EJECTION OF ROCKY AND ICY MATERIAL FROM BINARY STAR SYSTEMS: IMPLICATIONS FOR THE ORIGIN AND COMPOSITION OF 1I/'OUMUAMUA A.P. Jackson[1,2], D. Tamayo[1,3], N. Hammond[1], M. Ali-Dib[1,3], H. Rein[1], [1]Centre for Planetary Sciences, University of Toronto, Toronto, ON, Canada, [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA, [3]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON, Canada
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Introduction: With the discovery of 1I/2017 U1 ('Oumuamua) we now have our first glimpse of an interstellar object [1]. The existence of 1I/'Oumuamua can also be used to place constraints on the mass of material typically ejected by planetary systems, [e.g. 2, 3], 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. 4] and highly elongated shape [e.g. 5,1].

Ćuk [6] recently noted that binary and multiple star systems could be a major source of interstellar bodies and suggested that 1I/'Oumuamua might have originated as a fragment of a larger body that was tidally disrupted during ejection from its parent system.

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.

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 with the companion, the escape velocity of the companion should exceed its Keplerian orbital velocity [e.g. 7]. In the Solar system Jupiter, Saturn, Uranus and Neptune all satisfy this criterion, however Neptune and Uranus bodies can take ~10^8 years to eject bodies, long enough for galactic tides to perturb them into the Oort cloud. Moreover the lack of activity implies that 1I/'Oumuamua is rocky or devolatilised, suggesting it was ejected from inside the ice line.

For a solar-mass star, efficient ejection inside typical ice line distances of a few AU within the first few Myr requires that the companion has a mass greater than Saturn. However, radial velocity surveys show that the occurrence rate of giant planets at intermediate orbital periods of 100-400 days is low (~3-10% [8,9]). As such, we expect that at most 10% of Sun-like single stars will host a planet capable of efficiently ejecting material interior to the ice line. [2,3] thus argue that if 1I/'Oumuamua is indeed rocky, then typical extrasolar asteroid belts must be unusually massive.

While giant planets are relatively uncommon, tight binary systems are abundant [10], and are efficient at ejecting material [11]. They may therefore represent a dominant source of interstellar small bodies.

Method: To examine the ejection of small bodies from binary systems, and compare this with single stars, consistently across spectral classes we construct a population synthesis model using the system initial mass function of [12], the binary properties of [10] and the MIST stellar isochrones [13,14].

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% by number, while higher multiplicity rates for more massive stars mean that binaries constitute 41% of all mass.

We assume that disk dynamics are broadly the same across all systems and that disk masses are a roughly constant fraction of the total stellar mass, such that the mass of material that is ejected by each binary is a constant fraction of the system mass.

Physically, our picture is one of planetesimals migrating inwards during the early phases of planet formation, in the presence of a protoplanetary disk. Any material in circumbinary orbit migrating inward will become unstable on short timescales once it passes a stability boundary $a_{c,out}$ [15]. 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 $a_{c,out}$.

To examine the fate of particles that become unstable, and study distribution of close encounter distances prior to ejection, we conduct a set of 2000 *N*-body simulations using the high-order adaptive-timestep integrator IAS15 in the REBOUND integration package [16,17]. We sample the binary mass ratio and eccentricity uniformly and then initialize particles on coplanar and initially circular orbits at orbital distances beyond the instability limit. Finally, we apply an inward drag force that exponentially decreases the semimajor axis on a timescale 1000 times longer than the orbital period, and integrate for 10^4 binary orbits. We track ejections by flagging particles that go beyond 100 binary orbit separations.

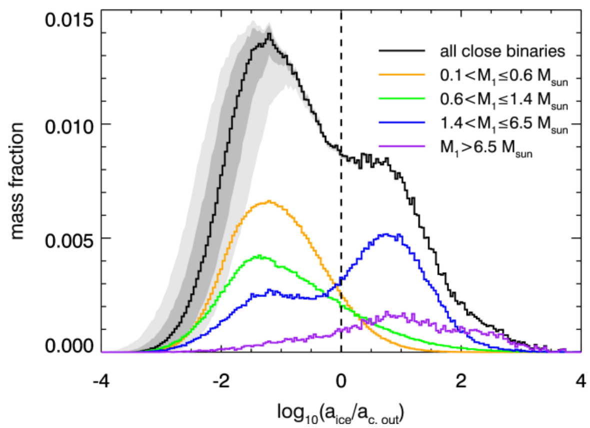

Figure 1: Histogram of $\boldsymbol{a_{ice}/a_{c,out}}$, for all close binaries, weighted by system mass. The total distribution is shown in black, while the orange, green, blue and purple curves show the contributions from stars of different masses. The grey shading shows the effect of changing the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

Results and discussion: Examing our *N*-body simulations we find that the fraction of particles ejected is near unity, reaching a minimum of 95% for O and B stars that have the largest collision cross-sections.

We then generate a population of 10^7 systems using our population synthesis model. We assume that each binary ejects a constant fraction, M_{ej}^{bin}, of the system mass. Since it is believed that 1I/`Oumuamua is rocky or has a substantial devolatilized crust, and bodies are rapidly ejected once they pass inside $a_{c,out}$ we are interested in the subset of circumbinary systems where the ice line is outside $a_{c,out}$.

We determine the ice line distance, a_{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.

In Fig. 1 we show the distribution of $a_{ice}/a_{c,out}$, 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 $a_{ice}/a_{c,out} > 1$ in this distribution tells us the fraction of interstellar material ejected by binaries that will be rocky or devolatilised. We find that this fraction is 36%, such that the ratio of icy to rocky/ devolatilized material is roughly 2:1. We also in Fig. 1 show the contributions from stars of different masses. This shows that the population of icy interstellar material predominantly originates from low mass stars while the population of rocky/devolatilised material is dominated by intermediate mass stars. The fraction of systems with $a_{ice}/a_{c,out} > 1$ is relatively insensitive to the choice we made for the wide binary cut-off, as shown by the grey shading in Fig. 1.

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_{ej}^{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 $M_{ej}^{sin,gp}$.

For the Solar system typical estimates give around 30 $M_\oplus$ of ejected material, of which perhaps 1 $M_\oplus$ is rocky. Taking this as typical gives $M_{ej}^{sin,gp} \sim 30\, M_\oplus/M_\odot$, with a rocky/icy ratio of $R_{sin} \sim 0.033$. We expect binary systems to be at least as efficient at ejecting material as the Solar system, and taking $M_{ej}^{bin} \sim 30\, M_\oplus/M_\odot$ leads to an interstellar population of $\sim 10\, M_\oplus/M_\odot$. For binary systems we find a rocky/icy ratio of $R_{bin} = 0.36$, which leads to $R_{interstellar} \sim 0.29$ for the combined interstellar population. With these estimates more than 75% of interstellar bodies originate from binary stars, rising even higher for rocky objects.

Ćuk [6] suggested that 1I/'Oumuamua might have originated as a tidal disruption event of a planet. We find that none of our 2000 simulations result in a close encounter within the Roche radius, using the ideal case of the Zero Age Main Sequence when stellar radii are at a minimum. This implies a frequency of direct tidal disruptions $\leq 10^{-3}$ times the ejection rate.

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