Probing Extrasolar Planetary Systems with Interstellar Meteors

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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 impact rate of interstellar meteors of its size $\sim 100$ m. The discovery of CNEOS 2014-01-08 allowed for a calibration of the impact rate of interstellar meteors of its size $\sim 1$ m. Analysis of interstellar dust grains have allowed for calibrations of the impact rate of smaller interstellar meteors down to the size $\sim 10^{-8}$ m. We analyze the size distribution of interstellar meteors, finding that for smooth power-law fits of the form $N(r) \propto r^{-q}$, the possible values of $q$ are in the range $3.41 \pm 0.17$. We then consider the possibility of analyzing interstellar meteors to learn about their parent planetary systems. We propose a strategy for determining the orbits and chemical compositions of interstellar meteors, using a network of $\sim 600$ all-sky camera systems to track and conduct remote spectroscopy on meteors larger than $\sim 5$cm once every few years. It should also be possible to retrieve meteorites from the impact sites, providing the first samples of materials from other planetary systems.

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-STARRS (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). ‘Oumuamua’s size was estimated to be 20m - 200m, based on Spitzer Space Telescope constraints on its infrared emission given its expected surface temperature based on its orbit (Trilling et al. 2018).

There is significant evidence for previous detections of interstellar meteors (Baggaley et al. 1993; Hajdukova 1994; Taylor et al. 1996; Baggaley 2000; Mathews et al. 1998; Meisel et al. 2002a,b; Weryk & Brown 2004; Afanasiev et al. 2007; Musci et al. 2012; Engelhardt et al. 2017; Hajdukova et al. 2018; Siraj & Loeb 2019c). CNEOS 2014-01-08 is the largest interstellar meteor discovered in the Solar System (Siraj & Loeb 2019c). Spectroscopy of gaseous debris of interstellar meteors as they burn up in the Earth’s atmosphere could reveal their composition (Siraj & Loeb 2019c). In this Letter, we explore the size distribution of interstellar meteors and motivate the investigation of interstellar meteors as a new branch of astronomical research. We present a strategy for conducting spectroscopy and obtaining physical samples of interstellar meteors.

2. Size Distribution

CNEOS 2014-01-08 and ‘Oumuamua serve as important calibration points for the size distribution of interstellar meteors, included with the results compiled by Musci et al. (2012) in Fig. 1. Non-detections from Hajdukova (1994), Hawkes & Woodworth (1999), Hajdukova & Paulech (2002), and Musci et al. (2012) serve as upper limits. Detections from Weryk & Brown (2004), Baggaley et al. (1993) serve as lower limits, and the range of values given by Meisel et al. (2002b) are from different models and fits for Geminga supernova particles. Mathews et al. (1998) reported 1 and Meisel et al. (2002a) reported 143 detections from Arecibo, but the results are controversial due to large velocity uncertainties (Musci et al. 2012).

The possible smooth power-law fits of the form $N(r) \propto r^{-q}$ for all $r > 5 \times 10^{-6}$ m except for the controversial Meisel et al. (2002a) result range from $q = 3.24$ to $q = 3.58$, consistent with $q = 3.3$ from Landgraf
et al. (2000) but not with the power-law fits from Mathis et al. (1977), Landgraf & Grun (1998), or Hajdukova & Paulech (2002).

3. DETECTION STRATEGY

The cores of meteoroids with radii larger than $\sim 5$ cm can reach the ground in the form of meteorites (Kruger & Grun 2014). Additionally, meteoroids on smaller size scales could be accelerated from the Poynting-Robertson effect and could have potential origins in the interstellar medium. Hence, interstellar meteors above this size are optimal for a systematic study of physical extrasolar material (in addition to the spectroscopy of the hot gases as the meteor burns up). Since we expect interstellar meteors of this size to strike the Earth a few times per year, a network of all-sky camera systems monitoring the sky above all land on Earth could detect an interstellar meteor of this size every few years. Such detections can be made with science-grade video cameras, such as those used in AMOS, CAMO, and CAMS\(^1\) (Toth et al. 2015; Weryk et al. 2013).

A conservative estimate for the total area of $\sim 70$ km altitude atmosphere visible from a system of two all-sky camera systems separated by 100 km is $5 \times 10^5$ km\(^2\), so to cover all land on Earth would require $\sim 300$ systems, or $\sim 600$ total all-sky camera systems, similar to CAMO but with an all-sky field of view, like AMOS and CAMS\(^2\) (Weryk et al. 2013; Toth et al. 2015).

We therefore advocate for a network of all-sky camera systems to conduct real-time remote spectroscopy of the hot gases as $r \geq 5 \times 10^{-2}$ m interstellar meteors burn up, and to precisely determine their trajectories for the immediate retrieval of interstellar meteorite samples.

4. DISCUSSION

We analyzed the updated size distribution of interstellar meteors, deriving a range of possible slopes of $q = 3.41 \pm 0.17$, consistent with the slope calculated by Landgraf et al. (2000). We then presented a strategy for studying interstellar meteors: using a network of $\sim 600$ all-sky camera systems to determine the orbits and chemical compositions of $r \geq 5$ cm meteors. This method also allows for the possibility of retrieving interstellar meteorite samples.

By extrapolating the trajectory of each meteor backward in time and analyzing the relative abundances of each meteor’s chemical isotopes, one can match meteors to their parent stars and reveal insights into planetary system formation. R-processed elements, such as Eu, can be detected in the atmospheres of stars (Frebel et al. 2016), so their abundances in meteor spectra can serve as important links to parent stars. This new field of astronomical research is significant as it would save the trip and allow us to study samples of materials from other planetary systems, be it natural or artificial in origin.

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Figure 1. Interstellar meteoroid impact rate estimates from various studies, compiled by Musci et al. (2012), with CNEOS 2014-01-08 and ‘Oumuamua added. The range of possible values for the Meisel et al. (2002b) measurement are for Geminga supernova particles assuming different models and fits. The AMOR data include results from Baggaley et al. (1993), as well as the interpretation of those data from Taylor et al. (1996) and Baggaley (2000). The Weryk & Brown (2004) values are for 2 and 3 standard deviations, respectively, above the hyperbolic speed limit. The power law fits that are consistent with all measurements for \( r > 5 \times 10^{-6} \) m (except for the controversial Meisel et al. (2002a) result) range from \( q = 3.24 \) to \( q = 3.58 \), consistent with the value of \( q = 3.3 \) inferred by Landgraf et al. (2000).
Figure 2. Apparent visual magnitude for $5 \times 10^{-2}$ s exposures as a function of meteor size at an altitude of 100 km, with $\theta$ measured from zenith to horizon. We assume a fiducial density of $\rho = 2 \times 10^3$ kg m$^{-3}$, an impact speed of $v_{\text{impact}} = 30$ km s$^{-1}$, and that the meteor lifetime is on the order of a few seconds. Dashed lines the flux limit for a 10-$\sigma$ detection in each spectral bin with a spectral resolution of $R = 10^3$, for telescope apertures of diameter 10cm and 1m.