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Ejection of rocky and icy material from binary star systems: implications for the origin and composition of 1I/‘Oumuamua

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ABSTRACT

In single-star systems like our own Solar system, comets dominate the mass budget of bodies ejected into interstellar space, since they form further away and are less tightly bound. However, 1I/‘Oumuamua, the first interstellar object detected, appears asteroidal in its spectra and lack of detectable activity. We argue that the galactic budget of interstellar objects like 1I/‘Oumuamua should be dominated by planetesimal material ejected during planet formation in circumbinary systems, rather than in single-star systems or widely separated binaries. We further show that in circumbinary systems, rocky bodies should be ejected in comparable numbers to icy ones. This suggests that a substantial fraction of interstellar objects discovered in future should display an active coma. We find that the rocky population, of which 1I/‘Oumuamua seems to be a member, should be predominantly sourced from A-type and late B-star binaries.

Key words: minor planets, asteroids: general – minor planets, asteroids: individual: 1I/2017 U1 (‘Oumuamua) – planets and satellites: formation – binaries: general – planetary systems.

1 INTRODUCTION

With the discovery of 1I/2017 U1 (‘Oumuamua), we now have our first glimpse of an interstellar object (Meech et al. 2017). With a velocity at infinity of around 26 km s^{-1}, and an inclination of 122° that precludes a close encounter with one of the Solar system planets,[1] 1I/‘Oumuamua is securely of interstellar origin. Furthermore, Mamajek (2017) showed that the trajectory of 1I/‘Oumuamua prior to encountering the Solar system is not consistent with a recent ejection from a nearby star and that its velocity relative to the galactic background is close to the local standard of rest. This suggests that 1I/‘Oumuamua was ejected at low speed from its parent system and that it has been wandering interstellar space for a long time since.

The existence of 1I/‘Oumuamua can also be used to place constraints on the mass of material typically ejected by planetary systems (e.g. Laughlin & Batygin 2017; Raymond et al. 2018), albeit that with only a single object such estimates are subject to large uncertainties. In addition, while the orbital characteristics of 1I/‘Oumuamua are consistent with our expectations for an interstellar object, its physical characteristics are rather more surprising, in particular its lack of observable activity (e.g. Jewitt et al. 2017) and highly elongated shape (e.g. Bolin et al. 2017; Meech et al. 2017).

Ćuk (2017) recently noted that binary- and multiple-star systems could be a major source of interstellar bodies and suggested 1I/‘Oumuamua might have originated as a fragment of a larger body that was tidally disrupted during ejection from its parent system.

In this work we quantitatively examine this scenario, showing that tidal disruptions are unlikely, but that tight binary systems can nevertheless eject an amount of rocky material comparable to the predominantly icy material thrown out by single- and wide binary-star systems.

2 THE COMPOSITION AND NATURE OF 1I/‘OUMUAMUA

Three clues to the composition of 1I/‘Oumuamua are its spectral reflectance profile, lack of a coma and elongated shape. A number of groups have obtained photometric colours across a variety of bands in the visible and near-infrared (VIR e.g. Bannister et al. 2017; Bolin et al. 2017; Jewitt et al. 2017; Masiero 2017; Meech et al. 2017; Ye et al. 2017). These observations reveal an object with a relatively constant shallow red slope to its reflectance in the VIR. It is redder than some inner Solar system asteroid classes and does not demonstrate the broad absorption longwards of 0.75 μm seen in many asteroid classes. However, it is also significantly less red

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[1] Orbital parameters from JPL small body data base, ssd.jpl.nasa.gov/sbdb.cgi

than many Kuiper belt objects. Rather it seems similar to D-type asteroids or nuclei of long-period comets.

Despite its spectral similarity to volatile rich objects, 1I/‘Oumuamua has shown no detectable level of activity. Jewitt et al. (2017) place an upper limit on the rate of mass loss due to activity at $\sim 2 \times 10^{-4}$ kg s^{-1}, limiting the area of exposed water ice on the surface to <1 m^2. As they point out however, this does not preclude the existence of water ice within the interior since regolith can be an extremely good insulator (with thermal diffusivities as low as $\sim 10^{-8}$ m^2 s^{-1}) and as such the thermal impulse during its transit of the inner Solar system may only have penetrated around 0.5–1 m below the surface at the present time.

One might propose that since 1I/‘Oumuamua has spent a very long time outside the envelope of a stellar magnetosphere, exposed to the background galactic radiation environment, it might have developed a thick volatile depleted layer (e.g. Fitzsimmons et al. 2018). We find this unlikely however, as nuclei of long period comets spend the majority of their time in the outer reaches of the Oort cloud, experiencing the same interstellar radiation field that 1I/‘Oumuamua would have done, yet they become active within the inner Solar system, an issue also acknowledged by Fitzsimmons et al. (2018). Additionally, detailed calculations have shown that interstellar radiation is only capable of altering the upper few centimetres, even after over 10^9 years beyond the Solar heliopause (Cooper et al. 2003). This penetration depth would be sufficient to change the colour of the surface, but not to generate an insulating layer that could keep volatiles from degassing during passage through the inner Solar system.

As such we conclude that the lack of activity from 1I/‘Oumuamua is unlikely to be related to radiation exposure during its long sojourn in interstellar space. Instead we argue that the lack of activity is related to its origin: either it is a truly volatile poor body, or it underwent sufficient processing within its parent system to generate a thick ($\gtrsim$0.5 m) insulating crust. Both of these options imply that 1I/‘Oumuamua spent a significant period of time within the inner parts of its parent system prior to being ejected.

3 THE CASE FOR BINARY SYSTEMS AS A MAJOR SOURCE OF EJECTED MATERIAL

If we consider a star with a companion and a population of small bodies, simple analysis shows that for ejection to dominate over accretion in encounters between the small bodies and the companion, the escape velocity of the companion should exceed the Keplerian orbital velocity at its semi-major axis (e.g. Wyatt et al. 2017). This is independent of whether the companion is a planet or a star. In the Solar system, Jupiter, Saturn, Uranus, and Neptune all satisfy this criterion, however as discussed by Wyatt et al. (2017) the time-scale for ejection is also important. For Neptune and Uranus, while ejection dominates over accretion, bodies can take 100s of millions of years to be ejected, long enough for galactic tides to perturb the bodies such that they enter the Oort cloud. Moreover, as we discussed in Section 2 1I/‘Oumuamua appears to be rocky or devolatilized, suggesting that it was ejected from inside the ice line.

For a solar-mass star, efficient ejection inside typical ice line distances of a few astronomical units within the first few Myr of the life of the system requires that the companion has a mass greater than Saturn. However, radial velocity surveys show that the occurrence rate of giant planets at orbital periods of 100-400 d is low – approximately 3 per cent (Santerne et al. 2016) rising to around 10 per cent for orbital periods of <10 yr (Mayor et al. 2011). As such, we expect at most 10 per cent of Sun-like single stars will host a planet capable of efficiently ejecting material interior to the ice line. Laughlin & Batygin (2017) and Raymond et al. (2018) thus argue that if 1I/‘Oumuamua is indeed rocky, then typical extrasolar asteroid belts must be unusually massive.[2] Similarly, recent results from micro-lensing surveys (e.g. Suzuki et al. 2016; Mróz et al. 2017) suggest giant planets at larger separations are also not common.

While giant planets are relatively uncommon, tight binary systems are abundant (Duchêne & Kraus 2013), and are extremely efficient at ejecting material (Smullen, Kratter & Shannon 2016). They may therefore represent a dominant source of interstellar small bodies. We now examine this hypothesis in detail.

4 METHOD

We want to be able to examine the ejection of small bodies from binary systems, and compare this with single stars, in a way that is consistent across spectral classes. As summarized by Duchêne & Kraus (2013), the properties of binary systems, in particular their separation and their multiplicity frequency, are dependent on the mass of the primary, though they note that these dependences are subject to a fair degree of uncertainty and are the subject of active investigation. As such, we need to take into account the relative abundance of stars of different masses to be able to build a complete picture of the binary population. To do this, we construct a population synthesis model as detailed below.

Physically, our picture is one of planetesimals migrating inwards during the early phases of planet formation, in the presence of a protoplanetary disc. Holman & Wiegert (1999) showed that any material in circumbinary orbit migrating inward will become unstable on short time-scales once it passes a stability boundary $a_{\mathrm{c,\,out}}$, for which they provide an empirical fit to results from *N*-body simulations (their equation 3). This critical distance is a function of the binary mass ratio and eccentricity and ranges from around 2 to 4 times the binary separation. We thus envisage planetesimals migrating in and then being ejected once they pass $a_{\mathrm{c,\,out}}$.

4.1 Population synthesis model

Our population synthesis model proceeds as follows for the construction of an individual system:

(i) Sample the system mass, M_{sys}, from the system initial mass function of Chabrier (2003).

(ii) Sample the mass ratio, $\mu = M_2/(M_1 + M_2)$ uniformly in the range [0, 0.5], as suggested by Duchêne & Kraus (2013), and use this to calculate M_1 and M_2.

(iii) Determine which of the Duchêne & Kraus (2013) mass bins M_1 falls into and use the appropriate multiplicity fraction to determine if the system is actually binary.[3] If system is not binary set $\mu = 0$, $M_1 = M_{\mathrm{sys}}$ return to step (i) and begin again for next system.

[2] While material can still be ejected from our own inner Solar system as a result of the terrestrial planets passing material out to Jupiter, the time-scales for doing so are longer ($\sim$10–100 Myr), which means that the total mass can be significantly depleted by collisional processing prior to ejection (Jackson & Wyatt 2012; Shannon et al. 2015).

[3] Hierarchical triples would act similarly to binaries in our models, so for simplicity we ignore multiple systems.

Table 1. Binary fractions and separation distributions used in the population synthesis model. Chosen to match Duchêne & Kraus (2013).

Mass ($M_\odot$)	Binary fraction (per cent)	Separation distribution
$0.1 \leq M_1 < 0.6$	26	Log-normal, mean = 5.30 au, $\sigma_{\log_{10} a} = 0.867$
$0.6 \leq M_1 < 1.4$	44	Log-normal, mean = 44.7 au, $\sigma_{\log_{10} a} = 1.53$
$1.4 \leq M_1 < 6.5$	50	Log-normal, mean = 0.141 au, $\sigma_{\log_{10} a} = 0.50$, + log-normal, mean = 316 au, $\sigma_{\log_{10} a} = 1.65$
$M_1 \geq 6.5$	70	Log-normal, mean = 0.178 au, $\sigma_{\log_{10} a} = 0.36$, + log-uniform, min = 0.50 au, max = 10^6

(iv) Sample the eccentricity uniformly in the range [0, 0.9][4] and the binary separation from the distributions listed in Table 1.

(v) Determine stellar radii and luminosities by interpolating on isochrones generated by MIST (MESA Isochrones and Stellar Tracks, Dotter 2016; Choi et al. 2016) for a system age of 1 Myr.[5]

Our population synthesis model ensures binary systems of different masses have the correct weighting and simultaneously constructs a single-star comparison population. Integrated over all stellar masses the model produces binary systems at a rate of 30 per cent by number, while higher multiplicity rates for more massive stars means binaries constitute 41 per cent of all mass.

We assume disc dynamics are broadly the same across all systems and that disc masses are a roughly constant fraction of total stellar mass, such that the mass of material that is ejected by each binary is a constant fraction of system mass. As such we weight systems by their total mass for our analysis in later sections.

In examining our binary systems, we should also take into account that binaries with very wide separations are unlikely to have substantial material in circumbinary orbit, but rather can be expected to behave like single stars. Exactly where to draw the boundary between a wide binary in which we expect the stars to have their own discs that are largely independent and close binaries in which we expect a dominant circumbinary disc is not clear. We choose to set the boundary as the point at which the outermost stable orbit around the larger star, $a_{\rm c,\,in}$ (as determined by equation (1) of Holman & Wiegert 1999), is greater than 10 au. Our results are not sensitive to the precise choice of this cut-off however, as discussed in Section 5. Given these assumptions, we estimate a mass fraction of 26 per cent in circumbinaries, with the remainder in singles and wide binaries.

One could envisage there being some intermediate separation binaries in which a circumprimary disc extends to $a_{\rm c,\,in}$ such that material in the outer regions can be ejected due to viscous spreading across $a_{\rm c,\,in}$. The mass available for ejection in such a system is fairly limited however, being sourced from lower density outer regions of the disc, whereas inward drift can potentially make a large fraction of the mass of a circumbinary disc available for ejection. As such we focus here on circumbinary systems.

4.2 *N*-body simulations

While an object that migrates inward past $a_{\rm c,\,out}$ will become unstable on short time-scales, this does not determine the fate of the object, which can be either ejected or accreted on to one of the stars. In addition, we also want to examine the distribution of close encounter distances prior to ejection to assess the possible role of tidal disruptions as suggested by Ćuk (2017). Since the unstable region inside $a_{\rm c,\,out}$ also applies to gas, we expect that the disc will have a central cavity where the gas density is low. The fate of bodies migrating into this central unstable region can thus be determined using simple *N*-body integrations.

We conduct a set of 2000 *N*-body simulations using the high-order adaptive-timestep integrator `IAS15` in the `REBOUND` integration package (Rein & Liu 2012; Rein & Spiegel 2015). As described in Section 4.1 the mass ratio is uniformly distributed on [0, 0.5] and the eccentricity is uniformly distributed on [0, 0.9]. We then initialize particles on co-planar and initially circular orbits at orbital distances beyond the instability limit from Holman & Wiegert (1999). Finally, we apply an inward drag force that acts on a time-scale 1000 times longer than the orbital period with the `REBOUNDx` package, and integrate for 10^4 binary orbits. We track ejections by flagging particles that go beyond 100 binary orbit separations.

Since Newtonian gravity is scale invariant, we express masses in terms of the primary mass and distances in units of the binary separation. Collisions introduce the scale of the stellar radii into the problem, so we first run a universal set of 2000 integrations of point particles, and dimensionalize after the fact, drawing stellar masses, radii, and binary separations as described above. We then look for collisions with the stars in this post-processing step.

5 RESULTS AND DISCUSSION

Comparing the distribution of collisional and ejection outcomes for our *N*-body simulations, we find that the fraction of particles ejected is near unity, reaching a minimum of 95 per cent for O and B stars that have the largest collisional cross-sections. As such, it is a good approximation to assume that all material that migrates to within the critical semi-major axis will be ejected.

We now generate a synthetic population of 10^7 systems using our population synthesis models. As noted in Section 4.1 we assume that the mass of material that is ejected by each binary is a constant fraction of the system mass. For now we remain agnostic as to what this ejection fraction is and label it as $M_{\rm ej}^{\rm bin}$. We discuss possible values for $M_{\rm ej}^{\rm bin}$ and their implications in Section 5.1.

As we discussed above, we believe that 1I/‘Oumuamua either is rocky or has a substantial devolatilized crust, implying that it spent a considerable time inside the ice line in its parent system. Since bodies are rapidly ejected once they move within $a_{\rm c,\,out}$, we are interested specifically in the subset of circumbinary systems where the ice line is outside $a_{\rm c,\,out}$.

We determine ice line distance, $a_{\rm ice}$, as the distance at which the radiative equilibrium temperature of a blackbody is 150 K, assuming the total luminosity of the two stars is located at the system centre of mass. While the presence of a massive protoplanetary disc can potentially have a large effect on ice line location through optical depth preventing stellar radiation reaching the interior and through viscous heating, we note that the region interior to $a_{\rm c,\,out}$ is expected to have a low gas density such that these effects can be ignored in that region. As such, while the precise location of the ice line might vary if it is outside $a_{\rm c,\,out}$ the fraction of systems with $a_{\rm ice} > a_{\rm c,\,out}$ determined in this way should provide a reasonable estimate.

[4] We cap the eccentricity at 0.9 to avoid computationally expensive *N*-body simulations.

[5] We take 1 Myr to be a representative age of a young system in which substantial disc migration may be ongoing.

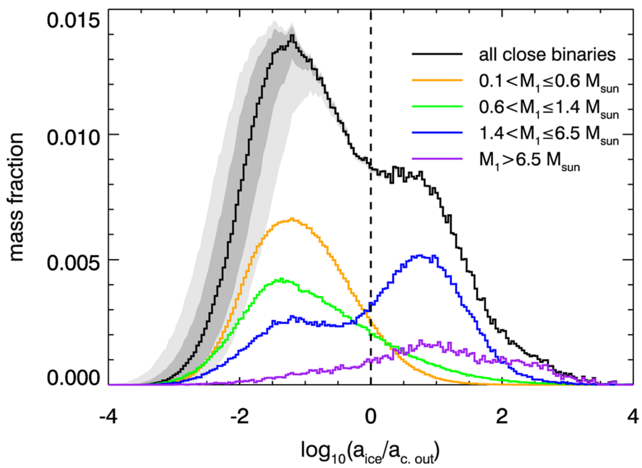

Figure 1. Histogram of $a_{\rm ice}/a_{\rm c,\,out}$ for all close binaries, weighted by the mass of the system. The total distribution is shown in black, while the orange, green, blue, and purple curves show the contributions from stars of different masses. The grey shading shows the effect of changing the wide binary cut-off to $a_{\rm c,\,in} > 2.5$, 5, 20, or 40 au. All curves are normalized to the total mass of close binaries for a wide binary cut-off of $a_{\rm c,\,in} > 10$ au. The dashed line indicates $a_{\rm ice}/a_{\rm c,\,out} = 1$.

Since we are allowing $a_{\rm ice}$ to be close to $a_{\rm c,\,out}$, it is worth considering how long a body might need to be inside $a_{\rm ice}$ to develop a substantial devolatilized layer. For Solar system, comets mass loss rates are typically a few 10^{-7} kg m^{-2} s^{-1} just inside the ice line (A'Hearn et al. 2012), corresponding to an erosion rate of ∼0.01 m yr^{-1}. These mass loss rates rise very rapidly as orbital distance decreases however, reaching ∼10^{-5}–10^{-4} kg m^{-2} s^{-1} (1–10 m yr^{-1}) by 1 au where Solar intensity is twice as high as at the ice line. As such we might expect to require a few centuries to perhaps a few millenia of continuous activity to generate a sufficiently thick devolatilized crust, which is very plausible for a 100 m cometary body migrating in via gas drag from close to $a_{\rm c,\,out}$.

In Fig. 1 we then show the distribution of $a_{\rm ice}/a_{\rm c,\,out}$, weighted by the mass of the system. With our assumption that the mass of material ejected relative to the system mass is the same for all binaries the fraction with $a_{\rm ice}/a_{\rm c,\,out} > 1$ in this distribution then tells us the fraction of interstellar material ejected by binaries that will be rocky or devolatilized. We find that this fraction is 36 per cent, such that the ratio of icy to rocky/devolatilized material is roughly 2:1. We also show the contributions from stars of different masses in Fig. 1. This shows that the population of icy interstellar material predominantly originates from low mass stars while the population of rocky/devolatilized material is dominated by intermediate mass stars. The fraction of systems with $a_{\rm ice}/a_{\rm c,\,out} > 1$ is relatively insensitive to the choice we made in Section 4.1 regarding where to place the wide binary cut-off, as shown by the grey shading in Fig. 1.

5.1 The population of interstellar bodies

The total population of interstellar bodies will be the combination of those ejected by binary systems and those ejected by single-star systems. We previously defined the fractional mass ejected by binary systems as $M_{\rm ej}^{\rm bin}$. For single-star systems (and wide binaries) we assume that ejection of significant masses of material is limited to those stars that host giant planets, and that those systems eject a fraction of their mass equal to $M_{\rm ej}^{\rm sin,gp}$. Averaged over all singles the fractional mass ejected is then $f_{\rm giant}M_{\rm ej}^{\rm sin,gp}$, where $f_{\rm giant}$ is the fraction of singles that host giant planets. The total fractional mass averaged over all stars is then

$$M_{\rm interstellar} = f_{\rm bin}M_{\rm ej}^{\rm bin} + (1 - f_{\rm bin})f_{\rm giant}M_{\rm ej}^{\rm sin,gp}, \qquad (1)$$

where $f_{\rm bin}$ is the mass fraction of stars that are binaries. In Section 4.1 we found $f_{\rm bin} = 26$ per cent, while in Section 3 we argued $f_{\rm giant}$ is no more than 10 per cent. Using these values equation (1) becomes

$$M_{\rm interstellar} = 0.26M_{\rm ej}^{\rm bin} + 0.074M_{\rm ej}^{\rm sin,gp}. \qquad (2)$$

We are also interested in the fraction of all interstellar bodies that are rocky or devolatilized rather than icy, $R_{\rm interstellar}$. We thus divide the ejected masses into rocky and icy components such that

$$R_{\rm interstellar} = \frac{M_{\rm interstellar,rock}}{M_{\rm interstellar}} = \frac{0.26R_{\rm bin}M_{\rm ej}^{\rm bin} + 0.074R_{\rm sin}M_{\rm ej}^{\rm sin,gp}}{0.26M_{\rm ej}^{\rm bin} + 0.074M_{\rm ej}^{\rm sin,gp}}, \qquad (3)$$

where $R_{\rm bin}$ and $R_{\rm sin}$ are the rock/ice fractions for binaries and single systems, respectively.

The Nice model for the early evolution of the outer Solar system suggests that the Solar system began with an outer planetesimal disc of ∼30 $M_\oplus$, the majority of which was ejected (e.g. Gomes et al. 2005; Levison et al. 2008). In addition, perhaps 1 $M_\oplus$ was ejected from the inner Solar system (e.g. Shannon et al. 2015). If other systems that host giant planets behave in a similar way to the Solar system then, taking a median value we can expect that $M_{\rm ej}^{\rm sin,gp} \sim 30M_\oplus/{\rm M}_\odot$ and that $R_{\rm sin} \sim 0.033$.

We must now estimate $M_{\rm ej}^{\rm bin}$. In doing so we first note that from our *N*-body simulations we expect binaries to eject essentially all material that migrates to within $a_{\rm c,\,out}$. Moreover since the ejection mechanism only relies on the central binary itself, material can be ejected from very early in the life of the system, whereas in an individual system ejection can only begin once a giant planet has formed. If most systems begin with discs close to the gravitational instability limit of ∼0.1 $M_{\rm sys}$ and a typical gas-to-dust ratio of around 100 this implies a total mass of solids of ∼300 $M_\oplus/{\rm M}_\odot$. If we estimate that around 10 per cent of this material migrates to within the critical stability radius, this implies that every binary system ejects as much material as a single-star system that hosts giant planets. Using $M_{\rm ej}^{\rm bin} \sim 30M_\oplus/{\rm M}_\odot$ as our fiducial value, we then find that $M_{\rm interstellar} \sim 10M_\oplus/{\rm M}_\odot$. Since we expect $R_{\rm bin} = 0.36$, this leads to $R_{\rm interstellar} \sim 0.29$. With this estimate more than three-quarters of interstellar bodies originate from binary stars, while for rocky objects the fraction would be even higher.

5.2 Tidal disruptions versus extreme heating

Ćuk (2017) suggested that 1I/'Oumuamua might have originated as a tidal disruption event of a planet. We can test this hypothesis with our *N*-body simulations. For massive stars, the Roche limit (inside which tidal disruptions will occur) is smaller than the stellar radius. To provide the best-case scenario for tidal disruptions, we re-calculate the stellar collision outcomes using stellar radii for the Zero Age Main Sequence, when the radii are at a minimum. Treating a gravity-dominated planet as a strengthless body, we compute the Roche radius as $R_{\rm Roche} = 1.26(\rho_*/\rho_p)^{(1/3)}R_*$, where we assume a lower bound for the density of the planet of $\rho_p = 3000$ kg m^{-3}. We find that none of our 2000 simulations results in a close encounter within the Roche radius. Indeed the majority of closest approach distances are far outside the Roche radius. This implies that the frequency of tidal disruptions is $\lesssim 10^{-3}$ times the ejection rate.

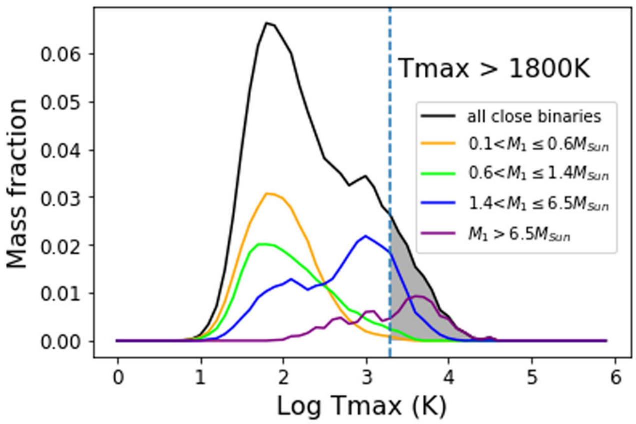

Figure 2. Mass weighted distribution of peak temperatures reached by particles ejected in our *N*-body simulations.

Note that there is no contribution from higher mass stars since they always have their Roche radius inside the star.

While we have shown that tidal disruptions are rare, material that is ejected can potentially be heated to high temperatures during a close approach. In Fig. 2 we show the mass weighted distribution of peak temperatures experienced by particles in our *N*-body simulations before they are ejected. Around 10 per cent of bodies experience peak temperatures in excess of 1800 K, sufficient to melt rock. These are drawn from systems independent of their ice line distances, though we note that systems with higher temperatures at the stability boundary $a_{\mathrm{c,\,out}}$ are more likely to experience extreme heating. It would be interesting to consider in future work how extreme heating may modify the shape and surface layers of 1I/‘Oumuamua. We do note that the extreme elongation would be easier to maintain for an annealed, monolithic body than for a rubble pile. The fact that such heating predominantly occurs around high-mass stars also further motivates understanding the planet formation process in these extreme regimes.

Since submission of this work, the revised manuscript of Ćuk (2017) points out that planets on circumprimary (S type), rather than the circumbinary (P type) orbits considered here, may be tidally disrupted more effectively. As he points out, a dynamical instability of several planets around a single star would be required to scatter the doomed planet into a region of phase space where it can chaotically transfer between stars and suffer a close enough encounter for tidal disruption. It would be valuable to extend the analysis of Ćuk (2017) to quantify the fraction of instabilities that deliver planets into this regime instead of directly ejecting them.

6 CONCLUSIONS

We have shown that the population of interstellar objects can be dominated by planetesimals ejected during planet formation in circumbinary systems. Even if a typical circumbinary only ejects as much material as the Solar system, we still expect close binaries to be the source of more than three-quarters of interstellar bodies due to the relatively low abundance of single-star systems with giant planets like the Solar system. Whereas in the Solar system ejected material is overwhelmingly icy, we expect around 36 per cent of binaries may predominantly eject material that is rocky or substantially devolatilized, leading to similar expectations for the abundance of rocky/devolatilized bodies in the interstellar population.

Within the close binary population the dominant sources of rocky/devolatilised material are intermediate mass stars, A-stars and late B-stars. As such, we suggest that the apparently rocky or devolatilized appearance of 1I/‘Oumuamua indicates that it likely originated in such an intermediate mass binary system.

We find tidal disruptions during ejection from binary systems, as suggested by Ćuk (2017), are rare. While close encounter distances that result in strong tidal effects are highly unusual around 10 per cent of bodies may experience extremely high peak temperatures during ejection. How extreme temperatures could influence the shape and surface layers of a body like 1I/‘Oumuamua is an interesting topic for future work, and that such heating predominantly occurs around high-mass stars also further motivates understanding the planet formation process in these extreme regimes.

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