HOW MANY INTERSTELLAR NITROGEN ICE FRAGMENTS LIKE ‘OUMUAMUA ARE THERE?

S. J. Desch[1] and A. P. Jackson[1], [1]School of Earth and Space Exploration, Arizona State University (steve.desch@asu.edu)

Introduction: While initially mysterious after its discovery [1], the first interstellar object ‘Oumuamua is now completely explained if it was a 45 × 45 × 8 m fragment of N_2 ice similar to ice seen on the surface of Pluto [2]. Such a fragment would have Bond albedo 0.65, matching Pluto’s surface, and would be pushed by sublimation of N_2 ice at a rate exactly matching ‘Oumuamua’s non-gravitational acceleration. The composition like Pluto’s surface would match its red color exactly, and explain the lack of observed dust, H_2O, or CO.

In addition, it is now recognized [3] that more fragments like this than comets would have been ejected from our Solar System during the outer Solar System giant planet instability (e.g., the Nice instability [4]). The primordial Kuiper Belt contained about 35 Earth masses of bodies, including 4000 objects ≥ 600 km in radius, and 2000 objects ≥ 1200 km in radius (larger than Pluto) [5]. All of these objects could have differentiated and emplaced thick (tens of km) layers of N_2 ice on their surfaces within the first < 100 Myr of the Solar System [2]. Multiplying the rate of collisions with the amount of mass ejected per collision (from the Housen-Holsapple [6] relations, for typical impact velocities ~3 km/s), [2] calculated that 0.013 Earth masses of fragments of typical size ~100 m were ejected, equivalent to $\sim 2\times10^{14}$ such fragments, compared to 10^{12}-10^{13} comets [7]. Collisional fragments like this were not previously considered as part of the debris ejected from stellar systems. The number of fragments approaches the number inferred from the occurrence rate of interstellar objects, roughly 3×10^{15} fragments per solar mass of star. The ejection of such objects early ($< 10^8$ years) in the lifetime of stellar systems furthermore explains the low velocity of ‘Oumuamua with respect to the Local Standard of Rest [2].

The exact match of an N_2 ice fragment to ‘Oumuamua’s observed behavior, and the large numbers of N_2 ice fragments thought likely to be ejected from stellar systems, make fragments from differentiated Kuiper Belt Objects (KBOs) in other stellar systems—“exo-plutos”—a compelling explanation for objects like ‘Oumuamua.

Frequency of ‘Oumuamua-like Objects: While fragments outnumber comets and approach the number needed to explain the occurrence rate of ‘Oumuamua, the number ejected by our Solar System nevertheless falls short of the number inferred from the occurrence rate of ‘Oumuamua-like objects. After accounting for their ejection efficiencies and survival rates against erosion by Galactic cosmic rays (GCRs) in the interstellar medium (ISM), [3,8] estimated a density of such objects ≈ 0.0005 AU^{-3}, if all stellar systems eject the same number of fragments per stellar mass as the Solar System did. This is to be compared to the estimate of 0.04 interstellar objects per AU^3 (the estimate of [1], revised downward by a factor of 2 to account for the longer timeframe), or a 95% confidence interval 0.002 to 0.12 AU^{-3} [8]. If all stellar systems ejected the same number of fragments per solar mass as the Sun, the predicted density of interstellar objects would be a factor of 80 lower than the expected value, and a factor of 4 outside the 95% confidence interval.

This discrepancy has been mischaracterized as being five or more orders of magnitude [9], but is only about one order of magnitude. Given the large uncertainties inherent in the problem, this is suggestive that N_2 ice fragments are a likely and perhaps dominant source of interstellar objects, but also suggestive of some incompleteness in our understanding.

N_2 Ice Fragments from M Star Systems: To match the inferred frequency of ‘Oumuamua-like objects, most stellar systems would have to eject about an order of magnitude more N_2 ice fragments (per stellar mass) than the Solar System did. This is most likely the case for planetary systems around M stars. Building on our theory [3], we [8] showed that a stellar system evolving like our Solar System did, with a dynamical instability in the outer system, should eject a mass of fragments

$$M_{FRAG} \sim M_{DISK}\,(M_{DISK} / r_{N2}^{3})\, V_{REL} V_{REL}^{1.65}\, t,$$

where M_{DISK} is the mass of the disk, r_{N2} is the innermost radius where KBO-like bodies could support N_2 ice on their surfaces, V_{REL} is the typical relative velocities of objects intercepting KBOs, the factor of 1.65 comes from the Housen-Holsapple [6] relations for mass of material ejected, and t is the duration of the dynamical instability. The factor (M_{DISK} / r_{N2}^{3}) is proportional to the spatial density of KBOs; multiplying by V_{REL} yields the rate of collisions; the next term provides the mass per collision; and integration over time gives the total mass of fragments produced. Comparing these factors to ones appropriate to the Sun shows that M stars should be much better ejectors of N_2 ice fragments.

M stars are better ejectors of N_2 ice fragments for several reasons. N_2 ice can survive much closer to an M star than it did to the early Sun, $r_{N2} \sim 15$ AU. Assuming a luminosity $\sim 0.003\ L_\odot$ for an M star with mass $M_\star \sim 0.1\ M_\odot$ and age ~100 Myr, $r_{N2} \sim 1$ AU. At this distance, $V_{REL} \sim 0.3\ (GM_\star/\ r_{N2})^{1/2} \approx 2.8$ km/s, about the same as the 2.3 km/s relative velocity as at 15 AU in the Solar System. Assuming the duration of the instability scales with the orbital period $\sim r_{N2}^{3/2}$, and M_{DISK} scales with the stellar mass $M_\star$, an M star system with mass $0.1\ M_\odot$ is almost exactly a factor of 10 more efficient at ejecting N_2 ice fragments than the Solar System. This does not take into account the greater ability of N_2 ice fragments to resist vaporization near their host stars as they are ejected, as accounted for by [3]; this would increase the fraction by a factor of 1.6.

About 1/3 of the mass of all stars is in M stars, so it would be reasonable to estimate that the average stellar system ejects about a factor of 5 more fragments per stellar mass than the Sun did. That would lead to a predicted density of interstellar objects 0.0025 AU^{-3}, at the lower end of the 95% confidence interval; or even high values more consistent with the best guess.

The Exoplanet-Solar System Connection: Solar System studies inform our understanding of interstellar objects from exoplanetary systems. ‘Oumuamua could be identified as N_2 ice precisely because it had been observed on the surface of Pluto. Quantities like the albedo and redness of natural, space-weathered N_2 ice were key to identifying ‘Oumuamua as a piece of an exo-pluto [2]. Likewise, studies of the Kuiper Belt and the dynamical instability that sculpted it [4] were necessary to understand how fragments could have been created and ejected from our Solar System. It is now possible to use the interstellar objects to infer the existence of exo-plutos, to infer that such bodies differentiated, and to infer that dynamical instabilities like the Nice model were common in such systems.

With better models of the early dynamical history of the Solar System, and the timing of the dynamical instability, more precise predictions of the ejection efficiency of N2 ice fragments can be produced; this in turn will allow new constraints on the frequency of interstellar objects from the Vera Rubin Observatory [10] to be turned into meaningful inferences about the frequency of dynamical instabilities in exoplanetary systems.

At the same time, studies of interstellar objects from exoplanetary systems inform new Solar System investigations. The lifetime of interstellar objects like ‘Oumuamua depends the rate at which N_2 ice is sputtered by Galactic cosmic rays [3], motivating laboratory experiments that would also have relevance to the persistence of N_2 ice on the surface of Pluto and other KBOs. The model of [3] has brought to the forefront the importance of collisional fragments produced during the Nice instability, and suggested the presence of some N_2 ice fragments among the population of long-period comets. The comet C/2016 R2, recognized when it was discovered as resembling the surface of a differentiated KBO [11], appears to be an analog to ‘Oumuamua.

Comparative studies of long-period comets, KBOs including Pluto, and interstellar objects from exo-Pluto surfaces, represent an important area in which Solar System science and exoplanetary system science overlap.

References: [1] Meech, K. et al. (2017) *Nature* 552, 378. [2] Jackson, A. P. and Desch, S. J. (2021) *JGR,* 12606706. [3] Desch, S. J. and Jackson, A. P. (2021) *JGR*, 12606807. [4] Tsiganis, K. et al. (2005) *Nature* 435, 459. [5] Nesvorny, D. and Vokrouhlicky, D (2016) *Ap.J.* 825, 94. [6] Housen, K. and Holsapple, K. (2011) *Icarus* 211, 856. [7] Dones, L. et al. (2015) *Space Sci. Rev.* 197, 191. [8] Desch, S. J. and Jackson, A. P. (2022) *Astrobiology* in press. [9] Siraj, A. and Loeb, A. (2022) *New Astronomy* 92, 101730. [10] https://www.lsst.org/ [11] Biver, N. et al. (2018) *A&A* 619, A127.