*Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC)*, **59**, 101–108 (2025)

https://doi.org/10.22201/ia.14052059p.2025.59.19

VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.19

# INTERSTELLAR VISITORS AND ELUSIVE EXTRASOLAR METEORITES

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RESUMEN

A pesar del inmenso vacío y las distancias que separan las estrellas, nuestro vecindario cósmico sigue siendo un escenario dinámico donde nuevos fenómenos desafían nuestra comprensión. El descubrimiento de visitantes en nuestro Sistema Solar supone una oportunidad científica sin precedentes. En este artículo proporcionamos una introducción al ámbito de los “intrusos interestelares”: 1I/’Oumuamua y 2I/Borisov. Además, exploramos la naturaleza de objetos que parecen haberse originado en otras nebulosas solares pero, en realidad, pertenecen a nuestro propio sistema planetario, apodados “impostores interestelares”. Asimismo, explicamos por qué los meteoros hiperbólicos han sido sistemáticamente categorizados como errores de medición. Por último, cuestionamos las afirmaciones sobre los presuntos meteoros interestelares: IM1 e IM2. Nuestro objetivo es arrojar luz sobre la siguiente paradoja: dada la creciente evidencia que indica la presencia de una población visitante de origen interstellar, ¿por qué los meteoritos extrasolares han eludido nuestro descubrimiento?

ABSTRACT

Despite the immense voids and vast distances that separate stars, our cosmic neighborhood remains a dynamic stage where emerging phenomena consistently challenge our present comprehension. One of the most intriguing enigmas involves the appearance of objects originating from distant stellar systems. We provide an introduction to the realm of “interstellar interlopers”, focusing on the first two documented sizable visitors: 1I/’Oumuamua and 2I/Borisov. Additionally, we explore the nature of objects that seem to have originated in other solar nebulae but, in reality, belong to our own planetary systemdubbed “interstellar impostors”. We explain why hyperbolic meteors have been systematically categorized as measurement errors. Lastly, we raise questions about the contentious assertions concerning the alleged interstellar meteors: IM1 and IM2. By pursuing these inquiries, our objective is to resolve the following paradox: given the growing body of evidence indicating the presence of an interstellar visiting population, why have authentic extrasolar meteorites eluded our discovery?

*Key Words:* Fireballs — Hyperbolic orbits — Interstellar — Meteorites — Oort cloud

## 1. 1I/’OUMUAMUA AND 2I/BORISOV

1I/’Oumuamua represents the inaugural macroscopic interstellar object confirmed within our Solar System, initially cataloged as C/2017 U1 (Williams et al. 2017), see Fig. 1. The discovery was made on October 19, 2017, by Robert Weryk at the Haleakal Observatory in Maui, Hawaii. Observational data yielded an effective radius estimate ranging from 55 to 114 meters for this object. In telescopic imaging, 1I manifested merely as a point source, with no discernible outgassing or material ejection detectable in the optical spectrum. One of the more perplexing characteristics was the detection of non-gravitational acceleration. A remarkable aspect of its observational profile was the extreme amplitude of its light curve, indicating variability in brightness by a factor of 10 (Meech et al. 2017). These unusual characteristics prompted the consideration of exotic hypotheses regarding its nature and origin (Loeb 2022, 2023).

The celestial mechanics of 1I were defined by an orbit with a semi-major axis ($a$) of -1.272 au, an eccentricity ($e$) of 1.201, and an inclination ($i$) of 122.8°. Prior to its identification, 1I had passed within a proximity of 0.16 au to Earth, a mere three days earlier. The orbit of this object was deter-

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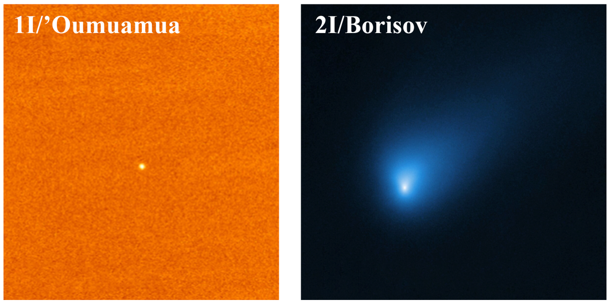


Fig. 1. 1I/'Oumuamua observed by the Nordic Optical Telescope in 2017 and 2I/Borisov observed by the Hubble Space Telescope in 2019.

mined from approximately 2.5 months of observational data. Initial shape estimates suggested an extreme axis ratio of 10:1, a figure that permeated popular representations with the dissemination of a 10:1:1 shape. However, subsequent refinements in shape assessments proposed a more oblate ellipsoid with a 6:6:1 axis ratio (Mashchenko 2019). The dominant component of the observed non-gravitational acceleration was radially aligned in opposition to the solar vector. Potential mechanisms for this acceleration include the sublimation of volatile substances such as solid hydrogen ($H_2$), nitrogen ($N_2$), or carbon monoxide (CO) (Jewitt & Seligman 2023). Alternatively, radiation pressure effects could be invoked, implying an extremely low-density, porous structure for the object (Bialy & Loeb 2018). A further hypothesis posits the release of molecular hydrogen, potentially accumulated through cosmic ray interactions during its interstellar voyage, which may have commenced with the object's outgassing upon solar approach (Bergner & Seligman 2023). 1I may be a planetesimal shaped by low-temperature, high-energy irradiation during its journey through interstellar space, undergoing significant outgassing when subjected to solar radiation.

2I/Borisov, the second macroscopic interstellar object officially recognized within our Solar System, was identified as C/2019 Q4 before its interstellar origin was confirmed (Borisov 2019), see Fig. 1. The discovery was credited to Gennadiy Borisov on August 30, 2019, who utilized a self-built 0.65-meter telescope for the observation. The nucleus of 2I was estimated to range between 0.2 and 0.5 km in diameter. Similar to 1I, 2I exhibited non-gravitational acceleration, but unlike its predecessor, it showed a clear and continuous mass loss, as well as a coma with distinct gas emission bands, indicating active processes commonly associated with comets. The nature and behavior of 2I do not seem as extraordinary as those of 1I.

The orbital parameters for 2I included a semi-major axis of -0.851 au, an eccentricity of 3.357, and an inclination of 44.05°. This interstellar visitor was first observed approximately three months before reaching its closest approach to the Sun, or perihelion. Observational efforts extended over a year (Jewitt & Seligman 2023). A bright coma around 2I hampered the direct observation of its nucleus. The radial acceleration exhibited by 2I was consistent with its observed mass loss. The detection of a high concentration of CO within the coma suggested that the object was likely formed under extremely cold conditions, possibly in the distant reaches of a protoplanetary disk (Jewitt & Seligman 2023). This origin provides a plausible explanation for the object's gravitational unbinding and its eventual incursion into our Solar System. The prospect of lasting dust trails from interstellar visitors, akin to those produced by cometary outbursts, presents a fascinating line of inquiry. Although comets are recognized for generating dust trails that can persist and remain visible over prolonged durations (Gritsevich et al. 2022), the behavior of these hyperbolic objects differs markedly in their dynamics.

## 2. HYPERBOLIC $\neq$ INTERSTELLAR

While dynamically probable, the interstellar provenance of 1I and 2I is not without contention. Numerical simulations suggest that massive bodies, with masses down to approximately $\sim$0.2 $M_J$ (Jupiter masses), traversing the Oort cloud can gravitationally perturb resident comets, catapulting them into hyperbolic trajectories that propel them into interstellar space or the planetary region (Higuchi & Kokubo 2020), see Fig 2. Statistical analyses indicate that roughly 0.1% of such perturbed objects could adopt orbital characteristics akin to those of 1I, while a mere 0.01% might attain the highly eccentric orbits that are characteristic of 2I.

The actual number density of such sub-stellar and sub-Jovian perturbers in the vicinity of the Solar System remains inadequately quantified. This uncertainty raises pivotal questions about the broader dynamics of Solar Systems and their role in the ejection of material into the galactic milieu. It is plausible to consider whether such interactions are an efficient mechanism through which systems lose material to the interstellar medium.

Furthermore, the potential for these hyperbolic objects to become Earth impactors cannot be overlooked. If planetary systems regularly eject debris

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in this manner, it could have significant implications for understanding the frequency and nature of hyperbolic impactors on Earth. Besides, interstellar impactors would elude our asteroid surveillance, preventing any possible prediction and planetary defense. These considerations underscore the importance of constraining the abundance and properties of massive perturber objects to better comprehend the dynamical processes governing the transfer of material between planetary systems, the broader interstellar environment, and the dynamics of our Solar System.

In this context, exploring the extensive meteor data collected by fireball networks today proves valuable. We focused on analyzing selected data from the Spanish Fireball and Meteorite Network (SPMN-CSIC; Trigo-Rodríguez et al. 2004) and the Finnish Fireball Network, FFN (Gritsevich et al. 2014; Lyytinen & Gritsevich 2016; Moilanen et al. 2021; Visuri & Gritsevich 2021). The FFN, in particular, observed an exceptional meteor On October 23, 2022, at 19:38:34 (UTC), a meteoroid (named FH1) was detected penetrating the atmosphere above Finland at a velocity marginally exceeding the escape speed of the Solar System by 200–700 m/s (Peña-Asensio et al. 2024a,b). This event was documented by three video stations within the FFN and a single image from an independent observer. The trajectory and physical parameters of the meteor were subsequently analyzed using the *3D-FireTOC* software (Peña-Asensio et al. 2021a,b, 2023).

The trajectory of FH1 is particularly notable due to its coincidence with the plane of the ecliptic, which is unusual for objects that are presumed to be interstellar in origin. Typically, interstellar objects are anticipated to exhibit a random distribution of orbital inclinations relative to the ecliptic plane. The absence of any detectable close planetary encounters before its detection reinforces the peculiarity of its orbital path. Given the modest velocity excess above the parabolic limit, we posit that FH1 is more likely an object originating from the Oort cloud that has been perturbed into a hyperbolic orbit, rather than an interstellar visitor.

Statistical analysis suggests that the probability of an interstellar object coincidentally sharing the same orbital inclination as FH1 is approximately 0.12%, further substantiating the likelihood that FH1 is of Solar System origin. Specifically, FH1 was found to be compatible with having undergone a gravitational perturbation by the close passage of the Scholz star binary system 80,000 years ago (Mamajek et al. 2015; Dupuy et al. 2019; de la Fuente Marcos et al. 2018; de la Fuente Marcos & de la Fuente Marcos 2022).

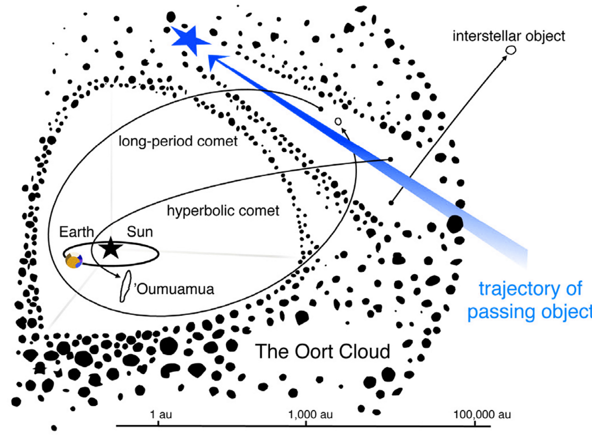


Fig. 2. Schematic illustration of a star penetrating the Oort cloud. Adapted from Higuchi & Kokubo (2020).

The detection and analysis of FH1 underscore a critical lesson: hyperbolic Earth impactors may not exclusively originate from interstellar space; instead, they may also be objects native to our own Solar System that have been accelerated to hyperbolic velocities. This realization has significant implications for assessing impact risks and understanding the processes governing the dynamics of our Solar System's Oort cloud and its interactions with the planetary region.

## 3. INTERSTELLAR METEORS

The detection of meteors possessing hyperbolic orbits is not a recent phenomenon; reports date back to the 1950s. Despite their consistent detection over decades, such hyperbolic meteors have historically been dismissed as observational or computational errors (Hajduková et al. 2014). This skepticism is partly due to the complex dynamics involved in accurately measuring the high velocities at which these objects enter Earth's atmosphere. In large automated databases of meteor observations, approximately 10% of recorded events exhibit non-elliptical, hyperbolic trajectories. Such a significant percentage suggests a systematic presence rather than sporadic anomalies.

Observational data indicate a tendency for these hyperbolic meteors to align closely with the ecliptic plane, which is the apparent path of the Sun across the sky where the Earth's orbital motion is also situated. There is a notable correlation between the direction from which these meteors appear to approach and the Earth's apex (the direction towards which Earth is moving in its orbit). Impacts that

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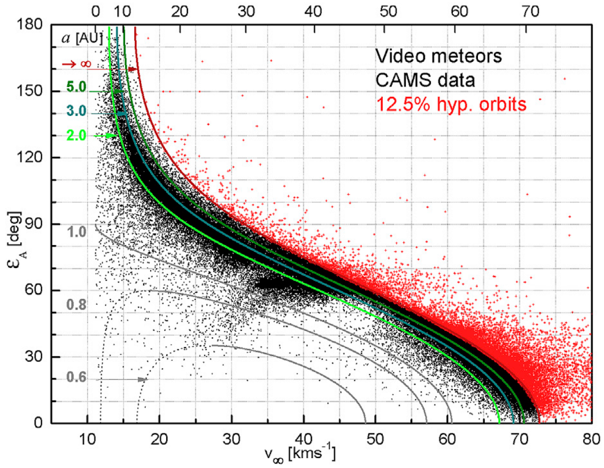


Fig. 3. Angular difference of the meteor apparent radiant and the Earths apex ($\epsilon_A$) in CAMS database versus the geocentric pre-atmosperic velocity ($v_\infty$) of the meteor. Reproduced from Hajdukova et al. (2020).

occur head-on, relative to Earth's apex, are more likely to be measured as hyperbolic because the relative velocities at impact are higher, which can result in spurious hyperbolic excess measurements, as depicted in Figure 3. These high-speed encounters increase the likelihood of measurement errors, potentially misclassifying the trajectory of an object as hyperbolic. Consequently, many hyperbolic orbits reported in meteor network databases could be artifacts of this high-velocity impact geometry.

### 3.1. *IM1 and IM2 CNEOS fireballs*

The identification of interstellar meteors presents a significant challenge in astrometric analysis and interpretation. The first two instances of such detections, referred to as IM1 and IM2 (Siraj & Loeb 2022a,b), were proclaimed based on luminous events captured by space sensors on United States Department of Defense (DoD) satellites, with their data subsequently published on the Center for Near-Earth Object Studies (CNEOS) website. Notably, IM2 was first recognized by Peña-Asensio et al. (2022). It is worth mentioning that within this database, a minuscule proportion (1%) of events are characterized by hyperbolic orbits. However, the data of these events is classified, rendering external verification infeasible.

IM1 was detected on January 8, 2014, near Papua New Guinea's northeast coast. The U.S. Space Command affirmed that the velocity estimate reported to NASA is sufficiently accurate to indicate an interstellar trajectory. This object had an asymptotic velocity of 42 km/s and disintegrated at an altitude of 18.7 km, with an estimated mass of around 500 kg and a diameter of approximately 0.5 m. Remarkably, IM1 exhibited a dynamic strength (the ram pressure at break up) twice that of known iron meteorites and maintained a heliocentric orbital inclination of 10°.

IM2 was observed on March 9, 2017, above the Atlantic Ocean near Portugal. The event peaked in radiance at an altitude of 23 km, with the object estimated to be 1 m in diameter and weighing 5,000 kg. Its aerodynamic strength was recorded as the third highest in the CNEOS catalog. IM2 entered the Solar System with an initial velocity of 26 km/s and had a heliocentric orbital inclination of 24°.

The strength anomaly presented by the interstellar meteor candidates IM1 and IM2 raises significant questions regarding our understanding of interstellar objects. Both events display an unexpectedly high aerodynamic strength, implying that only the most robust materials may endure the rigors of interstellar travel to reach our Solar System (Peña-Asensio et al. 2022). This observed robustness could point towards a detection bias, where only the sturdiest of objects are detected, as less resilient materials may not survive the journey intact. The calculation of aerodynamic strength, dependent on the atmospheric density and the square of the velocity, i.e., $\rho_{air} v^2$ (Trigo-Rodríguez & Llorca 2006; Vida et al. 2021), suggests that any overestimation in the velocity measurement could artificially inflate the perceived strength of these meteors. Consequently, the tremendous dynamic strength attributed to IM1 and IM2 could be a byproduct of inflated velocity measurements.

Furthermore, the heliocentric orbital inclinations for IM1 and IM2 are curiously low at 10° and 24°, respectively. This stands in marked contrast to the highly inclined orbits of the previously identified interstellar objects 1I and 2I, whose inclinations are -57.2° and 44.05°, respectively. The lower inclinations of IM1 and IM2 diverge from the expected distribution for an incoming interstellar population, which on average would exhibit inclinations closer to 45 degrees.

Theoretical models that aim to replicate the observed light curve of IM1 suggest that such observations could be consistent with an object possessing chondritic properties, albeit assuming velocities that are lower than those recorded (Brown & Borovička 2023)[10]. For IM1, aligning its observational data

[10]The authors contend that selecting errors to render IM1 elliptical is feasible, but requires a specific combination representing merely about ∼0.1% of all possible combination. Additionally, their assumption of velocity error being pro-

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with theoretical models necessitates assumptions of exceptionally low luminous efficiency, a highly aerodynamic shape, and materials with substantial inherent strength. Nevertheless, the event's uniqueness is further underscored by discrepancies between these observations and the measurements recorded by an infrasound station. Fernando et al. 2024 state that the reported seismic signals are spurious: one likely originates from local vehicular traffic, while the other is statistically indistinguishable from background noise. Additionally, Hajduková et al. 2024 conclude that the interstellar origin of IM1 is unsupported by available data, as all CNEOS hyperbolic fireballs show significant velocity component deviations, indicating mismeasurements potentially producing parameters statistically similar to IM1.

### 3.2. *Interstellar flux*

The estimation of interstellar flux, specifically through the detection of hyperbolic meteors, remains a subject of debate within the astronomical community. Radar-based detections of such meteors have frequently been challenged or dismissed as erroneous. Reports from radar systems like AMOR (Advanced Meteor Orbit Radar, Baggaley et al. 1993) and CMOR (Canadian Meteor Orbit Radar, Weryk & Brown 2004) have identified interstellar impactors in the 10-100 $\mu$m size range among millions of impacts.

Moreover, the Arecibo Observatory's radar system has reported the atmospheric entry of particles that appear to be of interstellar origin (Meisel et al. 2002). Complementing these ground-based observations, in-situ dust detections have been documented by spaceborne instruments aboard the *Galileo* and *Ulysses* spacecraft (Grun et al. 1993), lending credence to the presence of such particles within our Solar System.

In the six years that have passed since the groundbreaking discovery of 1I, the utilization of the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) survey has enabled astronomers to calculate an approximate number density of these interstellar objects. The number density is estimated to be 0.1 au$^{-3}$ for 1I-like objects (Jewitt et al. 2017). Extrapolating from this density, it is inferred that there could be around $10^4$ such objects within the vicinity of the Sun up to the orbit of Neptune at any given time. This translates to an influx of approximately $10^3$ such objects per year, or about three per day entering the Solar System.

portional to velocity lacks statistical support ($R^2$ = 0.027; Peña-Asensio et al. 2024a).

Emerging global surveys with broader sky coverage, such as Vera C. Rubin Observatory (formerly the Large Synoptic Survey Telescope or LSST) and the Global Network of Robotic Astronomical Observatories (BOOTES), have the potential to significantly enhance today's statistical data (Vinkovi et al. 2016; Bektešević et al. 2018; Vinkovic et al. 2020; Castro-Tirado 2023).

## 4. EXTRASOLAR METEORITES

The possibility of extrasolar meteorites reaching Earth's surface presents a captivating yet formidable challenge for detection and verification. Cometary objects, which originate at substantial distances from their stars, are more prone to becoming interstellar as they are weakly gravitationally bound to their host systems. However, these bodies are often composed of fragile icy conglomerates, which are unlikely to withstand the intense ablation of Earth's atmosphere if they impact at hypervelocities. More than half of the interstellar objects that enter our Solar System are traveling at velocities greater than 40 km/s (Cabot & Laughlin 2022). Should these objects impact Earth, they would do so at velocities exceeding 100 km/s, resulting in high-altitude airbursts rather than delivering meteorites to the surface.

In terms of frequency, based on the density number it is estimated that fewer than 50 impacts by 100-meter-sized interstellar objects have occurred over Earth's history (Jewitt et al. 2020). This rate is small compared to the impact frequency of similar-sized objects originating from within our Solar System, which is about 10,000 times higher. This discrepancy is reflected in the geological record, with only around 200 confirmed impact structures (Schmieder & Kring 2020) and approximately 70,000 meteorites found on Earth (according to The Meteoritical Society database). This suggests that, if asteroidal in nature, our collections would contain seven extrasolar meteorites (0.01%).

The identification of extrasolar meteorites poses a significant challenge. According to the nebular hypothesis, such objects would carry a distinct isotopic signature. However, the critical question remains: Are we adequately verifying this unique signature? And if so, is it sufficiently distinct to be discernible from Solar System materials?

The recent announcement of the recovery of mm-sized spherules in the Pacific Ocean has sparked interest (Loeb et al. 2023). To substantiate the claim that these spherules are indeed interstellar in origin and are associated with the IM1 fireball, several

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crucial points require demonstration: firstly, that the IM1 event was interstellar incursion and that the object did not completely disintegrate in the atmosphere; secondly, that there is a direct link between the collected material and the IM1 event; and thirdly, that these spherules display an unusual isotopic composition indicative of an interstellar origin.

To date, none of these points have been conclusively proven, although full data is still pending peer-reviewed publication. The chemical anomalies levels of nickel, beryllium, lanthanum, and uranium detected in the spherules are reminiscent of those previously described in micrometeorites of Solar System origin (Rudraswami et al. 2016; Van Ginneken et al. 2021) and have been reported to align with anthropogenic coal ash (Gallardo 2023). Additionally, the search region is known for debris from artificial satellite re-entries, which could potentially contaminate the area with refractory materials exhibiting atypical element concentrations (Moreno-Ibáñez et al. 2016).

The spherules' isotopic signatures align with the Terrestrial Fractionation Line (TFL), a characteristic consistent with other materials from within our Solar System. In contrast, interstellar spherules would be expected to display significant deviations in Fe isotope ratios and align along a distinct line, parallel to but separate from the TFL. The alignment with the TFL shown in Figure 4 strongly suggests that these spherules do not pertain to interstellar visitors but are indigenous to our solar nebula. Should the materials be of natural origin, it is more likely that they are conventional micrometeorites derived from common asteroids altered by prolonged interaction with seawater and terrestrial contamination (Desch 2023).

## 5. CONCLUSIONS

Whether Earth receives impacts of interstellar provenance can be affirmedobjects from outside the Solar System visit our planet. The evidence strongly suggests that both 1I and 2I are of interstellar origin, given their hyperbolic orbits and other properties that cannot be easily explained by conventional mechanisms within our Solar System. The anomalies associated with 1I, such as its non-gravitational acceleration and extreme elongation, have plausible explanations that do not necessarily require the invocation of an exotic nature.

While a hyperbolic orbit is a strong indicator of an interstellar trajectory, it is not a definitive criterion, as such orbits can also result from interactions within the Solar System, such as close encounters with stars as exemplified by the hyperbolic Finnish fireball FH1.

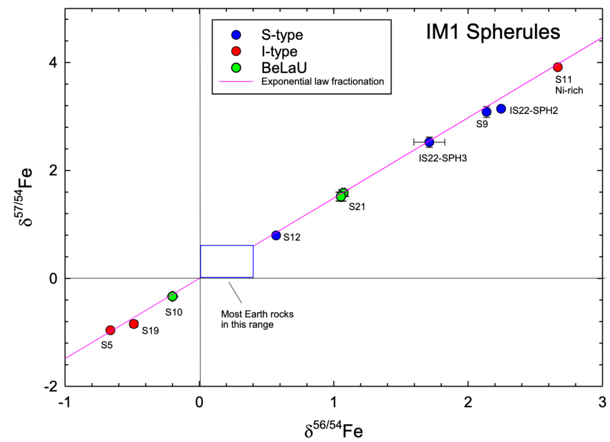


Fig. 4. Fe isotope ratios reported of the found spherules in the Pacific Ocean near the IM1 site. Reproduced from Loeb et al. (2023).

The classification of specific meteors as interstellar, including events such as IM1 and IM2, remains ambiguous. While initial assessments may suggest an interstellar pathway, further analysis often reveals inconsistencies with this interpretation. As such, there is no absolute certainty about the interstellar nature of IM1 and IM2, especially the latter.

The existence of extrasolar meteorites on Earth is a concept that continues to captivate the imagination of the scientific community. However, based on current detections, the likelihood of such discoveries remains extremely unlikely, primarily due to their low frequency and the challenges faced during atmospheric entry.

Regarding the spherules attributed to the IM1 event, their connection to IM1 and their interstellar nature is uncertain. The isotopic analysis does not support an interstellar origin, as their signatures are consistent with known Solar System materials.

In summary, while the pursuit of macroscopic interstellar samples is a scientific imperative, the likelihood of success increases when we turn our gaze upwards. Our endeavors should be directed toward enhancing sky surveillance capabilities and developing ready-to-launch interceptor missions. Such strategies will likely yield more definitive results in the quest to capture and study interstellar objects, as opposed to searching on the ground or in the seas.

**Acknowledgements:** This study was supported by the European Research Council (ERC) grant agreement No. 865657, projects PID2021-128062NB-I00 funded by MCIN/AEI /10.13039/501100011033, Unidad de Excelencia María de Maeztu CEX2020-001058-M, FEDER/Ministerio de Ciencia e Innovación Agencia Estatal de Investigación PID2021-126427NB-I00, and Academy of Finland project no. 325806.



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