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Review Article

The challenge of identifying interstellar meteors

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ABSTRACT

This review discusses the unsolved problem of the detection of interstellar particles in the Earth's atmosphere and the presence of interstellar meteors in meteor databases. Owing to the difficulties in obtaining accurate meteor measurements and, consequently, the meteoroids' orbital parameters, the identification of interstellar meteors based on their hyperbolic excess velocities is extremely challenging. Moreover, it has to be verified whether the orbit's hyperbolicity was not produced in the Solar System. Searches for interstellar meteors have been carried out using different observational techniques for more than a quarter of a century and, although they have produced many valuable results, not a single case of a meteor claimed to be produced by an interstellar particle has proven satisfactorily convincing. The reason rests in the constraints of the meteor observations, which we outline here, using meteor datasets obtained by various techniques.

1. Introduction

The motion of our Solar System in the interstellar medium should lead to the presence of interstellar particles (ISP). However, the proportion of interstellar meteoroids in comparison with the local population is still not known. The huge number of hyperbolic orbits among registered meteors has led to over-estimations of the possible occurrence of interstellar particles in the Earth's vicinity; these findings have consequently been called into question due to the constraints of the measurement accuracy (for more detail, see Hajduková et al., 2019). Thus, the ISP fluxes reported to date provide, in reality, only a statistically based upper limit for these fluxes (of particles of mass range corresponding to a particular observation). Possible interstellar meteoroids remain hidden within the error bars. This issue resulted in the field stagnating until the recent discovery of the first macroscopic interstellar object 1I/'Oumuamua (Meech et al., 2017), followed by another, comet 2I/Borisov (Guzik et al., 2019), less than two years later. The other end of the particle mass range also seems to be promising. Results from dust detectors, as yet at larger distances from the Sun, and in larger longitudes from the ecliptic plane, have provided a confirmed source of interstellar dust (ISD) in the Solar System (e.g. Krüger et al., 2015, 2019; Sterken et al., 2015, 2019; Strub et al., 2015, 2019; Grün et al., 2019).

Firstly, we describe theoretically interstellar particles entering the Solar System, penetrating into its inner part, and reaching the orbit of our planet. In the second part of this review, we deal with the possibility of observing them in the Earth's atmosphere as meteors and with the difficulties of identifying true interstellar meteors among them. The present paper is based on a detailed summary of research on interstellar particles by Hajduková et al. (2019).

1.1. Interstellar particles approaching the Earth's orbit

The Solar System currently moves through and/or near the edge of the Local Interstellar Cloud (LIC), which consists of gas and a small amount of dust, up to about 1 % by mass (Frisch et al., 1999). As seen from the Sun, there is an influx of interstellar material coming towards the Sun at a speed of about 26 km s^{-1}, reflecting the Sun's velocity relative to the LIC. However, whether a dust particle enters the heliosphere and penetrates the inner part of the Solar System or not depends on its mass, size, composition and morphology (Sterken et al., 2012). In the following, we recall briefly the dynamics of extra-Solar System particles in Solar System (Hajduková et al., 2019) and their possibilities to reach the Earth's orbit (Strub et al., 2019).

The first size-dependent filtering takes place at the heliopause. Very small dust particles (less than about 0.01 μm), which are tightly coupled to the magnetic field, are prevented from moving into the heliosphere.

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They gyrate and slide along the heliosphere boundaries, carried along by the plasma flow (Slavin et al., 2012). These particles are, however, too small anyway for meteor observations.

The dust particles from the LIC which move inside the heliosphere experience the solar gravity, solar radiation pressure and the Lorentz force. The strength of these forces is given by the ratio F_{SRP}/F_{grav} (β parameter), and by the particle's charge-to-mass ratio Q/m. The first two forces (combined) depend only on the material properties of the particle, on its mass and on the distance from the Sun. The latter depends on these properties and on the particle's velocity relative to the solar wind velocity, and also on the strength and polarity of the magnetic field at the particle's location. Yet again, interstellar dust particles may be prevented from reaching the region of our planet. The effect of the combined gravitation and radiation pressure forces (parameter β) on the ISP trajectory is shown in Fig. 1.

Small particles, for which the radiation pressure force dominates the gravity ($\beta > 1$), cannot reach the close vicinity of the Sun. When approaching the Sun, they decelerate and are then deflected by the radiation pressure force away from the Sun into interstellar space. Particles around 0.2 μm ($\beta \geq 1.4$) will be deflected at distances larger than 1 AU from the Sun. Therefore, they will not be observable from the Earth (Strub et al., 2019). Moreover, the smallest particles (with large charge-to-mass ratios) are also influenced by the Lorentz force, which can both narrow or widen their void regions (so called β cones) in the vicinity of the Sun, depending on the solar wind cycle (for more detail, see Sterken et al., 2012; Strub et al., 2019).

For dust particles larger than about 1 μm, solar gravity dominates the radiation pressure force ($\beta < 1$), and the Lorenz force can be neglected. The particles are pulled in the direction of the Sun by gravity and accelerate, then continue on their hyperbolic orbits into interstellar space. Their heliocentric speeds at the Earth's distance from the Sun can reach up to 49 km s^{-1} (for the largest particles, $\beta = 0$). On the other hand, some of them are slowed down by the radiation pressure and/or Lorentz forces to speeds comparable to interplanetary dust particles, which adds to the problem of distinguishing them from local interplanetary particles.

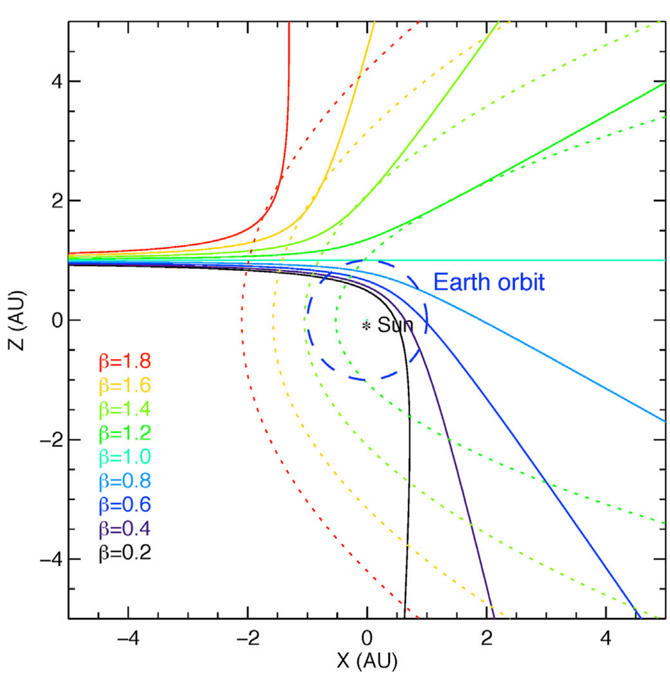

Fig. 1. Simulated trajectories of interstellar dust coming into the Solar System for different β-values. The dotted lines show the β-cones. Adapted from Sterken et al. (2012). Reproduced with permission from Astronomy & Astrophysics, ©ESO.

In any case, ISD from the LIC can reach the Earth's orbit, and thus be detected, or even collected, by space probes at 1 AU distance from the Sun (Strub et al., 2019). Scenarios for a dust sample return at the Earth's distance have already been elaborated (Srama et al., 2009).

ISP may also come into the Solar System from different sources of our local galactic neighborhood. Larger ISP (with sizes of a few tens of μm) may be ejected from other star systems, enter the Solar System, cross the Earth's orbit, and may be observed in the Earth's atmosphere. There are a number of nearby sources of such particles and simulations have shown that they can propagate for tens of parsecs through the interstellar medium (Murray et al., 2004). They can be observed as meteors by current ground-based systems, which would, retrospectively, allow their sources to be traced.

Taking into account a broad range of stellar velocities depending on the star's spectral type (Dehnen and Binney, 1998), and various ejection velocities depending on the source (Murray et al., 2004), one can estimate that ISP arrive at the edge of the Solar System with a speed of tens of km s^{-1} (Hajduková et al., 2019).

An interstellar meteoroid with an arrival speed v_a of 20 km s^{-1} with respect to the Sun (representing the Sun's relative velocity in its stellar neighborhood), will have, considering the equation $v_a^2 = v_H^2 - v_p^2$, a heliocentric speed at the Earth's distance of 46.5 km s^{-1}. This value is about 4.5 km s^{-1} above the parabolic limit (escape velocity from the Sun near Earth). The hyperbolic excess in the heliocentric velocity is the property which indicates the interstellar origin of the particle. It is expected to be several km s^{-1} but, considering the wide stellar velocity distribution in the vicinity of the Sun, as well as the encounter geometry, any value of a hyperbolic excess may be of interstellar origin. Interstellar meteors arriving from behind the Sun's motion, with respect to the local standard of rest, may arrive with almost zero excess velocity.

The basic problem is to distinguish whether the hyperbolic excess is due to the interstellar origin of a particle or the particles' acceleration in the Solar System or is only a consequence of measurement errors.

There is a possibility that a solar system particle which was accelerated to hyperbolic velocity inside the system encounters the Earth on its way out of the Solar System. In the Earth's atmosphere, it will be observed as a hyperbolic meteor. The majority of these processes produce very small hyperbolic excesses; although, planetary perturbations that generate hyperbolic orbits through the slingshot effect can produce speeds comparable to interstellar meteors (Wiegert, 2014). This option has to be investigated in any search for interstellar meteors. An overview of the processes operating in this way is given in Hajduková et al. (2019).

In principle, hyperbolic orbits generated in the Solar System can be classified and are thus discernible from true interstellar meteoroids. A more troublesome situation is that of identifying measurement errors which create spurious orbits or even spurious populations. This is by far the most common reason for the found hyperbolicity of meteoroid orbits. We will demonstrate it in the next section using real meteor data from several catalogues of meteoroid orbits.

2. Meteor observations and their accuracy

A particle of interstellar origin moves in the Solar System on a hyperbolic orbit with respect to the Sun. The semimajor axis a, and its reciprocal value $1/a$, is the element that defines the type of orbit. Its positive value represents a particle on a bound orbit in the Solar System and its negative value stands for an encounter with a particle on an unbound orbit.

For a constant distance r from the Sun (in the case of meteor observations, $r = 1$ au), the type of the orbit (a) is determined by the velocity of the particle on the orbit around the Sun (v_H). Thus, the semimajor axis a strongly depends upon the heliocentric velocity v_H, which is derived from the measured speed and is also influenced by the measured position of the meteor. Having made various corrections (such as corrections for atmospheric deceleration, diurnal aberration, acceleration by the Earth's gravitational field, vector addition with the Earth's motion, etc.), which depend on the observational technique used, we obtain the resulting value of the heliocentric velocity v_H, which is burdened by various errors arising from each step of the procedures used. Even in the photographic data, the error of the determined speed v_H can easily exceed 1 km s^{-1}, which corresponds to about 0.08–0.09 au^{-1} in $1/a$ (Kresák, 1992). Such errors can transfer near-parabolic orbits over the parabolic limit. The higher the velocity v_H of the meteoroid, the smaller the error needed for

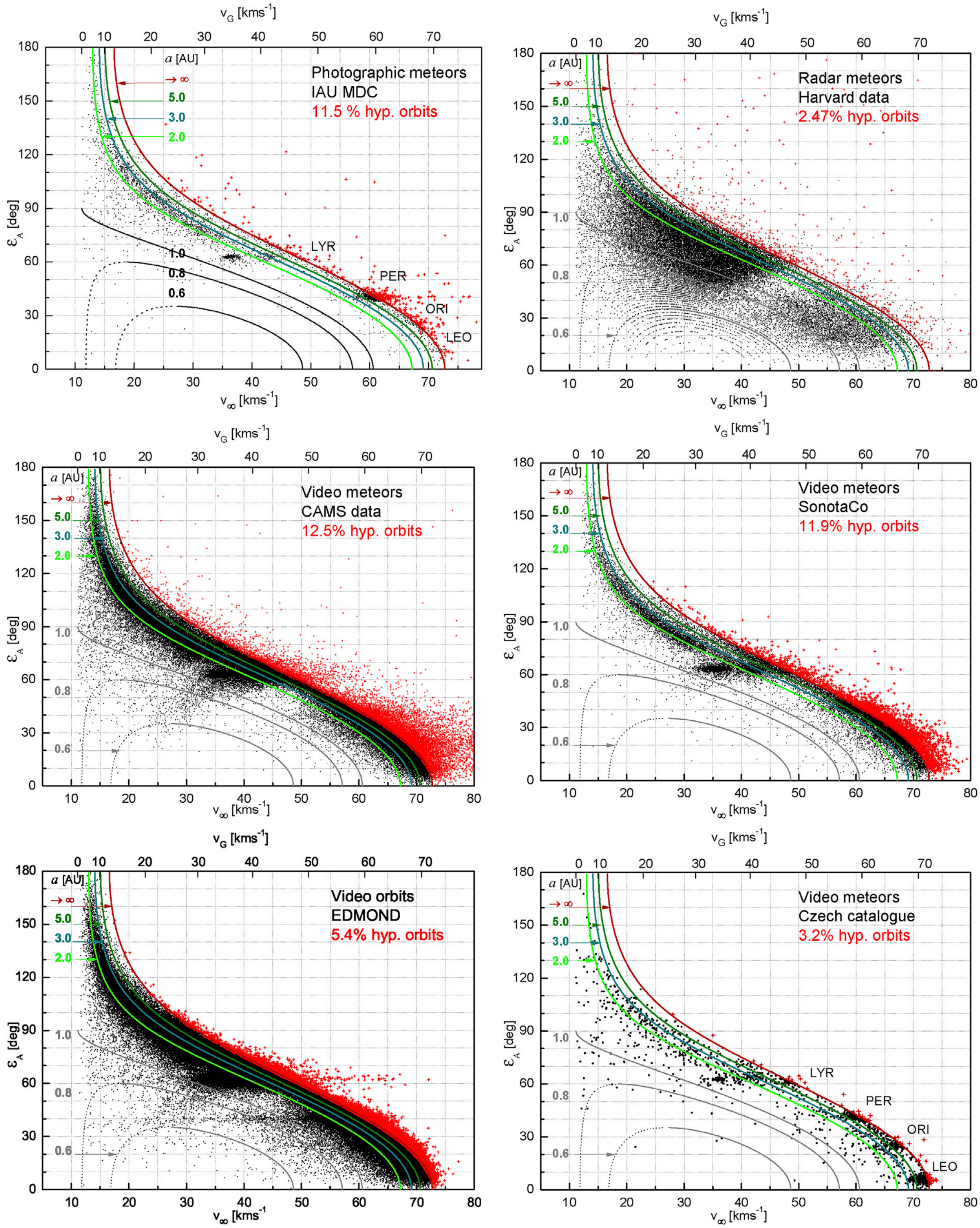

Fig. 2. The angular elongation of the apparent radiant from the apex ε_A is plotted against the pre-atmospheric velocity v_{inf} (or the geocentric velocity v_G). The lines indicate constant semi-major axes. The large number of hyperbolic orbits (red crosses) demonstrates the influence of the errors in radiant position and speed on the resulting semi-major axis of the meteoroid orbit. Individual orbits are taken from various databases and plotted in separate graphs (elliptical - black circles). Adapted from Hajduková et al. (2019) and Kresák and Kresáková (1976). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

this change.

The effect of both the measured speed and the measured radiant position on the semimajor axis can be demonstrated in a graph showing the relation between the non-atmospheric velocity v_{inf} (or geocentric velocity v_G) and the angular elongation of the apparent radiant from the apex, ε_A: $v_H^2 = v_G^2 + v_0^2 - 2v_G v_0 \cos \varepsilon_A$, where v_0 is the mean heliocentric velocity of the Earth. Based on Kresák and Kresáková (1976), we constructed graphs (Fig. 2) for different values of semi-major axis a (different curves in each plot) and used various meteor data (different plots).

The graphs clarify three main points:

(1) Measured velocity versus hyperbolic velocity

The plots in Fig. 2 demonstrate clearly that particles with hyperbolic velocities with respect to the Sun (the red crosses) do not necessarily require high geocentric velocities. Depending on the encounter geometry, they may exceed the maximum collisional velocity of two solar system objects, which is 72 km s^{-1} at the Earth (30 km s^{-1} Earth rotational velocity, and 42 km s^{-1} escape velocity w.r.t. Sun); but they may also be as low as 12 km s^{-1} when they encounter the Earth from behind the Earth's motion. However, there is an advantage to high geocentric velocities, i.e. particles with lower masses can create meteors in the atmosphere. Assuming that the mass distribution of interstellar particles has similar behavior to interplanetary ones, observing smaller particles increases the chances of finding ISP. A disadvantage is that faster meteors can be, because of a shorter measurement time, harder to measure accurately.

It is worth noting that a relatively wide range of geocentric velocities (11–72 km s^{-1} for local meteoroids) ultimately gives a narrow range of heliocentric velocities of meteoroids crossing the Earth's orbit (e.g. 36–42 km s^{-1} for orbits with aphelia between the asteroid belt and infinity). This occurs due to the correlation between the two plotted quantities and has consequences for the precision needed to discriminate between different kinds of orbits, which can be directly inferred from the graph. There are many independent reasons for the errors in the radiant position and in the velocity (which depend on the method used for observation as well as for the data reduction). Their influence on the orbital parameters is much stronger for particles with higher values of v_H than for low heliocentric velocity meteoroids.

(2) Required measurement accuracy

The required measurement accuracy in speed and radiant position for discrimination of various orbits is given by the resolution within a particular zone and is different for different regions in the plot (Fig. 2). The most demanding conditions are along the parabolic limit, especially for high velocities. Along this line, the vast majority of hyperbolic orbits (red crosses) is concentrated. Distinguishing between a long-period orbit and a hyperbolic orbit needs a resolution of about $\pm$ 1 km s^{-1} in speed and $\pm$1–2 deg in radiant coordinates. This requires higher accuracy measurements than the above-mentioned values, which is rarely fulfilled.

This is the reason the concentration of shower meteors (having known local sources) among the hyperbolic orbits is so high. For showers such as the Perseids, Orionids, Lyrids and Leonids, the difference δv between their mean heliocentric velocities v_H and parabolic limit $v_p = \sqrt{2}\, v_0$, ranges from 0.22 km s^{-1} for the Lyrids to 0.71 km s^{-1} for the Leonids. These values are often exceeded by the standard deviations of their determined heliocentric velocities (Hajduková, 2008). The smaller the δv of the stream, the higher the proportion of the hyperbolic orbits in the shower. The study showed that the proportion of hyperbolic orbits explicitly increases with the increasing mean heliocentric velocity of a particular shower $N_{e>1}/N = f(v_H)$. It has to be mentioned that there is a possibility that a small fraction of these hyperbolic orbits is real but not of interstellar origin. Comets with high heliocentric velocities (on highly eccentric orbits) may also release particles on hyperbolic orbits during the ejection processes. The ejection velocities (e.g. Ryabova, 2013), however, modify their orbits only slightly and their low hyperbolic excesses, observed in the atmosphere, should be discernible from the interstellar particles. In Fig. 2, these cases should be on, or very close to, the parabolic limit (red curve).

Clearly, the problem of insufficient accuracy measurements is also valid for individual sporadic meteors.

The only regions of the graphs (Fig. 2), where the lower accuracy would be sufficient, is the lower left or upper right. The first area corresponds to orbits with aphelia near the Earth (shown for semi-major axes of 0.6 and 0.8 au in all graphs). The dotted lines correspond to particles overtaken by the Earth and solid lines to the retrograde particles encountering the Earth head-on. The number of meteors in this area is low.

The upper right region of the graph corresponds to highly hyperbolic orbits. Hyperbolic excesses of interstellar meteors are expected to be lower but possible individual extreme values cannot be excluded. The reality of such cases can be judged on first view when we look at the distribution of the orbits beyond the parabolic limit in the data they belong to. In the most precise data, this area is empty.

(3) Velocity dispersion beyond the parabolic limit

The consequence of the difficulty in distinguishing between different orbits along the parabolic limit, seen on all graphs, is an apparent population of hyperbolic meteors (red crosses in Fig. 2), the distribution of which depends on the accuracy of the data.

Rough data from the photographic catalogues of the IAU MDC, version 2003 (Lindblad et al., 2003), which contain 4581 orbits, are shown in the first graph of Fig. 2. Most of the orbits determined as hyperbolic (11.5%) are situated along the parabolic limit. There are also a few cases of extreme hyperbolic excesses; all of them, however, belong to the catalogues of lower quality (Hajduková, 2008). The database is created from more than fifteen different catalogues (Lindblad et al., 2003), each containing data obtained with different equipment and different determination software; thus, with various precision. A detailed analysis of this database (Hajduková, 2008) showed that the vast majority of hyperbolic orbits was caused by various errors, setting the upper limit of their proportion in the data to be of the order 10^{-3}.

Radar data from older catalogues of the Harvard programs fused together (Lindblad, 2003) gave 39 145 orbits, which are shown in second graph of Fig. 2. The smallest proportion of hyperbolic orbits (2.47%) in the data exhibits the largest dispersion, which is continuously extended far beyond the parabolic border. Measurement errors were not available, but a deep error examination showed that they may reach 10 km s^{-1} (Hajduková and Paulech, 2007). In this data, it would not be possible to identify any interstellar meteors, even if they were there.

The situation in video data sets is shown in the next four graphs of Fig. 2. We used 108 880 orbits from the CAMS database from the years 2010–2013 (Jenniskens et al., 2011), 27 128 orbits from 2018 from the SonotaCo catalogue (SonotaCo, 2016) and 251 805 orbits from the EDMOND database (Kornoš et al., 2014). In the CAMS data, there are 12.5% apparent hyperbolic orbits; in the SonotaCo catalogue 11.9%; and in the EDMOND 5.4%. The first two data sets exhibit comparable spreads beyond the parabolic limits, concerning the relative number of orbits in them. The smaller percentage of hyperbolas in the EDMOND data, and their smaller dispersion, was caused by the post-processing of the rough data (having 14% hyperbolic orbits) using multiple selection criteria (the angle of observed trajectory had to be $>$ 1 deg; the duration of the meteor $>$ 0.1 s; the convergence angle $>$ 10deg; the difference between the two poles of ground trajectory $<$ 0.5 deg; and the difference in velocity between unified velocity and velocity from one of the stations $dv_{12} < 7\%$.), which removed the highest velocity meteors (Hajduková et al., 2017). This demonstrates the causality between the low quality of data and the presence of hyperbolic orbits in them.

The extreme values of hyperbolic excesses are probably, in all three data sets, well above their 3 sigma error. However, seeing the continuously wide spread of the orbits beyond the parabolic limit, one cannot consider all particles above 3 sigma error en bloc to be of interstellar origin. To identify individual interstellar particles that may be among them is not possible. After a proper error analysis, including the appropriate error estimates of the meteor speed and position measured and the analysis of errors of the calculated parameters of all the individual meteoroids which are candidates for interstellar origin, it is possible to derive an upper limit of their flux.

In contrast to the above-mentioned video data, the Czech catalogue of video meteor orbits (Ondřejov data, Koten et al., 2003) does not show any spread of meteors behind the parabolic limit. All the orbits determined as hyperbolic are located along this border. The database contains high quality data, at the expense of the total number of orbits (1931 meteors). The orbits are computed from the manual measurements of the individual meteor points. The achieved precision is a few tenths of a degree in the radiant position and up to 0.5 km s^{-1} in the velocity. Even with this precision, 3.2%, including members of the showers, have orbits determined as hyperbolic. The hyperbolic shower meteors with the smallest excesses may be real, being produced by their parent comets through outgassing processes. In the subset of 53 hyperbolic meteors, the median error of their geocentric velocities is 0.38 km s^{-1} and, in their radiant coordinates, 0.46 deg in right ascension and 0.23 deg in declination. These low values of errors, which change elliptical orbits to hyperbolas, indicate how critical the conditions along the parabolic limit are. In this data, however, a hypothetical meteor with an excess of several km s^{-1} could be treated as a candidate for interstellar origin. A larger set of sporadic background meteors would be useful, as it is rather small in this catalogue, since the observation campaigns were dedicated to selected meteor showers.

There are many studies related to interstellar meteoroids in the literature, each of which has, to a greater or lesser extent, dealt with the problem of their identification. Using various meteor observations, the detection of interstellar meteors and/or the determination of their fluxes have been reported by (e.g. Baggaley et al., 1993; Hajduková, 1994; Hawkes and Woodworth, 1997a, b; Baggaley, 1999; Weryk and Brown, 2004; Hajduková and Paulech, 2007; Musci et al., 2012; Froncisz, 2020). From their controversial results, we can conclude that there is a lack of statistical argument for the presence of interstellar meteoroids among registered meteors, and not one interstellar fireball in the Earth's atmosphere has yet been reported.

The flux distribution of ISPs with size can be illustrated in one plot (Fig. 3, after Hajduková and Paulech (2002); Musci et al. (2012)), from sizes as small as interstellar dust to large interstellar objects like asteroids and comets. The Figure shows the measurement methods and their limitations as well as the derived fluxes so far (solid line for dust, rocks for the meteor observations). The figure illustrates that the overall flux distribution is still unresolved. Scrutinizing the challenges in identifying interstellar meteors as well as new measurements from emerging new technologies are crucial towards resolving the interstellar flux-size distribution.

An interesting aim would be to consider the existence of interstellar streams. The second recently discovered interstellar object in the solar system is an active comet and has surely produced dust particles. However, they will leave the solar system together with the comet, since their heliocentric velocities are, after their release, similar to the comet's speed. Smaller (submicron) particles interact with the magnetic field and solar radiation pressure and can considerably be slowed down. During the only approach, mutual collisions or space weathering have weak effects. A spread of the larger particles into the sporadic background is unlikely.

Except for the two macroscopic interstellar objects, the only dependable detection of interstellar particles in our Solar System which we have to date are the measurements of ISP using the dust instruments, mainly, on board the Ulysses and Galileo spacecraft. The distribution of ISP from the LIC varies with their positions in the Solar System and their flux depend on the particles masses. Fluxes of ISP from meteor observations made from the Earth, together with those of the interstellar dust measurements from the space probes, were summarized by several authors (e.g. Grun et al., 1985; Landgraf et al., 2000; Hajduková and Hajduk, 2006; Musci et al., 2012), and recently collected and discussed in Hajduková et al. (2019).

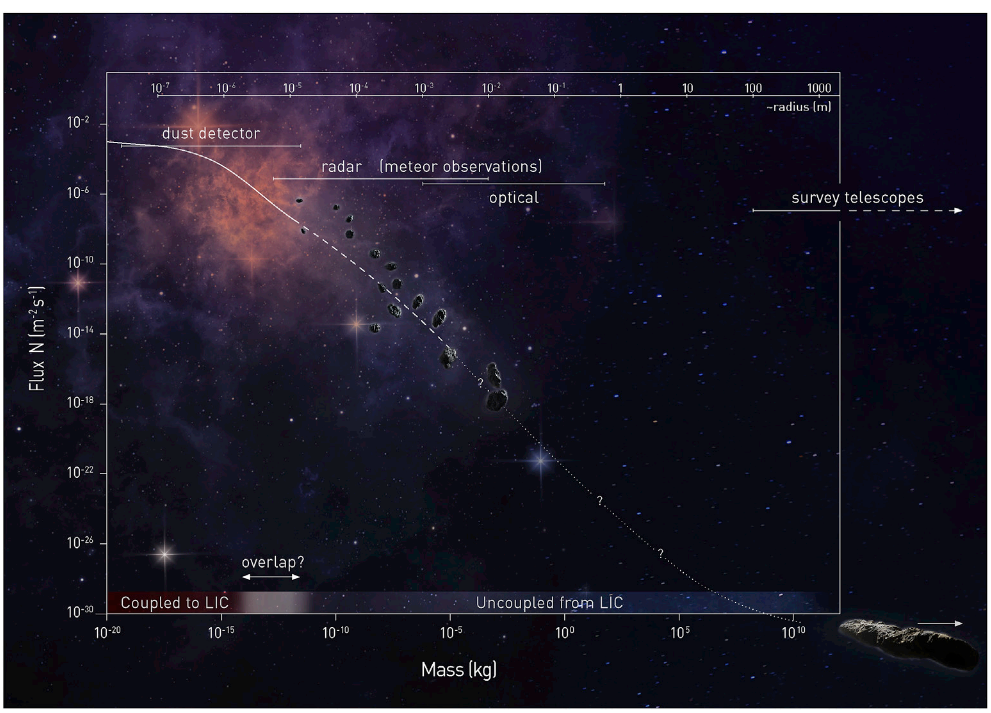

Fig. 3. The still somewhat precarious size-frequency distribution of interstellar visitors, from dust to meteoroids (after Hajduková and Paulech (2002); Musci et al. (2012)), asteroids and comets. 'Overlap' refers to interstellar particles released from interstellar comets, after having been transported into the solar system by their parent body – as 'hitchhikers' through the Local Interstellar Cloud (LIC). "Visualisation: ETH Zürich/D-PHYS, Veerle Sterken, Mia Hajdukova, Sara Hartmann".

3. Conclusions

This review shows how challenging the identification of interstellar particles, and distinguishing them from detected meteors, is. The orbit of a meteoroid around the Sun is determined from measured parameters of a meteor, its position and speed. Both of them influence the resulting value of the heliocentric velocity, which is, very sensitively, related to the semi-major axis, a parameter intimately connected to the origin of the particle. This process requires an appropriate error examination and high accuracy orbits. On the one hand, measurement errors can transfer near-parabolic orbits over the parabolic limit and create an artificial population of hyperbolic meteors, often interpreted as of interstellar origin; on the other hand, possible detected interstellar meteors remain hidden within the error bars.

Since the heliocentric velocity determination is crucial for orbit determination, without any improvements to meteor velocity and position measurements (Hajduková et al., 2017, 2019), and corrections which involve ablation modelling and assumptions about the meteoroid composition (Vida et al., 2018), the problem of distinguishing interstellar meteors from interplanetary ones remains, at least for fainter meteors.

The problem could be overcome by increasing the astrometric accuracy, from which both the position of the meteor radiant and the geocentric velocity result, and by accurate meteor trajectory estimations and orbital parameter determinations. However, it is a very complex problem. It would be advantageous to use the long-focal systems (such as the Canadian Automated Meteor Observatory, Weryk et al. (2013)), which follow a meteor with all its details after an impulse from the allsky camera. If using a proper trajectory estimation method, such a system could provide a solution which would allow an unambiguous identification of a particle's origin.

Recently, Vida et al. (2020a, b) developed a new meteor trajectory method that searches for a solution which best determines the geometry and fits the dynamics of the atmospheric flight that is most consistent when seen from all stations.

Hajduková and Kornoš (2020) tested the influence of meteor measurement errors on the heliocentric orbits of meteoroids. In the case of a "perseid-like" orbit with a nominal value of the semi-major axis $a = 19$ au, a simulated error of 1 km s^{-1} in the pre-atmospheric velocity and 1 deg in the radiant, resulted in one third of about 14 000 cloned orbits being determined as hyperbolic. Thus, the accuracy needed in both the radiant position and in the v_{inf} must be much higher. The authors also calculated that, if the accuracy in these two parameters reaches values of 0.1 deg and 0.1 km s^{-1}, respectively, as estimated by Vida et al. (2020b) for "CAMS-like" moderate field of view systems when using their simulator, no cloned orbit would reach the parabolic limit. This means, a true hyperbolic orbit could be identified.

In any case, a conclusive detection of interstellar meteors would be of high significance, since it may, for the first time, permit the study of the debris disks of other stars from observations of particles in the Solar System. Moreover, it would provide new characteristics additional to the in-situ measurements of interstellar dust, as well as more information on the processes taking place in interstellar space.

CRediT authorship contribution statement

Maria Hajdukova: Conceptualization, Writing - original draft, Writing - review & editing, Formal analysis, Interpretation of data. **Veerle Sterken:** Modeling, Interpretation of data, Writing - review & editing. **Paul Wiegert:** Interpretation of data, Writing - review & editing. **Leonard Kornoš:** Data curation, Methodology, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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