CHIPS OFF THE OLD BLOCK: 1I/‘OUMUAMUA AND C/2016 R2 AS FRAGMENTS OF THE SURFACES OF PLUTO-LIKE PLANETS Alan P. Jackson[1] and Steven J. Desch[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ (alan.jackson@asu.edu)

Oumuamua as a collision fragment: The existence of interstellar objects had been discussed long before the discovery of 1I/‘Oumuamua in 2017 [e.g., 1], yet ‘Oumuamua defied expectations in several ways. Whereas it had been expected that interstellar objects would be predominantly comets, no dust production or outgassing was detected [e.g., 2, 3]. This led to initial speculation that ‘Oumuamua was a volatile-poor body, but further observations revealed that the trajectory of ‘Oumuamua demanded a non-gravitational force directed away from the Sun varying roughly as $1/r^2$ [4]. Such a force would be consistent with cometary outgassing, albeit at a slightly higher magnitude than is typical for comets, but again no species typically observed in cometary comae were detected. Additionally, ‘Oumuamua has an extremely flattened shape, more extreme than any known Solar System object, with the most recent estimates corresponding to an oblate object with axis ratios of roughly 6:6:1 [5].

Recently, we demonstrated that all of the unusual properties of ‘Oumuamua are explained if it is composed of N_2 ice like that found on the surface of Pluto [6]. We found that N_2 ice provides the non-gravitational acceleration necessary to match observations at either a low albedo ∼0.1, or a high albedo ∼0.64 (see Fig. 1). This high-albedo solution, compellingly, matches the albedos of the N_2-covered surfaces of outer Solar System bodies like Pluto and Triton. The red color and spectral slope of ‘Oumuamua also were a good match to Pluto’s surface. N_2 gas is difficult to detect, explaining the lack of detected outgassing, despite the non-gravitational acceleration. Moreover, an N_2 ice composition also explains the extreme axis ratio, which is a natural result of the extreme mass loss ‘Oumuamua would have undergone as it passed perihelion at 0.255 au, within the orbit of Mercury.

The similarity between the high-albedo solution for N_2 ice and the surfaces of Pluto and Triton also provides a clue to the origin of ‘Oumuamua. Today Pluto and Triton have N_2 ice layers a few km thick [9, 10], but this could have been tens of km thick in the past if one considers the cosmic abundance of nitrogen (which allows for the mass of N_2 ice to be as high as 16% that of H_2O ice [11]). We showed that, given a thicker initial N_2 ice layer, collisions between Kuiper Belt objects during the outward migration of Neptune (which ejected ∼20-35 $M_\oplus$ of material from the Solar System [12, 13]) would have produced sufficient numbers of N_2 ice fragments to explain the estimated number density of ‘Oumuamua-like objects, provided other stellar systems ejected fragments with efficiency comparable to the Solar System [14].

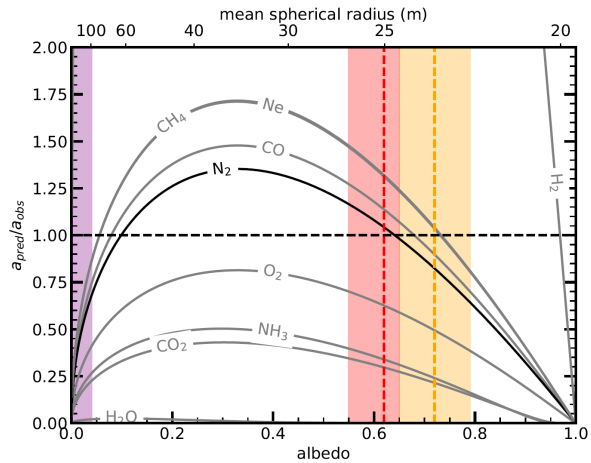

Figure 1: Predicted non-gravitational acceleration at 1.42 au due to sublimation and jetting, relative to the observed value, assuming ‘Oumuamua is an oblate ellipsoid of pure ice with the labelled compositions, for a range of values of the common geometric and bond albedo. The top axis converts albedo into mean spherical radius assuming a 6:6:1 axis ratio. Note that the H_2 curve extends far above the plotted range, peaking at ∼13. The orange and red bands show the reported Bond and geometric albedos for Pluto respectively [7, 8]. The purple band shows the range disallowed by the Spitzer non-detection. (Figure from [6].)

In total we estimate that 0.5 - 3% of the mass of Pluto-sized (∼1200 km radius) to Gonggong-sized (∼600 km radius) bodies respectively could have been converted into impact fragments, with N_2 ice comprising about 1/3 of the ejecta and the remainder being H_2O ice. The total mass of collisional fragments is thus relatively small, but ejecta fragments have a steep size distribution, such that we expect them to have dominated the material ejected from the early Solar System at small sizes. Both N_2 and H_2O ice fragments must slowly erode in the interstellar medium through the action of galactic cosmic rays, such that we expect average age of N_2 ice fragments ejected from stellar systems to be ∼0.5 Gyr (lifetime ∼1 Gyr), and the average H_2O ice fragment to have an age of ∼2 Gyr.

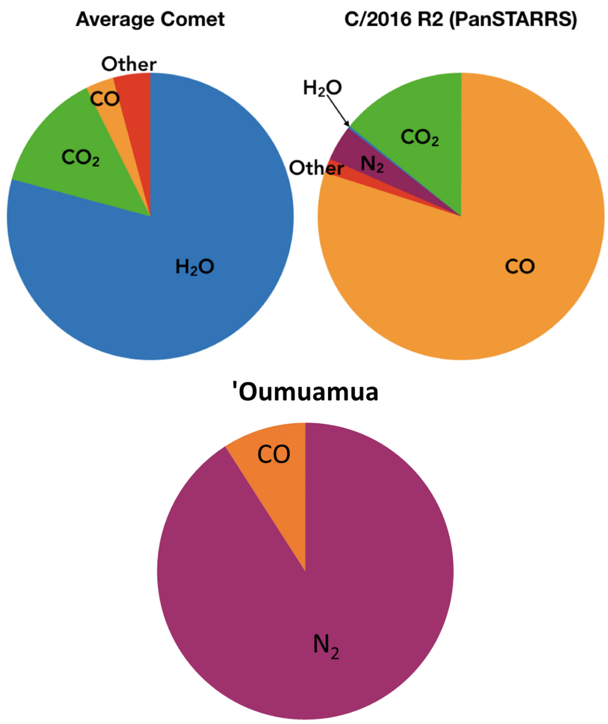

Figure 2: *Top*: composition of the outgassed species of C/2016 R2 as compared to the average of Solar System comets, after [15]. *Bottom*: composition of 'Oumuamua including possible CO contribution of up to 10%.

Cometary examples of Oumuamua-like objects? A robust prediction of the model of [6,14] is that a fraction of the objects ejected from the Solar System remained trapped in the Oort cloud. These could be observable today as long-period comets. Most of the initial inventory of N_2 ice fragments in our Oort cloud would now have been depleted due to cosmic ray erosion over 4.5 Gyr, but some may still remain. An intriguing comet that might represent such a collisional fragment is the extremely unusual Solar System comet C/2016 R2 (PanSTARRS). H_2O, usually dominant in comets, is only a trace species in C/2016 R2. It is instead dominated by CO, and N_2 is also far more abundant than usual, dominating the nitrogen-bearing species (see Fig. 2, [15]). These characteristics led [16] to conclude it was a collisional fragment of a Pluto-like planet.

The comparison between 'Oumuamua and C/2016 R2 is intriguing. Both objects are remarkably, almost uniquely, H_2O-poor. N_2 is nearly absent in most comets but is a major component of C/2016 R2, and likely dominates 'Oumuamua. That N_2 was detected in R2 but not 'Oumuamua can be attributed to the fact that C/2016 R2 is a much larger object than 'Oumuamua, with an N_2 production rate (4.8×10^{27} molecules/second) around 500 times higher than we infer for 'Oumuamua during the main observations. The CO that dominates R2 also could be a substantial component of 'Oumuamua: the observational limits allow for a CO contribution of up to 10% of the total, as shown in Fig. 2 (note that there is a mistake in the CO upper limit stated by [3], and used by [6], and it should actually be 10 times higher than the CO_2 limit, not 10 times lower [17]).

The ices of CO and N_2 are near thermodynamic twins, with very similar (low) sublimation temperatures, being retained in the Solar System today only on larger KBOs capable of supporting a thin atmosphere to balance the vapor pressure, or on even colder objects beyond the Kuiper Belt. Although no observed Kuiper Belt Objects appear dominated by CO like R2, it is possible. The sublimation temperature of CO is very slightly higher than N_2, leading to a narrow orbital band in which N_2 will be lost while CO would be retained. More likely the difference is related to the physical processes of differentiation on the parent body of C/2016 R2.

The inventory of collisional fragments from the surfaces of ultra-cold bodies, both originating from the Solar System and from other planetary systems, will dramatically increase over the next decade thanks to the Vera Rubin Observatory Legacy Survey in Space and Time (LSST). This will allow collisional fragments to become important tracers for understanding differentiation processes on Pluto-like planets bodies in other stellar systems.

References

[1] McGlynn T.A. and Chapman R.D. (1989) *Astrophys. J. Lett.*, 346, L105
[2] Jewitt D., et al. (2017) *Astrophys. J. Lett.*, 850(2), L36
[3] Trilling D.E., et al. (2018) *Astron. J.*, 156(6), 261
[4] Micheli M., et al. (2018) *Nat.*, 559, 223
[5] Mashchenko S. (2019) *Mon. Not. R. Astron. Soc.*, 489(3), 3003
[6] Jackson A.P. and Desch S.J. (2021) *J. Geophys. Res. (Planets)*, 126(5), e06706
[7] Buratti B.J., et al. (2015) *Astrophys. J. Lett.*, 804(1), L6
[8] Buratti B.J., et al. (2017) *Icarus*, 287, 207
[9] Cruikshank D.P., et al. (1998) In B. Schmitt, C. de Bergh, and M. Festou, eds., *Solar System Ices*, volume 227 of *Astrophysics and Space Science Library*, p. 655
[10] McKinnon W.B., et al. (2016) *Nat.*, 534(7605), 82
[11] Lodders K. (2003) *Astrophys. J.* , 591(2), 1220
[12] Tsiganis K., et al. (2005) *Nat.*, 435(7041), 459
[13] Nesvorný D. and Vokrouhlický D. (2016) *Astrophys. J.* , 825(2), 94
[14] Desch S.J. and Jackson A.P. (2021) *J. Geophys. Res. (Planets)*, 126(5), e06807
[15] McKay A.J., et al. (2019) *Astron. J.*, 158(3), 128
[16] Biver N., et al. (2018) *Astron. Astrophys*, 619, A127
[17] 'Oumuamua ISSI Team, et al. (2019) *Nat. Ast.*, 3, 594