann constant.

$$E_{\text{sub}} = H\dot{z},$$
(8)

is cooling per unit area by sublimation. Due to the very low temperatures, the energy conductivity term E_{con} is insignificant for H_2O, CO and CO_2, and will be neglected here. We note that the area of evaporation and cooling can be $4\pi R_{\text{ExtraKBO}}^2$ depending on if the heat had time to spread over the ExtraKBO. Although rotation is possible, since the conductivity is negligible, we assume that most of the cooling and sublimation is from the surface facing the ILOT. Therefore, we take the effective area for energy and mass-loss of one object to be $\pi R_{\text{ExtraKBO}}^2$.

The supervolatile CO, that is known to exist in comets, can be in its gaseous form even in the low temperatures of the Kuiper belt. The CO sublimation rates for several known KBOs (such as 2060 Chiron, 1998 WH24, 7066 Nessus and others) are calculated to be on the order of $\dot{Z}_S \approx 10^{28}$ molecules s^{-1} (for more details, see table 6 in Bockelée-Morvan et al. 2001). Due to low absorption in the CO, it has only been detected on Pluto and Triton (e.g., Schaller & Brown 2007; Brown 2012 and references within). Sublimation of CO can be significant for ExtraKBOs around ILOTs (see Fig. 1 below).

The dust temperature is calculated by balancing radiation heating and cooling. When the temperature exceeds the sublimation temperature, the dust is destroyed. The sublimation distance of dust particles from an energy source is given by (e.g., Netzer & Laor 1993; Laor & Draine 1993)

$$R_{\text{sub-dust}} \approx 24\left(\frac{L_{\text{ILOT}}}{10^6 L_\odot}\right)^{\frac{1}{2}} \text{ AU}.$$
(9)

As we are interested in the ExtraK-Belt at a distance of $\gg 100$ AU, the dust that is carried out by sublimating gas from the ExtraKBOs survives and does not sublimate.
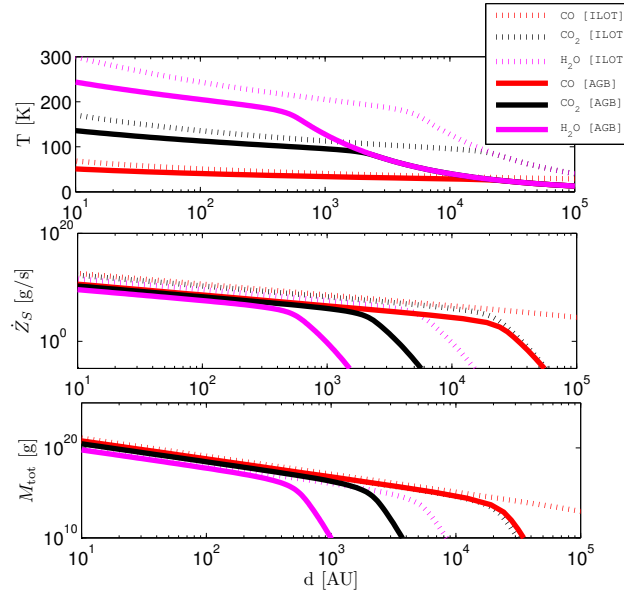
Fig. 1 Properties of an ExtraKBO during an ILOT event and during the AGB phase, as a function of its distance from the ILOT. The upper panel presents ExtraKBO temperature, the middle panel depicts the ExtraKBO sublimation rate per object for $R_{\mathrm{ExtraKBO}} = 5$ km and the lower panel displays the total mass ejected from this object. Two options are considered and represented by different lines: ExtraKBO around ILOT (*dotted lines*) and ExtraKBO around AGB stars (*solid lines*). Red, black and pink represent an ExtraKBO composed completely of CO, CO_2 and H_2O respectively. The vapor pressure parameters for all three molecules in all panels are taken from Table 1. For the lower panel, we take the duration of the ILOT event and the effective duration of the AGB as $t_{\mathrm{ILOT}} = 10$ yr and $t_{\mathrm{AGB}} = 500$ yr, respectively.
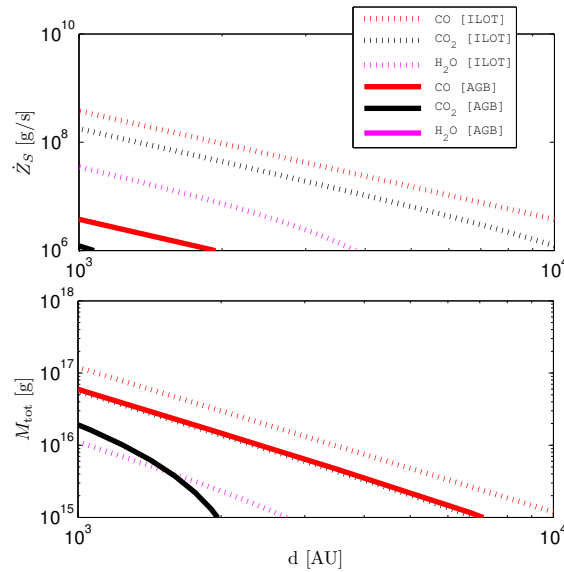
Fig. 2 The same as the corresponding panels in Fig. 1, but zooming in on the distance range of $10^3 - 10^4$ AU.

2.4 Sublimation of ExtraKBOs by ILOTs

In order to simplify the calculation, we assume that the ExtraKBO is composed of only one type of gas. In Figure 1 we present the temperature on the ExtraKBO as a function of orbital separation from the ILOT according to

Equation (5). For the ILOT event we scale quantities with a luminosity of $L_{\mathrm{ILOT}} = 10^6 \, L_\odot$ and a duration of $t_{\mathrm{ILOT}} = 10$ yr; later we will substitute $t_{\mathrm{ILOT}} = 0.1$ yr for the case of ILOTs by MS stars. For the upper AGB phase of the star, we take $L_{\mathrm{AGB}} = 10^4 \, L_\odot$ and an effective duration of $t_{\mathrm{AGBw}} = 500$ yr. The effective duration of the AGB star is

the time span of the wind in the location of the ExtraK-Belt

$$t_{\text{AGBw}} \approx 500 \left(\frac{d}{1000 \text{ AU}} \right) \left(\frac{v_{\text{w}}}{10 \text{ km s}^{-1}} \right)^{-1} \text{ yr}, \quad (10)$$

where v_{w} is the AGB wind speed (e.g., Winters et al. 2003). AGB dust that was lost earlier will be further away and cooler. Since we cannot differentiate the dust carried by the AGB wind from the dust carried by gas sublimating from the ExtraKBOs once they are in the same region, we regard this as the effective duration of the AGB phase.

We compare the effects from the AGB star and the ILOT event on temperature (Fig. 1, upper panel), evaporation rate per object with a radius of $R_{\text{ExtraKBO}} = 5$ km (Fig. 1, middle panel) and total mass that evaporates from the object (Fig. 1, lower panel). In the lower panel, we calculate the evaporated mass during the effective duration of the AGB described by Equation (10) and during the ILOT outburst (10 yr). The luminosities are given above, which are $L_{\text{AGB}} = 10^4 L_\odot$ and $L_{\text{ILOT}} = 10^6 L_\odot$, respectively. In Figure 2 we zoom in on the distance range $d = 10^3 - 10^4$ AU.

Figure 1 indicates that the temperature of a single ExtraKBO around the ILOT event is, as excepted, higher than the temperature during the AGB phase for all compositions. For the sublimation rate per object, we can see that for each molecule there is a "knee" (gap) where the sublimation rate for ExtraKBOs around the AGB star substantially drops while for the ILOT event it is still significant. For ExtraKBOs residing at these distances, a prominent IR excess is expected due to ILOT sublimation. We emphasize that this IR excess is not a result of the dust from the ILOT wind but rather a result of the dust carried by the sublimating gas from the ExtraKBOs. This gap in mass-loss is apparent in the lower panel which represents the total gas mass from a single ExtraKBO. The interesting distance ranges of the ExtraKBO where the influence of the ILOT is much larger than that of the AGB star are as follows: $d \approx 10^3 - 10^4$ AU for H_2O, $d \approx 3 \times 10^3 - 2 \times 10^4$ AU for CO and $d \gtrsim 3 \times 10^4$ AU for CO_2, as can be seen from Figures 1 and 2. Since the ExtraKBOs are not composed of a single gas, it is hard to predict the exact interesting distance ranges. However, observing the distance of $\approx 1000 - 10\,000$ AU after an ILOT event during the first few months to years might reveal an excess amount of dust and might hint at the presence of an ExtraK-Belt. For the purpose of our calculations, we choose to look specifically at a distance of $d = 1000$ AU.

We scale the total mass of the ExtraK-Belt M_{Belt} by the solar system one of $0.1\ M_\oplus$ (e.g., Gladman et al. 2001) so that the number of objects in the ExtraK-Belt is

$$N_{\text{obj}} \approx 10^9 \left(\frac{M_{\text{Belt}}}{0.1\ M_\oplus} \right) \left(\frac{\rho_{\text{ExtraKBO}}}{1 \text{ g cm}^{-3}} \right) \left(\frac{R_{\text{ExtraKBO}}}{5 \text{ km}} \right)^{-3}, \quad (11)$$

where ρ_{ExtraKBO} is the average density of the ExtraKBOs. We find that the total mass of the sublimated dust and gas from the ExtraK-Belt in the outburst around an ILOT event is

$$M_{\text{dust−ILOT}} = \eta M_{\text{gas−ILOT}} \approx 5 \times 10^{-9} \eta \left(\frac{\dot{Z}_{S(1000 \text{ AU})}}{3.5 \times 10^7 \text{ g s}^{-1}} \right) \left(\frac{t_{\text{ILOT}}}{10 \text{ yr}} \right) \left(\frac{\gamma}{1} \right) \left(\frac{N_{\text{obj}}}{10^9} \right) M_\odot, \quad (12)$$

where η is the dust to gas ratio, which is estimated from comets to be $\eta \approx 0.1 - 10$ (e.g., Fulle et al. 2010; Lara et al. 2011; Schmidt et al. 2015), and γ is a scaling factor depending on whether the ILOT event occurs during the AGB or the MS phase. For an MS star, the duration of the ILOT event is only ≈ 0.1 yr, so that $\gamma = 0.01$. The distance of the ExtraK-Belt was taken at $d = 1000$ AU and the sublimation rate per object ($\dot{Z}_S$) is calculated for H_2O. The ILOT luminosity was taken to be $L_{\text{ILOT}} = 10^6 L_\odot$. The average total mass-loss rate from the ExtraK-Belt is $\dot{M}_{\text{gas−ILOT}} = \dot{Z}_S N_{\text{obj}}$.

The ratio of the dust mass from the ILOT to that from the AGB star is an important quantity given by

$$\begin{aligned} \frac{M_{\text{dust−ILOT}}}{M_{\text{AGBw}}} &= N_{\text{obj}} \left(\frac{\dot{Z}_S}{\dot{M}_{\text{AGBw}}} \right) \left(\frac{t_{\text{ILOT}}}{t_{\text{AGBw}}} \right) \left(\frac{\eta_{\text{ILOT}}}{\eta_{\text{AGB}}} \right) \\ &\approx 10^{-3} \left(\frac{\dot{Z}_S(1000 \text{ AU})}{3.5 \times 10^7 \text{ g s}^{-1}} \right) \left(\frac{\dot{M}_{\text{AGBw}}}{10^{-6} M_\odot \text{ yr}^{-1}} \right)^{-1} \left(\frac{N_{\text{obj}}}{10^9} \right) \left(\frac{t_{\text{ILOT}}}{10 \text{ yr}} \right) \\ & \quad \left(\frac{t_{\text{AGBw}}}{500 \text{ yr}} \right)^{-1} \left(\frac{\eta_{\text{ILOT}}}{1} \right) \left(\frac{\eta_{\text{AGB}}}{0.01} \right)^{-1}, \end{aligned} \quad (13)$$

where $\dot{M}_{\text{AGBw}}$ is the mass-loss rate of the wind and η_{ILOT} and η_{AGB} are the dust to gas ratio of the ILOT and AGB respectively. Despite the much lower sublimated dust from the ILOT than that residing in the AGB wind, for the parameters chosen here, the sublimated dust from the ExtraK-Belt is concentrated in a particular radius, and hence will have strong emission at a particular temperature. It might possibly be detected, but we estimate that will only occur if the AGB wind has a lower mass-loss rate than chosen here.

More promising might be ILOTs from MS stars (or slightly evolved off the MS), such as those observed in V838 Mon, V1309 Sco and similar events (e.g., Tylenda et al. 2011; Kamiński et al. 2015; Pejcha et al. 2016). In MS stars, the wind mass-loss rate is much lower and dust production is less efficient than in AGB stars. Taking the ratio of dust mass for an ILOT and an MS star gives

$$
\frac{M_{\text{dust-ILOT}}}{M_{\text{MSw}}} \approx 5000 \left(\frac{\dot{Z}_S(1000 \text{ AU})}{3.5 \times 10^7 \text{ g s}^{-1}} \right) \left(\frac{\dot{M}_{\text{MSw}}}{10^{-12} M_\odot \text{ yr}^{-1}} \right)^{-1} \left(\frac{N_{\text{obj}}}{10^9} \right)
$$
$$
\left(\frac{t_{\text{ILOT}}}{0.1 \text{ yr}} \right) \left(\frac{t_{\text{MS}}}{10 \text{ yr}} \right)^{-1} \left(\frac{\eta_{\text{ILOT}}}{1} \right) \left(\frac{\eta_{\text{MS}}}{0.001} \right)^{-1},
$$

(14)

where $\dot{M}_{\text{MSw}}$ is the wind mass-loss rate from the MS star, η_{MS} is the gas to mass ratio of the MS star and t_{MS} is the effective duration of the mass-loss phase. Because of the faster MS wind compared to the AGB wind, $v_{\text{MSw}} \approx 500 \text{ km s}^{-1}$, and the closer ExtraK-Belt, about 1000 AU, the effective duration is shorter (Eq. (10)).

3 IR EXCESS

Our solar system contains the asteroid belt and the Kuiper belt. Some of the dust observed in our solar system results from collisions in the asteroid belt, which form 'hot' dust (zodical) at $2 - 4$ AU at ≈ 270 K and 'cold' dust at $30 - 50$ AU from the Sun at a temperature of $50 - 60$ K which is a result of collisions between KBOs. Observation of ExtraK-Belts is not simple. Beichman et al. (2006) note that inferred IR excess for the solar system Kuiper belt is $L_{\text{IR}}/L_\odot \approx 10^{-7} - 10^{-6}$ while that for the asteroid belt is $L_{\text{IR}}/L_\odot \approx 10^{-7}$ (e.g., Beichman et al. 2006 and references therein).

The IR excess due to the dust released from gas sublimation can be crudely estimated assuming a uniform distribution of 1 μm-size dust grains (Jura 2004)

$$
\frac{L_{\text{excess}}}{L_{\text{ILOT}}} \approx \frac{\chi M_{\text{dust-ILOT}}}{4\pi d^2} .
$$

(15)

The opacity is estimated as (Jura 2004)

$$
\chi = \frac{\pi a_{\text{dust}}^2}{4\pi \rho_{\text{dust}} a_{\text{dust}}^3/3}
$$
$$
\approx 7500 \left(\frac{\rho_{\text{dust}}}{1 \text{ g cm}^{-3}} \right)^{-1} \left(\frac{a_{\text{dust}}}{1 \text{ μm}} \right)^{-1} \text{ cm}^2 \text{ g}^{-1},
$$

(16)

where a_{dust} is the dust radius. We note that Jura (2004) takes into account different models for the mass-loss rate of KBOs. He differentiates between large and small populations of KBOs and follows their evolution along with the change in luminosity of the host star. Since our outburst is short and we assume that its duration is only $0.1 - 10$ yr, we do not differentiate and simply take the sublimation rate per object from the energy equation (Eq. (1)) for a uniform distribution of ExtraKBOs. Substituting Equation (16) into Equation (15) yields

$$
\frac{L_{\text{excess}}}{L_{\text{ILOT}}} \approx 10^{-5} \left(\frac{M_{\text{dust-ILOT}}}{5 \times 10^{-9} M_\odot} \right) \left(\frac{d}{1000 \text{ AU}} \right)^{-2}
$$
$$
\left(\frac{a_{\text{dust}}}{1 \text{ μm}} \right)^{-1} \left(\frac{\rho_{\text{dust}}}{1 \text{ g cm}^{-3}} \right)^{-1} .
$$

(17)

This serves as a lower limit and can be higher depending on composition, grain size, ILOT duration and mass of the ExtraK-Belt. Riviere-Marichalar et al. (2014) observe a tiny IR excess of $L_{\text{IR}}/L_\odot \approx 2 \times 10^{-6}$ around the young star HD 29391 (an F0IV star, Abt & Morrell 1995), that is part of the beta Pictoris moving group. This IR excess suggests a debris disk with a lower limit on the inner radius of 82 AU. We note that Eiroa et al. (2010) report an initial result of the presence of a dust ring at ≈ 100 AU from the solar type star ζ^2 Ret with $L_{\text{excess}}/L_* \approx 10^{-5}$.

Wyatt (2008) estimates the fractional luminosity from a collisional cascade (orbital eccentricities greater than 10^{-3} to 10^{-2}) in his equation (15). Substituting ExtraKBOs with a diameter of ≈ 10 km and total mass of $M_{\text{tot}} = 0.1 M_\oplus$ as in our Equation (11), we find the fractional IR luminosity to be $f_{\text{coll}} \approx 10^{-8}(r/1000 \text{ AU})^{-2}$. This is three orders of magnitude lower than the IR emission produced from the sublimated ExtraKBOs (our Eq. (17)). Furthermore, calculating the timescale for mutual collisions, using the parameters given in Wyatt (2008) for a fitted population of debris disks around A-type stars, and our belt mass of $M_{\text{tot}} = 0.1 M_\oplus$, we find that the timescale to establish a collisional cascade is $\approx 3 \times 10^9$ yr. This implies that an ExtraK-Belt around stars with an initial mass larger than about $1.5 M_\odot$ will not have time to establish the cascade, and the values of f_{coll} will be even lower than 10^{-8}. Therefore, IR emission from a collisional cascade is insignificant relative to IR excess due to sublimation of ExtraKBOs. We note that a few single collisions can occur, but they are rare and result in an insignificant IR excess (see eq. (19) in Wyatt 2008).

The observations of an evaporated ExtraK-Belt at hundreds of AU and more from an ILOT event will be quite difficult. The low temperature of the dust implies that most of the radiation will be at a longer wavelength than the Spitzer band. Detecting rotational emission lines from CO molecules is not expected to be sensitive enough. Matrà et al. (2015) used ALMA to observe the debris disk of Fomalhaut with CO lines, and set an upper limit on the CO mass there. For cases studied here, the emission is expected to be even lower, as both the evaporated mass is lower than their upper limit, and there are no H_2 molecules to colli-

sionally excite CO. Hence, luminosity in CO will be very weak. It seems that the most optimistic situation will be for a future mission comparable to or better than the Wide-field Infrared Survey Explorer (WISE). If an ILOT event takes place during the operation of such a far IR space observatory, then it might be a prime target for a search of an evaporated ExtraKBO.

4 SUMMARY

In the present study, we examined the influence of ILOT events, in both post-MS stars and MS stars, on very small substellar objects. We considered the sublimation of comets and similar objects, Kuiper belt analogues (ExtraK-Belts), in rare cases of ILOTs that might last weeks to years. Such ILOTs can take place in AGB stars, (e.g., NGC 300 OT Monard 2008; Berger et al. 2009; Bond et al. 2009), and during earlier phases of the evolution, including the MS. Although ILOT events are rare, metal pollution of WDs shows that many planetary systems survive the post-MS evolution (e.g., Jura 2006; Jura et al. 2007; Jura 2008; Debes et al. 2012; Farihi et al. 2011, 2012; Melis et al. 2012; Farihi et al. 2014). So, we expect that sublimation of comet-like bodies as far as a few thousand AU from the star will take place in ILOT events, and dust will be released (Eq. (12)).

If the ILOT event lasts for several weeks (in MS stars) to several months or years (in AGB stars), enough dust might be ejected from these bodies (Eqs. (13) and (14)) for the IR emission to be detected (Eq. (17)). This dust would be concentrated at the ExtraK-Belt and therefore might be distinguished from the dust formed in the stellar wind. Although a star spends millions of years on the AGB with high luminosity, there is a region where ILOT events will release gas and dust from comets, but not AGB stars (Fig. 2).

The extra dust that might be observed at thousands of AU from the ILOT event is the dust formed by the sub-limating ExtraKBOs. Lots of dust is formed in the ILOT event itself, but it will take this dust tens of years or longer to reach the ExtraK-Belt region discussed here. The IR excess luminosity should be searched for months to years after the ILOT event. The phenomenon can be observed where the influence of the ILOT is much larger than that of the AGB star. In Section 3, we noted that the release of dust by collisions will be small and will not contribute significantly to the IR excess. Although ILOTs themselves turn red, their typical temperature at early times is hotter than that of the sublimated dust at large distances studied here. So spectroscopically, the sublimated dust can be distinguished from the IR emission of the ILOT event itself. At distances of thousands of AU from the ILOT, such IR emission might even be resolved with future instrumentation.

ILOT events in MS stars only last several weeks. However, the MS stellar mass-loss rate and dust production in the wind are several orders of magnitude below those of AGB stars. Therefore, the IR excess due to the evapora-

tion of ExtraKBOs might be much more prominent than for ILOTs in AGB stars. Due to the region that is clean of dust around many MS stars (relative to the region around AGB stars), in particular for stars in the halo of the Galaxy, ILOT events of MS stars in the distant past might lead to small IR excess today. The evaporated dust might survive for a relatively long time, long after the star has returned to the MS after the ILOT event. Due to uncertainties, we do not quantify the expected IR excess in this case.

To summarize, we encourage the search for evaporated Kuiper-like belts around ILOTs within several years after an outburst.

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