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# Discovery of a Meteor of Interstellar Origin

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## ABSTRACT

The first interstellar object, 'Oumuamua, was discovered in the Solar System by Pan-STARRS in 2017, allowing for a calibration of the abundance of interstellar objects of its size $\sim 100$ m. One would expect a much higher abundance of smaller interstellar objects, with some of them colliding with Earth frequently enough to be noticeable. Based on the CNEOS catalog of bolide events, we identify the $\sim 0.45$m meteor detected at 2014-01-08 17:05:34 UTC as originating from an unbound hyperbolic orbit with an asymptotic speed of $v_\infty \sim 43.8^{+12.9}_{-31.2}$ km s$^{-1}$ outside of the solar system. Its origin is approximately towards R.A. $51.1°^{+14.6°}_{-40.5°}$ and declination $+10.4°^{+2.2°}_{-11.8°}$, implying that its initial velocity vector was $57 \pm 24$ km s$^{-1}$ (all error bars representing $\pm 2\sigma$) away from the velocity of the Local Standard of Rest (LSR). Its high LSR speed implies a possible origin from the deep interior of a planetary system or a star in the thick disk of the Milky Way galaxy. The local number density of its population is $10^{6^{+0.75}_{-1.5}}$ AU$^{-3}$ or $9 \times 10^{21^{+0.75}_{-1.5}}$ pc$^{-3}$ (necessitating 0.2 - 20 Earth masses of material to be ejected per local star). This discovery enables a new method for studying the composition of interstellar objects, based on spectroscopy of their gaseous debris as they burn up in the Earth's atmosphere.

*Keywords:* Minor planets, asteroids: general – comets: general – meteorites, meteors, meteoroids

## 1. INTRODUCTION

'Oumuamua was the first interstellar object detected in the Solar System by Pan-STAARS (Meech et al. 2017; Micheli et al. 2018). Several follow-up studies of 'Oumuamua were conducted to better understand its origin and composition (Bannister et al. 2017; Gaidos et al. 2017; Jewitt et al. 2017; Mamajek 2017; Ye et al. 2017; Bolin et al. 2017; Fitzsimmons et al. 2018; Trilling et al. 2018; Bialy & Loeb 2018; Hoang et al. 2018; Siraj & Loeb 2019a,b; Seligman et al. 2019). Its size was estimated to be 20m - 200m, based on Spitzer Space Telescope constraints on its infrared emission given its temperature (Trilling et al. 2018). Forbes & Loeb (2019) predicted that spectroscopy of 'Oumuamua-like objects grazing the Sun could reveal their chemical compositions. Since there should be a higher abundance of interstellar objects smaller than 'Oumuamua, we could observe small interstellar objects impacting the Earth's atmosphere. Spectroscopy of the gaseous debris from such objects as they burn up in the Earth's atmosphere could reveal their composition. This raises the question: is there evidence of interstellar meteors?

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The CNEOS catalog includes the geocentric velocity components and geographic coordinates for bolides detected by U.S. government sensors.[1] In this *Letter*, we identify a meteor from the CNEOS catalog that is likely of interstellar origin.

## 2. METHODS

We analyzed the bolide events in the CNEOS catalog, and found that the meteor detected at 2014-01-08 17:05:34 UTC had an unusually high heliocentric velocity at impact.[2] Accounting for the motion of the Earth relative to the Sun and the motion of the meteor relative to the Earth, we found that the meteor had a heliocentric velocity of $\sim 60$ km s$^{-1}$ at impact, which implies that the object was unbound. To uncover the kinematic history of this meteor, we integrated its motion from impact backward in time.

[1] https://cneos.jpl.nasa.gov/fireballs/

[2] The fastest meteor in the CNEOS catalog obtains its high speed from a head-on orbit relative to the Earth and its extrapolated orbit is found to be bound to the Sun. The meteor we focus on is the second fastest. The orbit of the third fastest meteor in the catalog is possibly bound within uncertainties.

The Python code created for this work used the open-source N-body integator software REBOUND[3] to trace the motion of the meteor under the gravitational influence of the Solar System (Rein & Liu 2012).

We initialize the simulation with the Sun, the eight planets, and the meteor, with geocentric velocity vector $(vx_{obs}, vy_{obs}, vz_{obs}) = (-3.4, -43.5, -10.3)$ km s$^{-1}$, located at 1.3° S 147.6° E, at an altitude of 18.7 km, at the time of impact, $t_i$ = 2014-01-08 17:05:34 UTC, as reported in the CNEOS catalog. We then use the IAS15 adaptive time-step integrator to trace the meteor's motion back in time (Rein & Spiegel 2014).

## 3. RESULTS

### 3.1. *Trajectory*

There are no substantial gravitational interactions between the meteor and any planet other than Earth for any trajectory within the reported errors. Based on the impact speed reported by CNEOS, $v_{obs} = 44.8$ km s$^{-1}$, we find that the meteor was unbound with an asymptotic speed of $v_\infty \sim 43.8$ km s$^{-1}$ outside of the solar system. In order for the object to be bound, the observed speed of $v_{obs} = 44.8$ km s$^{-1}$ would have to be off by more than 45%, or 20 km s$^{-1}$.

The typical velocity uncertainty for meter-scale impactors in the CNEOS catalog was estimated by Brown et al. (2016) and Granvik & Brown (2018) to be less than 1 km s$^{-1}$, but 2 of 10 events analyzed by Devillepoix et al. (2019) have errors up to 28% in speed.[4] Assuming a Gaussian distribution of uncertainty, this implies that the standard deviation of speed, $\sigma = 21.5\%$. We therefore quote central values $\pm 2\sigma$ throughout the paper, and note that the result discussed in this paper has a certainty of $> 2\sigma$. While Devillepoix et al. (2019) also report that 2 of the 10 analyzed events had radiant vectors that were significantly off ($\sim 90°$), we note that larger impactors produce larger debris as they break apart, making it more likely for their radiant vectors to be misidentified. The two meteors cited by Devillepoix et al. (2019) have volumes that are larger by factors of $\sim 20$ and $\sim 100$ compared to the meteor discussed here, making it far more plausible for their trajectories to be misidentified as a result of break-up.

We find that the heliocentric orbital elements of the meteor at time of impact are as follows (with error bars representing $\pm 2\sigma$): semi-major axis, $a = -0.45^{+0.25}_{-3.13}$ AU, eccentricity, $e = 2.4^{+1.5}_{-1.2}$, inclination $i = 10 \pm 3°$,

[3] https://rebound.readthedocs.io/en/latest/

[4] We are conservatively assigning the entire error budget in these cases to the reported CNEOS data, whereas in reality, some of it may be atrributable to the independent measurements.

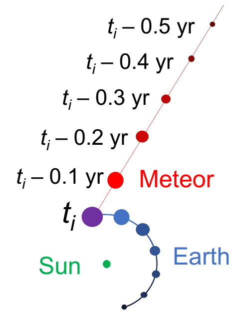


**Figure 1.** Trajectory of the January 8, 2014 meteor (red), shown intersecting with that of Earth (blue) at the time of impact, $t_i$ = 2014-01-08 17:05:34.

longitude of the ascending node, $\Omega = 108 \pm 2°$, argument of periapsis, $\omega = 59 \pm 2°$, and true anomaly, $f = -59 \pm 2°$. The trajectory is shown in Fig. 1. The origin is towards $51.1°^{+14.6°}_{-40.5°}$ and declination $+10.4°^{+2.2°}_{-11.8°}$. The heliocentric incoming velocity at infinity of the meteor in right-handed Galactic coordinates is $v_\infty(\mathrm{U,V,W}) = (34.6^{+23.8}_{-32.0}, -4.4^{+3.7}_{-0.5}, 26.5^{+3.6}_{-14.9})$ km s$^{-1}$, which is $57 \pm 24$ km s$^{-1}$ away from the velocity of the Local Standard of Rest (LSR), $(\mathrm{U,V,W})_{\mathrm{LSR}} = (-11.1, -12.2, -7.3)$ km s$^{-1}$ (Schonrich et al. 2010).

### 3.2. *Size distribution*

Given the impact speed of the meteor, $\sim 44.8$ km s$^{-1}$, and the total impact energy, $4.6 \times 10^{18}$ ergs, the meteor mass was approximately $4.6 \times 10^5$ g. Assuming bulk density values of 1.7 g/cm$^3$ and 0.9 g/cm$^3$ for Type II and Type IIIa objects respectively, we obtain a radius, $R$, of 0.4m - 0.5m for a spherical geometry (Ceplecha 1988; Palotai et al. 2018).

The CNEOS catalog includes bolide events at a relatively high frequency for the past decade, so we approximate the yearly detection rate of interstellar meteors to be at least $\sim 0.1$ yr$^{-1}$. We estimate the number density of similarly sized interstellar objects by dividing the yearly detection rate by the product of the impact speed of the meteor and the cross sectional area of the Earth, finding the approximate number density of interstellar objects with a size of order $R \sim 0.45$m and a speed $v \sim 60$ km s$^{-1}$ km s$^{-1}$ relative to the LSR, to be,

$$n \sim \frac{0.1\ \mathrm{yr}^{-1}}{(13\ \mathrm{AU/yr})(5.7 \times 10^{-9}\ \mathrm{AU}^2)} \sim 10^6\ \mathrm{AU}^{-3}. \quad (1)$$

Given 95% Poisson uncertainties, the inferred[5] local number density for interstellar objects of this size is

[5] Gravitational focusing by the Earth is negligible since the meteor speed exceeds considerably the escape speed from the Earth.

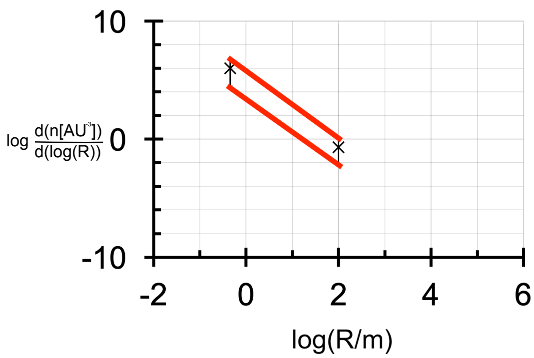


**Figure 2.** Size distribution of interstellar objects based on the detection of ‘Oumuamua and of the meteor detected at 2014-01-08 17:05:34 UTC. Red lines indicate the envelope for possible power-law fits (slopes of -1.9 to -3.8), given 95% Poisson distribution confidence intervals on each number density (based on a single detection for each). The range of possible power-law slopes is consistent with that inferred for small bodies in the Kuiper belt, -2.5 to -3 (Kenyon & Bromley 2004).

$n = 10^{6^{+0.75}_{-1.5}}$ $\mathrm{AU}^{-3}$. This figure necessitates $6 \times 10^{22^{+0.75}_{-1.5}}$ similarly size objects, or 0.2 - 20 Earth masses of material, to be ejected per local star. This is at tension with the fact that a minimum-mass solar nebula is expected to have about an Earth mass of total planetesimal material interior to the radius where the orbital speed is $\sim 60$ km s$^{-1}$ (Desch 2007), with similar values for other planetary systems (Kuchner 2004). Our inferred abundance for interstellar meteors should be viewed as a lower limit since the CNEOS data might have a bias against detection of faster meteors (Brown et al. 2016). Do et al. (2018) estimated the number density of ‘Oumuamua-size ($R \sim 100$m) objects to be 0.2 AU$^{-3}$. Using this number density, along with our estimated density for $R \sim 0.45$m objects, we construct a range of estimates for the slope of the power-law of the size distribution for interstellar objects as shown in Fig. 2. The range of possible power-law slopes, -1.9 to -3.8, is consistent with that inferred for small bodies in the Kuiper belt, -2.5 to -3 (Kenyon & Bromley 2004). The range is also consistent with the lower limits for the flux of $R \sim 10^{-4}$m interstellar meteors calculated by Weryk & Brown (2005), assuming a smooth power-law distribution. However, the power-law extrapolation may not hold at all bolide radii down to dust particles.

The density enhancement due to gravitational focusing by the Sun is well below the uncertainty in the estimated value of $n$, so that our inferred range of local values also corresponds to the density outside of the Solar System.

## 4. DISCUSSION

We presented and analyzed impact data from the meteor detected at 2014-01-08 17:05:34 UTC, showing that it had an unbound hyperbolic orbit with an asymptotic speed of $v_\infty \sim 43.8^{+12.9}_{-31.2}$ km s$^{-1}$ outside of the Solar System. All reported error bars represent $\pm 2\sigma$. Its size, trajectory, and excess speed exclude the possibility that it was gravitationally scattered within the Solar System prior to impact (Wiegert 2014). Its $\sim 57 \pm 24$ km s$^{-1}$ deviation from the LSR suggests that it perhaps originated in the thick disk, which has velocity dispersion components of $(\sigma_{\rm U}, \sigma_{\rm V}, \sigma_{\rm W}) = (50, 50, 50)$ km s$^{-1}$ relative to the LSR (Bland-Hawthorn & Gerhard 2016). However, the ratio of local thick disk stars to thin disk stars is 0.04, making this a minority population. Alternatively, for a parent planetary system with a more typical velocity relative to the LSR, the object could have originated in the deep interior, where the orbital speeds of objects are of the necessary magnitude. Either way, the meteor had an unusual origin. We obtained a range of estimates for the slope of the power-law of the size distribution for interstellar objects implied by the detection of this interstellar meteor and that of ‘Oumuamua, which is consistent with that inferred for small bodies in the Kuiper belt. The mass density of interstellar objects of radius $R \sim 0.45$m implied by the discovery of this meteor is similar to that of $R \sim 100$m objects implied by the discovery of ‘Oumuamua, the two mass densities being $3 \times 10^{25^{+0.75}_{-1.5}}$ kg pc$^{-3}$ and $6 \times 10^{25^{+0.75}_{-1.5}}$ kg pc$^{-3}$, respectively.

The discovery of additional interstellar meteors will serve as an important calibration for population-wide parameters of interstellar objects, including their abundance and origin.

We estimate the impact rate of similarly sized objects with the Earth, given 95% Poisson distribution confidence intervals, to be at least $0.1^{+0.457}_{-0.097}$ per year. Future meteor surveys could flag incoming objects with excess heliocentric velocities for follow-up pre-impact observations. Spectroscopy of gaseous debris from these objects as they burn up in the Earth's atmosphere would reveal their composition. Given that some isotope ratios are expected to be markedly different for objects of interstellar origin compared to the Solar System, could validate an interstellar origin (Lingam & Loeb 2018a; Forbes & Loeb 2019). Precision tracking with the upcoming Large Synoptic Survey Telescope (LSST[6]) could determine the trajectory of meteors of interstellar origin to their parent systems in the Gaia catalog.[7] Our discovery also implies that at least $4.5 \times 10^{8^{+0.75}_{-1.5}}$ similarly sized interstellar bolide events have occurred over Earth's lifetime. Potentially, interstellar meteors could deliver life from another planetary system and mediate panspermia (Ginsburg et al. 2018). Interestingly, the high speed for the meteor discussed here implies a likely origin in the habitable zone of the abundant population of dwarf stars, indicating that similar objects could carry life from their parent planetary systems.

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[6] https://www.lsst.org/
[7] https://gea.esac.esa.int/archive/