Implications for Planetary System Formation from Interstellar Object 1I/2017 U1 (‘Oumuamua)

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Abstract

The recently discovered minor body 1I/2017 U1 (‘Oumuamua) is the first known object in our solar system that is not bound by the Sun’s gravity. Its hyperbolic orbit (eccentricity greater than unity) strongly suggests that it originated outside our solar system; its red color is consistent with substantial space weathering experienced over a long interstellar journey. We carry out a simple calculation of the probability of detecting such an object. We find that the observed detection rate of 1I-like objects can be satisfied if the average mass of ejected material from nearby stars during the process of planetary formation is ~20 Earth masses, similar to the expected value for our solar system. The current detection rate of such interstellar interlopers is estimated to be 0.2 yr⁻¹, and the expected number of detections over the past few years is almost exactly one. When the Large Synoptic Survey Telescope begins its wide, fast, deep all-sky survey, the detection rate will increase to 1 yr⁻¹. Those expected detections will provide further constraints on nearby planetary system formation through a better estimate of the number and properties of interstellar objects.

Key words: comets: individual (1I/2017 U1 (‘Oumuamua)) – local interstellar matter – minor planets, asteroids: individual (1I/2017 U1 (‘Oumuamua)) – planetary systems – protoplanetary disks – solar neighborhood

1. Introduction

On 2017 October 18, the minor body C/2017-UT (PANSTARRS), which would become known as A/2017 U1 and later 1I/2017 U1 (‘Oumuamua)—hereafter, 1I—was discovered by the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) survey (Chambers et al. 2016). In a matter of days, it became clear that this object was on an unbound (hyperbolic) trajectory, with eccentricity $e \approx 1.2$ (Williams 2017). In addition to its high eccentricity, 1I’s orbit is inclined to the solar system plane at an angle $i \approx 123°$, so it is very unlikely to have encountered any massive objects within our solar system (other than the Sun).

With no gravitational perturbations to explain its anomalously high eccentricity, the most likely explanation is that this object originated outside of our solar system and happened to pass close to the Earth during its journey through interstellar space. This implies that 1I formed in another planetary system and was ejected, presumably through dynamical interactions in its natal planetary system. Consequently, we refer to 1I and similar bodies as “ejectoids.”

The theoretical existence of ejectoids has been long proposed (e.g., Sekanina 1976), with various authors using nondetections to place upper limits on the population (McGlynn & Chapman 1989; Sen & Rama 1993; Engelhardt et al. 2017). Jewitt (2003) and Francis (2005) suggested that PanSTARRS could detect an interstellar object, if the number density was great enough. In the two weeks since the discovery of 1I and its identification as an interstellar object, we have learned about its optical spectrum (Masiero 2017; Ye et al. 2017), its light curve (Knight et al. 2017), its orbit (de la Fuente Marcos & de la Fuente Marcos 2017), and its potential origin scenarios (Gaidos et al. 2017; Laughlin & Batygin 2017; Mamajek 2017).

Here we use a simple calculation to estimate the probability of detecting such an object and explore the implications for the prevalence and properties of planetary systems that are implied by the existence and properties of 1I.

2. Ejectoid Encounters and Ejected Mass Constraints

Gravitational microlensing results have shown that, on average, every star in the Milky Way is accompanied by at least one bound planet (Cassan et al. 2012), which implies that planet formation is a near-universal process. We assume here that the formation of a typical planetary system results in a mass $m$ of ejectoids with a typical size of $r_e$ and mass density $\rho_e$. The number of ejectoids per star is therefore

$$\frac{m}{\frac{3}{2}\pi r_e^3 \rho_e}. \tag{1}$$

We can write the number density of stars (in, e.g., stars per cubic parsec) $n_s$ in terms of a characteristic stellar spacing, $R$, as

$$n_s = \frac{1}{\frac{3}{2}\pi R^3}. \tag{2}$$

This enables us to express the number density of ejectoids (number/volume) as

$$n_e = \left(\frac{m}{\frac{3}{2}\pi r_e^3 \rho_e}\right) \left(\frac{1}{\frac{3}{2}\pi R^3}\right). \tag{3}$$

We next wish to determine the number of ejectoids that we expect to have encountered. We assume that telescopic searches for 1I-like objects have swept out a cylindrical volume of interstellar space given by

$$V_{obs} = \pi r_{obs}^2 \Delta v_\odot \Delta t, \tag{4}$$

where $r_{obs}$ is the geocentric distance out to which we are sensitive to 1I-like objects, $\Delta v_\odot$ is the Sun’s velocity through
the solar neighborhood (and the presumed cloud of ejectoids), and \( \Delta t \) is the time interval over which observational surveys have been capable of discovering \( 1 \)I-like objects. Using this volume and the number density of ejectoids, we find that the number of detections of \( 1 \)I-like objects is

\[
N = n_e V_{\text{obs}} = \left( \frac{m}{\pi r_e^3 \rho_e} \right) \left( \frac{1}{\pi R^3} \right) (\pi r_{\text{obs}}^2 \Delta v_e \Delta t),
\]

which simplifies to

\[
N = \frac{9}{16\pi} \frac{m r_{\text{obs}}^2 \Delta v_e \Delta t}{r_e^2 \rho_e R^3}.
\]

We can now use \( 1 \)I to constrain the characteristic mass in ejectoids for a forming planetary system. With \( N = 1 \), we can rearrange Equation (6) to write that

\[
m = \frac{16\pi}{9} \frac{\rho_e r_e^3 R^3}{r_{\text{obs}}^2 \Delta v_e \Delta t}.
\]

The absolute magnitude of \( 1 \)I is given in the Minor Planet Center catalog as 22.1 (as of 2017 November 2), which corresponds to a radius \( r_e \) of around 100 meters, assuming a moderate-to-dark albedo.

The range of densities for cometary and asteroidal material that may be relevant is around 500 to 3000 kg m\(^{-3}\) (Davidsson & Gutierrez 2006; Davidsson et al. 2007; Richardson et al. 2007; Carry 2012). While \( 1 \)I’s highly eccentric orbit would typically be associated with a comet, and theoretical predictions suggest that most ejectoids should be more comet-like (Raymond et al. 2011), there are no signs of activity from \( 1 \)I (Knight et al. 2017; Ye et al. 2017). Thus, here, we assume that \( 1 \)I may be more asteroidal than cometary and adopt a density of 2000 kg m\(^{-3}\).

There are 357 stars within 10 parsecs of the Sun.\(^3\) This gives an average distance between adjacent stars \( R \) of 1.4 pc. The average discovery distance of near-Earth objects in the minor planet center \( r_{\text{obs}} \) is 0.3 au.

The velocity of the Sun relative to nearby stars is around 20 km s\(^{-1}\) (Schönrich et al. 2010). \( 1 \)I has been found\(^4\) to have an interstellar speed (velocity at infinity) of 26 km s\(^{-1}\), while Mamajek (2017) reports that an object entering the solar system with median velocity of the local stellar population would have a speed of around 22.5 km s\(^{-1}\). The fact that the Sun’s relative velocity is comparable to the velocity of \( 1 \)I confirms our assumption that the population of interstellar ejectoids has zero mean velocity (due to the fact that both the source planetary systems and ejection trajectories are assumed to be isotropic). Based on these three estimates, we set \( \Delta v_e \) to be 25 km s\(^{-1}\).

In recent years, improvements on detector size and field of view at the Catalina Sky Survey and Pan-STARRS (the two major NEO surveys) have enhanced the ability to detect \( 1 \)I-like objects, so we estimate \( \Delta t \) to be 5 years.

Our characteristic values, when inserted in Equation (7), yield a typical mass in ejected \( 1 \)I-like objects of \( 10^{26} \) kg, or 20 \( M_\oplus \). This is in remarkably good agreement with values derived for mass loss during the formation of our solar system. For example, Weidenschilling (1977) and Bottke et al. (2005) derive 1–5 \( M_\oplus \) of material lost from the asteroid belt. Kuiper (1951), Kenyon & Luu (1999), and Morbidelli (2005) find 12–30 \( M_\oplus \) lost from the Kuiper Belt. Together, these imply a total mass lost from our solar system of close to 20 \( M_\oplus \).

Identifying the characteristic size and density of ejectoids as being the most uncertain terms in our analysis, and inserting the parameter values adopted above, we can write

\[
m = 20 M_\oplus \left( \frac{\rho_e}{2000 \text{ kg m}^{-3}} \right) \left( \frac{r_e}{100 \text{ m}} \right)^3.
\]

This relationship is shown in Figure 1. The plausible range of ejection masses is roughly 1–100 \( M_\oplus \). We note that in principle the radius of \( 1 \)I, which we take to be characteristic of ejectoids, will be determined through our forthcoming thermal infrared observations of \( 1 \)I with the Spitzer Space Telescope (observations scheduled for late 2017 November). There is no direct way to constrain the density of \( 1 \)I, though indirect constraints may be possible from the rotation period.

Alternatively, if we adopt the \( \sim 20 \) \( M_\oplus \) in ejectoids lost during the formation of the solar system as a characteristic number, we can use Equation (6) to derive the number of \( 1 \)I-like objects expected over five years. We find that \( N \) is very close to unity—exactly matching the observations. The detection rate \( (N/\Delta t) \) is therefore 0.2 \( 1 \)I-like objects per year, or one \( 1 \)I-like object every five years. The number density of ejectoids is, from Equation (3), around 0.1/au\(^3\), which is around \( 10^{15}/\text{pc}^3 \).

3. Caveats and Uncertainties

We do not claim that this is the only mechanism for producing \( 1 \)I-like objects or delivering such objects to the detectable space near the Earth, as the above calculation admittedly contains a number of assumptions. However, this does give a plausible explanation for \( 1 \)I that in turn has several interesting implications that are discussed below.

The radius and density of \( 1 \)I are unknown, though the values above are unlikely to be in error by more than a factor of two. Similarly, the geometry arguments (average stellar distance, solar velocity, and observational distance) are likely within a factor of two, while the time interval is approximately correct. We ignore gravitational focusing here. The largest overall uncertainty is simply the unknown statistical likelihood of detecting this ejectoid and our extrapolation from a single object. \( 1 \)I may be part of a constant stream of interstellar objects moving through our solar system (as implied here), or a very unlikely occurrence, in which case the arguments made here are less applicable.

In addition, the true population of ejected extrasolar material must follow some size distribution, and will not consist of only 100 m \( 1 \)I-like objects. Small objects are presumably more numerous in any planet formation scenario, but larger objects will be preferentially detected by our surveys. We must simply take \( 1 \)I to be representative.

In the above calculation, we have assumed that a steady-state population of \( 1 \)I-like objects is ejected from all planetary systems. However, we might instead assume that the majority of ejectoids are produced during the earliest phases of planetary system formation, in a single pulse of material. The nearest star formation regions are some 100 parsec away, with typical ages of 1–10 Myr (Andrews et al. 2009; Currie & Sicilia-Aguilar 2011; Esplin & Luhman 2017). If we take the escape velocity from those systems to be on the order of 10 km s\(^{-1}\) then material from one of these nearby star formation regions
would reach the Earth in a few million years, and we would therefore be moving through a cloud of ejected 1I-like objects. However, the rest of the assumptions still apply, and the expected value does not change significantly. A more complicated model (perhaps not warranted, given this single detection) could account for the total number of stars contained in the Milky Way, integrated over its history, as even stars that no longer exist could have contributed ejectoids to an interstellar stream of material.

Finally, we note that the above calculation implies a typical ejected mass of 20 $M_\oplus$, but that need not imply that every stellar or planetary system ejects mass, or that amount of material. For example, while planet–planet scattering among gas giant planets is likely to produce a pulse of ejected planetesimals (Raymond et al. 2011; Marzari 2014), and while systems with gas giants on stable orbits can eject planetesimals on longer timescales (Raymond et al. 2011; Barclay et al. 2017), systems without gas giants rarely eject planetesimals because in that case escape velocity cannot readily be achieved by planetesimals. Thus, if the fraction of nearby stars with gas giants is (for example) 50%, then the average mass ejected by those systems must be a factor of $\sim$2 greater than our nominal value in order to produce the necessary interstellar density of ejectoids.

4. Implications

The 520–950 nm reflectance spectrum of 1I, albeit noisy, indicates no absorption features and a red spectral slope (Masiero 2017; Ye et al. 2017), making compositional characterization difficult. However, we note that a red spectral slope over this range is not unexpected and is characteristic of many primitive objects in our solar system (Cruikshank et al. 1998; Jewitt & Luu 1998; Bus & Binzel 2002; Sheppard 2010; Carry et al. 2016). Whether this slope is something intrinsic to the bulk properties of 1I or a consequence of its surface being altered via energetic processing is unclear. Given the presence of cosmic rays in the interstellar medium and other forms of ionizing radiation that would have been present in 1I’s natal stellar environment, 1I’s red spectral slope is entirely consistent with formation elsewhere and a long journey to our solar system. This implies that the surface of 1I may have different properties than its bulk material.

1I’s trajectory makes it very unlikely that it experienced a gravitational encounter with any of the proposed as-yet unknown planets in the outermost part of our solar system (Trujillo & Sheppard 2014; Brown & Batygin 2016; Volk & Malhotra 2017). Another possibility is that 1I was a member of our solar system’s Oort Cloud and was perturbed inbound onto an unbound orbit by a passing star. We do not comment on these scenarios; in this work, we have assumed that 1I is an interstellar interloper that originated in a different planetary system.

The Large Synoptic Survey Telescope (LSST; Ivezić et al. 2008) will commence its 10-year all-sky survey in 2022. One of the driving science cases for LSST is the detection of moving objects. Most moving objects detected by LSST will be “unremarkable” asteroids in the main belt, but this very large and deep survey (20,000 deg$^2$ surveyed to $r$ magnitude 24.5 repeatedly over 10 years) naturally has the possibility to discover unusual objects in all areas of astrophysics. Several authors have studied the detectability of interstellar interlopers in LSST data (Moro-Martín et al. 2009; Cook et al. 2016; Engelhardt et al. 2017).

LSST will help constrain nearby planetary system formation by measuring the number of 1I-like objects. LSST will be sensitive to fainter and therefore smaller and/or more distant objects, and is therefore likely to have a greater detection rate than the current rate. The possibility of LSST detecting interstellar comets increases by an order(s) of magnitude when

Figure 1. Characteristic ejection mass (colors and contours, in Earth masses) required to produce the observed rate of 1I-like objects as a function of the primary unknown parameters in our analysis: 1I’s density ($\rho_e$) and radius ($r_e$). For nominal values of 2000 kg m$^{-3}$ and 100 m, respectively, the required average ejection mass per star in the solar neighborhood is 20 $M_\oplus$ (black star), remarkably close to various calculations of the mass lost from our solar system during the era of planet formation. Our upcoming observations of 1I with the Spitzer Space Telescope in late 2017 November should place a constraint on 1I’s radius.
considering cometary outbursting (Cook et al. 2016), which makes objects brighter, although 1I has shown no signs of activity so far in its observational record.

As described above, with our current detection sensitivities, the detection rate for 1I-like objects is \(0.2 \text{ yr}^{-1}\). The LSST detection limit will be around three magnitudes deeper than Pan-STARRS’ typical limiting magnitude of \(V \sim 21.5\); this translates to a factor of three smaller in size. The only measured size distribution in this size range in our solar system is for the near-Earth object population; a factor of three in size corresponds roughly to a factor of five in number of objects (Trilling et al. 2017). Thus, the expected detection rate of interstellar objects for LSST is around \(1 \text{ yr}^{-1}\). The LSST discovery rate of ejectoids will help us constrain the frequency and properties of planetary system formation in our nearby galaxy.

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