TO SEE A WORLD IN A SHARD OF ICE: ‘OUMUAMUA AS A FRAGMENT OF N_2 ICE FROM AN EXO-PLUTO.

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Introduction: The first confirmed interstellar object [1], 1I/‘Oumuamua has been the subject of much discussion and speculation since its discovery in 2017. The are a number of features of ‘Oumuamua that seem unusual by comparison with what we might have expected based on our experiences in the Solar system, though many are not as mysterious as they appear at first glance [e.g., 2].

Most of the odd features of ‘Oumuamua appear to have rather prosaic explanations, but the most enduring mystery regards its composition and, related to this, its non-gravitational acceleration. Observations placed strict upper limits on outgassing of dust, CO and CO_2 [3,4]. With no direct observations of outgassing, much initial work focused on the idea of a very volatile-poor body and explaining the possible origins of such an object. Further observations, however, revealed that matching the observed trajectory of ‘Oumuamua required the addition of a non-gravitational force directed away from the Sun, with a magnitude around 10^{-3} that of the gravitational force, and varying as roughly $1/d^2$ (d being distance from the Sun) [5]. Such a force would be consistent with cometary outgassing, but appears at odds with the strict upper limits on species that are typically found in cometary comae. It has not been clear what ice composition could provide sufficient force through sublimation to explain the non-gravitational acceleration, while at the same time remaining undetectable.

Seligman & Laughlin [6] proposed that ‘Oumuamua contained a substantial quantity of H_2 ice, which they showed could provide the necessary non-gravitational acceleration if it covered around 6% of the surface. H_2 is highly problematic, however, because it has an extremely low condensation temperature, ~4 K, that cannot be reached anywhere but the most extreme molecular cloud core environments [7]. Moreover, an H_2 ice body would sublimate away rapidly even in interstellar space, with even a multi-km body lasting less than 10^8 years [8].

In this work, we focus on a possibility that was overlooked by Seligman and Laughlin [6]: N_2 ice.

The case for N_2 ice: In recent work [9], we revisited the non-gravitational acceleration calculations of [6] and some of the assumptions that they made, producing a revised formulation. In particular, the calculations of [6] assumed a fixed albedo of 0.1, but it is not at all clear that this is justified for ices. An important part of calculating the non-gravitational acceleration is knowing the shape of the body. We adopted the oblate solution of Mashchenko [10], which has roughly 6:6:1 axis ratios, scaling the absolute size of the body to match the albedo. Using our revised formulation, we calculated the non-gravitational acceleration provided by a selection of different sublimating ices, including species commonly observed in comets such as H_2O, CO and CO_2, making no assumptions about the albedo. The results are shown in Fig. 1. We find 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. This high-albedo solution, compellingly, matches the albedos of the N_2-covered surfaces of outer Solar system bodies like Pluto and Triton.

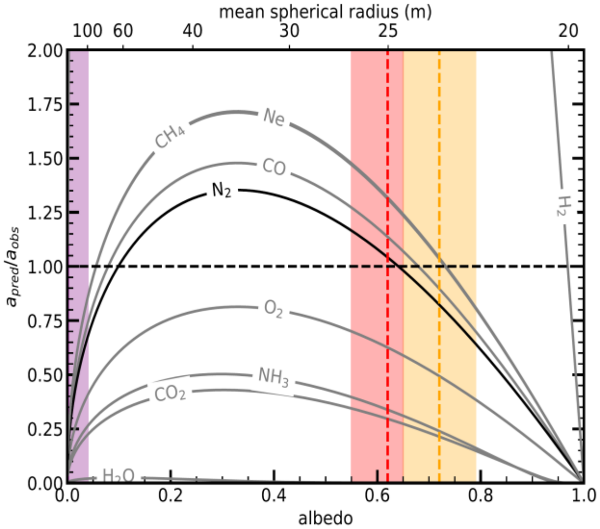

Fig. 1: Predicted non-gravitational acceleration at 1.42 au due to sublimation and jetting, relative to the observed value, assuming ‘Oumuamua is an oblate ellipsoid of pure ice with the labelled compositions, for a range of values of the common geometric and bond albedo. The top axis converts albedo 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 [11,12]. The purple band shows the range disallowed by the Spitzer non-detection.

Fig. 1 provides strong evidence for an N_2 ice composition. The common astrophysical ices H_2O and CO_2 are immediately ruled out as being unable to provide sufficient acceleration at any albedo. While sublimation of H_2 ice could provide sufficient force to match observations, there are many problems with the assembly and survival of large accumulations of H_2 ice [8]. With a sublimation temperature of only 9 K most of the issues that apply to H_2 also apply to Ne, with the added problem of much lower cosmic abundance. CO and CH_4 would be potentially viable, but the *Spitzer* observations place strict upper limits on the CO production rate at only ~0.1% of that required to match the non-gravitational acceleration. CH_4 ices are observed on Pluto, but overwhelmingly as a trace species dissolved in N_2 ice at no more than a few weight percent [13]. Except for H_2O and CO or CO_2 ices, which are ruled out, the only ice observed to exist in the Solar System is N_2 ice. This makes N_2 ice the most plausible composition for ‘Oumuamua.

Origin of an N_2 ice fragment: In recent work [14] we consider the likelihood that ‘Oumuamua could be a fragment of N_2 ice. In considering the origin and expected occurrence rate of N_2 ice fragments we return to our comparison with the surfaces of Pluto and Triton. Today N_2 ice covers the surfaces of Pluto and Triton to depths of a few km [15,16], but the N_2 ice layer may have been much thicker in the past. The cosmic abundance of nitrogen allows for the mass of N_2 ice to be as high as 16% that of H_2O ice [17]. On Pluto, an N_2 ice layer of this thickness would be around 35 km thick, while on a smaller body like the Kuiper belt object (KBO) Gonggong, with radius ~600 km, an equivalent layer would be around 18 km thick.

The Kuiper Belt is estimated to have contained 20-35 Earth masses of material prior to the outward migration of Neptune, of which only ~0.1% remains today [18,19]. It is likely that around 6 Earth masses of this primordial Kuiper belt were in KBOs larger >600 km in radius to satisfy requirements on the ‘graininess’ of Neptune’s migration [19], and the number of such objects remaining today. During the migration of Neptune and the depletion of the primordial Kuiper belt these bodies would have been scattered and undergone numerous impacts by smaller bodies. These impacts would have excavated and ejected N_2 ice chunks from the thick surface layer, provided that 5 conditions are met: 1) KBOs accrete the cosmic abundance of nitrogen; 2) the nitrogen is converted efficiently to N_2; 3) the N_2 is transported to the surface; 4) this occurs before the erosion accompanying the dynamical instability; and 5) the surface N_2 ice does not sublimate before the dynamical instability. We find [Y] that these conditions would be met for objects the size of Gonggong (radius ~600 km) or larger, but likely not for smaller bodies.

On Pluto-sized bodies, impacts during scattering by Neptune would excavate on average 0.5% of the mass of the body, equivalent to a layer 4 km deep. On a Gonggong-sized body around 3% of the mass would be eroded, equivalent to an 11 km layer. In both cases these are less than the expected 35 and 18 km thick N_2 ice layers, though individual impacts can excavate more deeply. We calculate [14] that N_2 ice would constitute around 1/3 the mass of the ejecta, with H_2O ice making up the remainder.

Ejecta fragments have a steep size-distribution, such that we expect them to dominate the material ejected from the Solar system at small sizes. Both N_2 and H_2O ice fragments will slowly erode in the ISM such that we expect the average N_2 ice fragment to have an age of ~0.5 Gyr and the average H_2O ice fragment to have an age of ~2 Gyr. In total if other stellar systems have a similar ejecta profile to the Solar system we expect about 4% of bodies in the ISM to be N_2 ice fragments, making ‘Oumuamua a mildly unusual body, but not exceptional.

A typical N_2 ice fragment age of ~0.5 Gyr for ‘Oumuamua would be consistent with its low velocity relative to the local standard of rest and would suggest a possible origin in the Perseus spiral arm ~3.6 kpc away. N_2 ice fragments would also constitute a small fraction, ~0.1%, of Oort cloud objects.

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