Why is Interstellar Object 1I/2017 U1 (‘Oumuamua) Rocky, Tumbling and Very Prolate?

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ABSTRACT

The recently discovered first interstellar object 1I/2017 U1 (‘Oumuamua) has brightness that varies by a factor of 10, a range greater than that of any Solar System asteroid, a spectrum characteristic of Type D asteroids, and no evidence of evaporating volatiles, contrary to expectation for exo-Oort clouds. This object was the first example of the proposed “Jurads”, objects depleted in volatiles and ejected from planetary systems during the post-main sequence evolution of their parent star. I suggest that heating by the star’s giant stage fluidized a precursor cometary object as volatiles escaped, causing it to assume the Jacobi ellipsoidal shape of a self-gravitating incompressible liquid. The collision that produced the inferred tumbling motion must have occurred thousands of years after the formation of 1I/2017 U1 ‘Oumuamua. Jacobi ellipsoids have a unique relation among rotation rate, density and axial ratio. The inferred axial ratio $\geq 5$ implies a lower bound on the density of 1.6 g/cm$^3$, excluding an icy interior unless it is almost entirely frozen CO$_2$. This object is the first Jurad to be discovered and may be related to accreting objects that pollute white dwarf atmospheres and may make Soft Gamma Repeaters.

Key words: minor planets, asteroids: 1I/2017 U1 ‘Oumuamua – stars: white dwarfs – stars: neutron

1 INTRODUCTION

The recently discovered interstellar object (ISO) 1I/2017 U1 (‘Oumuamua) is remarkable for its hyperbolic Solar orbit (Meech et al. 2017; Mamajek 2017), its deep brightness modulation (a factor of ten, greater than that of any Solar System asteroid) (Meech et al. 2017; Fraser et al. 2017; Drahus et al. 2017) and the absence (with tight upper bounds) of evaporating volatiles. The light curve is not strictly periodic but rather indicates tumbling (Fraser et al. 2017; Drahus et al. 2017). Although interstellar objects expelled from exo-planetary systems have been predicted for many years (Hansen & Zuckerman 2017), they have been predicted to be overwhelmingly cometary, evaporating volatiles and emitting dust during close approaches to the Sun (1I/2017 U1 ‘Oumuamua approached within 0.25 AU (Meech et al. 2016)). Thus, while the discovery of an interstellar object was not unexpected, its properties require explanation.

The brightness modulation of 1I/2017 U1 ‘Oumuamua implies an extraordinary axial ratio and indicates a novel origin. The very slight ($\lesssim 100$ erg/cm$^3$) strength required to support the less prolate nonequilibrium shapes of rotating Solar System bodies of similar size indicates that this interstellar object had an extraordinary history during which its strength was reduced to essentially zero. Its unexpected absence of volatiles is also remarkable, and these two facts point towards a hypothesis of its origin and history.

Here I discuss the possible origin of 1I/2017 U1 ‘Oumuamua in the post-main sequence stage of a planetary system (Hansen & Zuckerman 2017; Raymond et al. 2017). The increasing luminosity of a post-main sequence star will evaporate volatiles from its cometary satellites. Even those in Oort-cloud like orbits will pass close enough to the star to be heated because those orbits are nearly parabolic, with small periastrons. The rapid mass loss of white dwarf formation or the essentially instantaneous mass loss of neutron star formation in a core-collapse supernova will unbind many of the small bodies of the exoplanetary system. It will also put massive exoplanets on elliptic orbits in which they will interact gravitationally with each other and with the small bodies, expelling some and putting others on the low angular momentum orbits required to explain the “pollution” of white dwarf atmospheres (Jura & Young 2014; Farihi 2016; Xu et al. 2017; Veras et al. 2017; Mustill et al. 2017) by heavier elements. Additional mechanisms of expulsion of small bodies operate in binary systems (Stephan et al. 2017).
One consequence of heating is the loss of volatile ices, turning cometary nuclei into asteroidal bodies without further volatiles to evaporate, explaining the absence of volatiles in 1I/2017 U1 ‘Oumuamua. Evaporating volatiles fluidize beds of refractory particles. There is evidence for this (at the lower levels of heating occurring in Solar System comets) in images obtained by the Rosetta spacecraft of Comet 67P/Churyumov-Gerasimenko (European Space Agency 2017). Regions near the center of the cometary nucleus, near the minimum of its gravitational potential, are covered by fine material, in contrast to the rough craggy appearance of the rest of the body. This is likely the result of flow of fluidized particulates to the minimum of the gravitational potential. A comet heated by the intense radiation of a red giant star may be entirely fluidized and the residual refractory material assume the shape, a Maclaurin spheroid or, if it has more angular momentum, a Jacobi ellipsoid, of a rotating self-gravitating incompressible liquid.

The purpose of this paper is to investigate the consequences of this explanation of the unprecedentedly prolate shape of 1I/2017 U1 ‘Oumuamua. This hypothesis implies a lower density limit that likely excludes the possibility (Fitzsimmons et al. 2017) of an icy interior protected from Solar heating by an insulating mantle. Finally, the inference that exoplanetary systems may be disrupted by the evolution of their stars and that white dwarf pollution may be caused by single bodies as massive as $\sim 10^{22}$ g (Xu et al. 2017), or possibly even more massive (Jura et al. 2009), is consistent with the explanation of Soft Gamma Repeater outbursts as the result of accretion of such minor-planet sized bodies onto neutron stars (Katz et al. 1994).

2 GEOMETRY

Jacobi ellipsoids are the equilibrium state of uniformly rotating strengthless homogeneous incompressible fluids with too much angular momentum to be (oblate) Maclaurin spheroids. Even were their specific angular momentum to be increased, strengthless Jacobi ellipsoids will not break up (spinning mass off their extremities) provided they have time to relax to their equilibrium shape. Extremely elongated Jacobi ellipsoids may be unstable to “pear-shaped” (actually, more like egg-shaped) $\ell = 3$, “dumb-bell” $\ell = 4$ and higher instabilities (Eriguchi et al. 1982; Hachisu & Eriguchi 1982) but the nonlinear development of these instabilities is not understood so here I assume Jacobi ellipsoids.

The ten-fold modulation of the brightness of 11/2017 U1 ‘Oumuamua would imply, in a naïve model that assumes a prolate spheroid, Lambert’s Law reflectivity with uniform albedo and oppositional geometry (the actual Solar angle during photometric observations was about 20°), an axial ratio of 10:1 if viewed in the plane of rotation, and greater for other viewing angles (Meech et al. 2017). However, Lambert’s Law is not valid for Solar System asteroids. Modeling that assumes 11/2017 U1 ‘Oumuamua is described by the scattering properties of known Solar System asteroids (Fraser et al. 2017; Drahus et al. 2017) sets a lower bound on the axial ratio of about 5:1. No upper bound on the axial ratio can be obtained because the angle between the line of sight and the rotation axis is unknown, but a lower bound of about 65° can be set on the angle (Drahus et al. 2017). Assuming a plausible upper bound on the density of 3 g/cm$^3$ leads to an upper bound on the axial ratio of about 8 (Sec. 3), from which a somewhat more stringent lower bound on the angle may be found.

Uniformly rotating (friction very quickly enforces uniform rotation) self-gravitating incompressible fluids of uniform density are oblate Maclaurin spheroids (with no modulation of their scattered light) if their angular momentum is low, or triaxial Jacobi ellipsoids if they have higher angular momentum (Chandrasekhar 1969; Tassoul 1978). For large angular momenta the two smaller semi-axes $b$ and $c$ of the Jacobi ellipsoids converge, as shown in Fig. 1, and the ellipsoids approaches a prolate spheroid.

3 DENSITY

Jacobi ellipsoids have a unique relation among their semi-axes, density and rotation rate that can be used to establish bounds on their density from the measured rotation rate and the axial ratio inferred from their light curve. Alternatively, assumed bounds on their density can be used to constrain their geometry.

Several slightly different values of the rotation rate have been reported (Meech et al. 2017; Fraser et al. 2017; Drahus et al. 2017; Bolin et al. 2017). Adopting a period of 7.55 h (Drahus et al. 2017), roughly the mean of these values, leads to the relation between axial ratio and density shown in Fig. 2. The lower bound on the axial ratio of...
about 5 fitted (Dralius et al. 2017; Fraser et al. 2017) to the light curve implies a minimum density of 1.6 g/cm$^3$. This is inconsistent with all plausible icy materials except CO$_2$, whose density is close to this value; even the density of CO$_2$ is inconsistent unless we happen to lie almost exactly in the plane of rotation, the axial ratio is less than inferred from the light curve or the rotation period is significantly longer than the adopted value. This argues against the hypothesis (Fitzsimmons et al. 2017) that an icy core is protected against heating and evaporation by an insulating nonvolatile mantle.

4 TUMBLING: THE EVOLUTIONARY HISTORY

The tumbling motion of 1I/2017 U1 ‘Oumuamua (Fraser et al. 2017; Dralus et al. 2017) implies that it is not rotating exactly around its axis of greatest moment of inertia. Tumbling requires at least minimal elastic strength to maintain. It must have been the result of collision after the epoch of fluidization because any viscous, plastic or frictional flow would lead to very rapid relaxation to periodic rotation about the axis of greatest moment of inertia. The required strength is difficult to estimate (we have only the crudest hint of the rotational dynamics), but is less than the extremely small central pressure $p$. For high axial ratios $a \gg b \approx c$ (Fig. 1) and the ellipsoid can be approximated as an infinite cylinder of radius $b$:

$$p \approx \pi G \rho b^2 \sim 20 \text{ erg/cm}^3$$  

(1)

for a density $\rho \sim 3 \text{ g/cm}^3$ and radius $b \sim 30 \text{ m}$.

Fitzsimmons et al. (2017) indicate a thermal diffusivity $D \sim 10^{-11} \text{ cm}^2/\text{s}$. This implies a cooling time for an object of this size

$$t_{\text{conduction}} \sim \frac{b^2}{D} \sim 10^{11} \text{ s}.$$  

(2)

In order for a collision to have produced tumbling it must have occurred after 1I/2017 U1 ‘Oumuamua was no longer fluidized, either because the volatiles were exhausted or because it cooled below volatilization temperatures. The red giant stages of stellar evolution are longer than $t_{\text{conduction}}$ so a cometary body of these dimensions would have heated throughout.

If 1I/2017 U1 ‘Oumuamua was completely fluidized and did not recover mechanical strength while still hot but depleted of volatiles, then at least thousands of years (and possibly much longer) must have elapsed from the end of the red giant stage of the parent star and intense heating to the collision that made it tumble; 1I/2017 U1 ‘Oumuamua must have remained in the fossil planetary system surrounding the former red giant, where the density of solid bodies was high enough to make collision likely, for at least that long before being expelled.

The dynamical processes that expel small bodies also put other small bodies on collision orbits with their parent stars. This is consistent both with the inference that polluted white dwarfs accrete solid bodies for $\sim 10^9 \text{ y}$ and with the active lifetimes of Soft Gamma Repeaters of a few thousand years after the supernovae in which their neutron stars were born.

5 DISCUSSION

The data contain rich implications that were not expected when interstellar objects were first hypothesized:

(i) Some of the light curves of 1I/2017 U1 ‘Oumuamua (Meech et al. 2017) are asymmetric about their minima, rising more slowly than they fell. This may be explained as a shadowing effect if the rotation is prograde with respect to its orbital motion (an accident with 50% probability of occurrence for an interstellar object).

(ii) The extraordinary and unanticipated axial ratio of 1I/2017 U1 ‘Oumuamua, combined with the absence of volatiles, indicates its origin in the exoplanetary system of a star that had passed through the red giant stage.

(iii) The combination of the rotation period with the inferred large axial ratio sets a lower bound on the density of 1I/2017 U1 ‘Oumuamua that excludes an icy composition, even one under a non-volatile crust that might be consistent with the observed absence of a coma.

(iv) The inference that 1I/2017 U1 ‘Oumuamua is tumbling sets further constraints on its history: it likely remained in a region of comparatively high density of solid objects for at least thousands of years after it formed.

(v) The discovery of an interstellar interloper confirms expectations from the study of “polluted” white dwarfs, and suggests that analogous processes may produce Soft Gamma Repeater outbursts.
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