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Hyperbolic meteors: Interstellar or generated locally via the gravitational slingshot effect?

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ABSTRACT

The arrival of solid particles from outside our Solar System would present us with an invaluable source of scientific information. Attempts to detect such interstellar particles among the meteors observed in Earth's atmosphere have almost exclusively assumed that those particles moving above the Solar System's escape speed – particles on orbits hyperbolic with respect to the Sun – were precisely the extrasolar particles being searched for. Here we show that hyperbolic particles can be generated entirely within the Solar System by gravitational scattering of interplanetary dust and meteoroids by the planets. These particles have necessarily short lifetimes as they quickly escape our star system; nonetheless some may arrive at Earth at speeds comparable to those expected of interstellar meteoroids. Some of these are associated with the encounter of planets with the debris streams of individual comets: Comet C/1995 O1 Hale–Bopp's 1996 pre-perihelion encounter with Jupiter could have scattered particles that would have reached our planet with velocities of almost 1 km s^{-1} above the hyperbolic velocity at Earth; however, such encounters are relatively rare. The rates of occurrence of hyperbolically-scattered sporadic meteors are also quite low. Only one of every $\sim 10^4$ optical meteors observed at Earth is expected to be such a locally generated hyperbolic and its heliocentric velocity is typically only a hundred metres per second above the heliocentric escape velocity at Earth's orbit. The majority of such gravitationally-scattered hyperbolics originate at Mercury, though Venus and Mars also contribute. Mercury and Venus are predicted to generate weak 'hyperbolic meteor showers': the restrictive geometry of scattering to our planet means that a radiant near the Sun from which hyperbolic meteors arrive at Earth should recur with the planet's synodic period. However, though planetary scattering can produce meteoroids with speeds comparable to interstellar meteors and at fluxes near current upper limits for such events, the majority of this locally-generated component of hyperbolic meteoroids is just above the heliocentric escape velocity and should be easily distinguishable from true interstellar meteoroids.

1. Introduction

The first measurement of a meteor velocity may have been due to Elkin (1900). He used a bicycle wheel as the basis for a rotating shutter that would interrupt the meteor's image on a photograph, and the segmented image was used to determine the meteor's velocity. The idea of using photographs to measure meteor velocity goes back further, at least to Lane (1860) but was not initially widely-used. The difficulty with photographic observations was its limited sensitivity in its early days: a hundred hours of observation might be required for a single successful result *e.g.* (Lovell, 1954, chap. IX). Though photography goes back to the early 1800s, as late as 1932 Shapley et al. (1932) noted that "several hundred meteors are visible to the unaided eye to one that can be photographed".

Naked-eye visual observations provided the first substantial number of meteor velocity measurements, along with the first indication of meteors that might be from outside our Solar System. Von Nießl and Hoffmeister's Fireball Catalogue (Von Nießl and Hoffmeister, 1925) contains visually determined orbits of fireballs. Many of their entries are hyperbolic with respect to the Sun, that is, their velocities are so large that they cannot be gravitationally bound to our Solar System. At the Earth's orbit, the parabolic or escape velocity with respect to the Sun is about 42 km s^{-1}, and 79% of Von Nießl and Hoffmeister's (1925) orbits exceed this value, some ranging up to 99 km s^{-1} (as quoted in Lovell (1954, chap. VIII)).

A simple interpretation of hyperbolic meteors was that, since they were not bound to our Solar System, they must be from

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outside it and thus represent material originating elsewhere in our Galaxy. However, not all researchers agreed that substantial numbers of meteors had hyperbolic velocities, attributing them rather to measurement error. The discussion of the reality of hyperbolic meteors centred on the sporadic meteors: many showers were already accepted to be on bound orbits near those of their parent comets and thus part of streams of particles originating within our planetary system. A vigorous debate as to the existence of hyperbolic meteors spanned the next few decades. Fisher (1928) and Watson (1939) concluded that since the hyperbolic meteors of Von Nießl and Hoffmeister (1925) largely coincided in time with the major showers and in space with the ecliptic plane, that they were unlikely to be of true interstellar origin; they instead concluded that a systematic over-estimation of the velocities, which were at the time still measured by observers using the naked eye, was more likely. Others argued conversely that, if some showers were in fact interstellar in nature, meteor showers and hyperbolic meteors might be expected to coincide in some cases.

The problem was considered sufficiently important that the Harvard Observatory organized the Arizona Expedition to resolve the question (Shapley et al., 1932). Ernst Öpik led a campaign that erected two 'meteor houses' in Arizona where observers would record meteor data – still taken visually by human observers – in an organized fashion. The houses, really small protective shelters for the observers, had windows with built-in reticules to aid in positional measurements. The campaign also made use of the clever 'double-pendulum' or 'rocking mirror' technique whereby the meteors' motion would be translated into a pseudo-cycloidal motion, the number of cusps/loops of which could be used to facilitate trail length and speed measurements (Shapley et al., 1932; McFarland et al., 2010).

The initial results of this work (Öpik, 1940) reported 57.2% of meteors as being hyperbolic, with heliocentric velocities in rare cases reaching over 280 km s^{-1}. The expedition leader was aware of the potential pitfalls: "As in all kinds of visual observations of meteors in which the observer has finally to rely upon his memory, considerable accidental and systematic errors are involved in the observed velocities too; in a statistical discussion of velocities such as given below the data must be freed, in the first place, from the influence of these errors. Only after that can the bearing of the statistical data upon cosmic problems be investigated" (Öpik, 1940).

Despite the Arizona results, some astronomers remained sceptical that sporadic meteors were interstellar. Porter (1943, 1944), working from other visual observations, concluded that meteors are not hyperbolic in any great numbers, and emphasized the need for a careful statistical analysis of a sample with known errors. The interstellar hypothesis received a serious blow when the first photographic meteor studies (Whipple, 1940) identified the Taurid stream, once conjectured to be an interstellar stream, and found it to be bound to the Sun and associated with Comet Encke.

Though Öpik continued to stand by the Arizona expedition's conclusions (Öpik, 1950), new photographic programs began finding the interstellar fraction of meteors to be quite small. The Harvard Super-Schmidt photographic program (Jacchia and Whipple, 1961) detected very few hyperbolic orbits. Radar meteor observations from Jodrell Bank (Almond et al., 1951, 1952, 1953; Clegg, 1952; see Gunn, 2005, for a review) and from Ottawa (McKinley, 1949, 1951) showed little or no evidence for interstellar velocities. Öpik (1969) eventually conceded that there was a failure in the basic assumptions underlying the rocking mirror technique, due partly to height differences between sporadic and shower meteors, and partly due to 'psychological' differences in their perception by observers.

Though the hyperbolic component is now recognized to be small at visual meteor sizes ($\gtrsim 1$ mm), they have been detected convincingly in interplanetary space at smaller sizes. Dust detectors aboard the Ulysses, Galileo and Helios spacecraft (Grün et al., 1993; Frisch et al., 1999; Krüger et al., 2007) have detected very small (10^{-18}–10^{-13} kg) grains moving at speeds above the local Solar System escape velocity and parallel to the local flow of interstellar gas. This result provides perhaps the first generally-accepted detection of interstellar meteoroids. However, these particles are too small to be detected as meteors at the Earth: sizes $\gtrsim 10^{-10}$ kg may be required for this.

Meteor radars are typically more sensitive than the human eye or photographs and can detect particles much smaller than those seen in early surveys of sporadic meteors. The Advanced Meteor Orbit Radar (AMOR) reported that a few percent of meteors with sizes of $\sim$50 μm (masses $\sim 10^{-10}$ kg) were hyperbolic, many of which were proposed to be particles ejected from the β Pictoris dust disk (Baggaley, 1999, 2000; Baggaley and Galligan, 2001). Radar hyperbolics have also seen by Janches et al. (2001) at Arecibo though these were determined to be meteoroids originating within our own Solar System that had been accelerated by solar radiation pressure. Some Arecibo radar meteor detections have been interpreted as true interstellar meteoroids (Meisel et al., 2002a,b), and thus the possibility remains that substantial numbers of interstellar meteoroids reach the Earth at sizes that do not produce naked eye meteors. However, not all radar studies show evidence for hyperbolic meteors: radar observations at the Canadian Meteor Orbit Radar (CMOR) do not contain appreciable hyperbolics: less than 0.0008% (Weryk and Brown, 2004).

Harvard super-Schmidt photographic observations (McCrosky and Posen, 1961), photographic meteor observations (Babadzhanov and Kramer, 1967), TV meteor observations (Jones and Sarma, 1985), and image-intensified video meteor studies (Hawkes and Woodworth, 1997) all show a minority fraction of hyperbolic orbits. Between 1% and 22% of meteors observed at the Earth by various surveys, optical and radar-based, have shown a hyperbolic component according to reviews by Hawkes et al. (1999) and Baggaley et al. (2007). It remains unclear whether these represent true hyperbolics or result from experimental uncertainties. Musci et al. (2012) present image-intensified optical results of a small number (22 of 1739) of possible interstellar meteoroids but ultimately attribute these to measurement errors. Work by Hajduková and her colleagues (Hajduková and Paulech, 2002, 2007; Hajduková and Hajduk, 2006; Hajduková, 2008, 2011; Hajduková et al., 2014) has shown that – even with modern photographic and video techniques – in many cases hyperbolic meteors only appear so as the result of measurement errors.

The true population of interstellar meteoroids within our Solar System remains unknown. The most recent theoretical work on the expected component of interstellar meteoroids in our Solar System is Murray et al. (2004), but the question must ultimately be answered by measurement. However, even given an unequivocal measurement of hyperbolic velocity for a meteor, the question remains: did the particle originate outside our Solar System? Given that processes within our Solar System might produce particles with high velocities and that could "contaminate" our sample of interstellar meteors, we need to understand the population of hyperbolic meteors produced internally to our planetary system in order to tease the two apart.

Here we address the question of whether or not hyperbolic meteoroids could be produced within our own Solar System, in particular by the gravitational slingshot effect. It has long been recognized that planetary scattering must produce some hyperbolic meteors whose origin is contained wholly within our Solar System (Lovell, 1954, chap. XII; Öpik, 1969). Recent work by Hajduková et al. (2014) examines the possibility of contamination of video meteor samples by scattered meteoroids and finds the effect to be small. In that study meteor paths are traced back in time to determine if an encounter with a planet had occurred, a useful diagnostic for any hyperbolic meteor. Not that gravitational scattering is the only mechanism by which they might be produced. The ejection processes of comets may inject meteoroids directly onto hyperbolic orbits. Small ($\lesssim 1\ \mu m$) cometary particles may feel enough radiation pressure to be unbound from the Sun independent of their ejection velocity from their parent (the so-called beta meteoroids). Collisional or rotational breakup of meteoroids and subsequent radiation pressure modification of their orbits are also thought to contribute to this population (Zook and Berg, 1975). The magnetic fields of the planets Jupiter and Saturn are also able to accelerate electrically charged grains to escape speeds, as was measured by the Ulysses and Cassini spacecraft (Grün et al., 1993; Kempf et al., 2005; Flandes et al., 2011).

Most of these mechanisms only produce hyperbolic meteoroids if the particles are small enough that radiation pressure can play a role in accelerating them out of our Solar System, and are not effective for larger particles. Particles small enough to be ejected via radiation pressure are not easily detected by Earth-based meteor sensors, and so reports of high-speed meteors are unlikely to be of this origin. Direct cometary ejection may also produce larger particles on hyperbolic orbits without the action of radiation forces; however, meteoroids of this type are likely to be part of a freshly deposited meteoroid stream and unlikely to be mistaken for interstellar meteoroids. Gravitational scattering is perhaps the only source of meteoroids larger than a few microns in size which could be readily confused with an interstellar influx of particles.

Here we examine the properties of gravitationally scattered meteoroids produced within our Solar System. Though in some sense "contaminants" of the interstellar meteoroid sample, their intrinsic properties are of interest as well for they come to us directly from the vicinity of the planets and may thus carry important information about these bodies and their environments. The techniques of meteor velocity measurement continue to improve and it is only a question of time before a substantial number of reliable hyperbolic meteors is measured: an understanding of the flux of such meteors produced within our Solar System is needed before the true interstellar component can be separated from the local one.

2. Methods

2.1. Scattering of a meteoroid by a planet

This work expands on the preliminary results of Wiegert (2011). The scattering is calculated analytically by taking a patched conic approximation to the meteoroid's trajectory past the scattering planet. The meteoroid is taken to be on a bound heliocentric orbit prior to its intersecting the planet's Hill sphere. From this point onward, it is assumed to travel on a two-body orbit around the planet until it leaves the Hill sphere once more, and then is taken to return to a purely heliocentric orbit. We allow the meteoroid to approach the planet from an arbitrary direction, and the scattering takes place in three dimensions. Here we are most interested in those particles whose post-scattering orbits are unbound with respect to the Sun and which also subsequently pass close to the Earth.

The procedure for calculating the scattering is straightforward and well-known *e.g.* Roy (1978, chap. 11), but is rarely presented in its full three dimensional form and so we outline it here.

For simplicity, we assume that the planet orbits the Sun on a circular orbit of radius a and velocity

$$v_p = \sqrt{\frac{GM_\odot}{a}} \tag{1}$$

where G is the usual gravitational constant and $M_\odot$ is the Sun's mass. The planet's Hill sphere has a radius H of

$$H = a\left(\frac{M_p}{3M_\odot}\right)^{1/3} \tag{2}$$

where M_p is the planet's mass. Inside the Hill sphere, the particle is taken to move on a Keplerian two-body path around the planet. Upon reaching the Hill sphere again (which is guaranteed by conservation of energy: the meteoroid cannot become bound to the planet in this approximation), the meteoroid proceeds onwards along a heliocentric Keplerian orbit.

The initial heliocentric approach velocity is taken to be anti-parallel to the vector $\vec{r}_0$ which runs from the planet to the centre of the target plane (see Fig. 1). The vector $\vec{r}_0$ is defined to be

$$\vec{r}_0 = H(-\sin\phi\cos\psi, \cos\phi\cos\psi, \sin\psi) \tag{3}$$

where $\phi \in [0, 2\pi)$ is the angle measured counterclockwise from the y–z plane along the Hill sphere (see Fig. 1). The latitude $\psi \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ is the angle between $\vec{r}_0$ and the planet's orbital plane, and is zero if the particle's motion is parallel to the ecliptic plane. The Sun-planet line defines the y direction and the z-axis is perpendicular to the plane of the planet's orbit. The heliocentric velocity $\vec{v}_p$ of the planet is in the negative x-direction.

A meteoroid enters the Hill sphere with a heliocentric velocity $\vec{v}_i$ anti-parallel to $\vec{r}_0$ given by

$$\vec{v}_i = v_i(\sin\phi\cos\psi, -\cos\phi\cos\psi, -\sin\psi) \tag{4}$$

The meteoroid crosses into the Hill sphere at the location (x_{tp}, y_{tp}) on the target plane where both x_{tp} and y_{tp} may run from $-H$ to $+H$. Note that (x_{tp}, y_{tp}) are defined to correspond to the x and y positions on the target plane as seen by the approaching particle (note the definition of x_{tp} in Fig. 1).

Taking $x_{tp} \equiv H\sin\beta$ and $y_{tp} \equiv H\sin\zeta$ we can write the vector $\vec{R}_i$ from the planet to where the particle enters its Hill sphere as

$$\vec{R}_i = H(-\sin(\phi+\beta)\cos(\psi+\zeta), \cos(\phi+\beta)\cos(\psi+\zeta), \sin(\psi+\zeta)) \tag{5}$$

The initial planetocentric velocity $\vec{V}_i$ is then given by the vector sum of Eq. (4) and $\vec{v}_p$

$$\vec{V}_i = (v_i\sin\phi\cos\psi + v_p, -v_i\cos\phi\cos\psi, -v_i\sin\psi) \tag{6}$$

With the initial planetocentric position $\vec{R}_i$ and velocity $\vec{V}_i$ now defined, we can proceed to calculate the parameters of the scattering.

A check of the sign of the dot product $\vec{R}_i \cdot \vec{V}_i$ allows a determination as to whether or not the particle is approaching the planet: if this quantity is greater than zero, the particle is receding in the

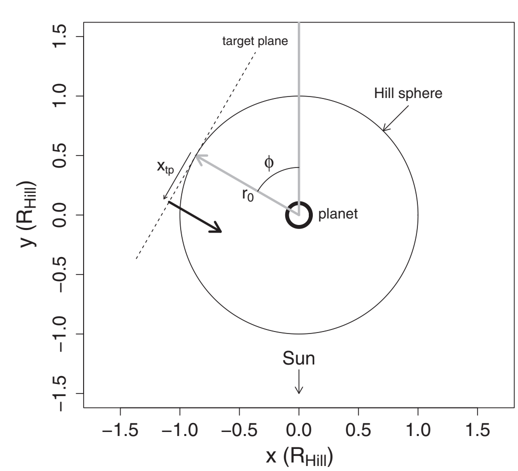

Fig. 1. The coordinate system used in this study. See the text for more details.

planetocentric frame and no scattering occurs. If the particle does approach the planet, a vector along the pole $\vec{U}$ of the planetocentric orbit is given by the vector cross-product

$$\vec{U} = \vec{R}_i \times \vec{V}_i \tag{7}$$

As the particle passes its point of closest approach to the planet and then recedes its initial velocity vector is rotated through an angle γ. A well-known result of the scattering problem, in this case γ can be shown to be

$$\gamma = 2\arctan\left(\frac{GM_p}{B|\vec{V}_i|^2}\right) \tag{8}$$

where $B \geqslant 0$ is the impact parameter in the planetocentric frame

$$B = \frac{|\vec{U}|}{|\vec{V}_i|} \tag{9}$$

where the absolute value symbol indicates taking the length of the vector in question.

At this point one may also wish to calculate the planetocentric eccentricity

$$e = \frac{1}{\sin(\gamma/2)} \tag{10}$$

Note that e in Eq. (10) cannot be less than unity, since the sine function cannot exceed one, and so the particle's orbit relative to the planet is always unbound. The closest approach distance to the planet q is given by

$$q = GM_p(e-1)/|\vec{V}_i|^2 \tag{11}$$

which is valid for the case $e > 1$ which applies here.

The pericentre distance should be checked for collision with the planet. The planet radius r_p is here taken to be distance from the centre of the planet where the atmospheric density drops to 10^{-6} kg m^{-3}. This density occurs at an altitude of 100 km on the Earth and corresponds to the start of meteoroid ablation. If $q < r_p$, the meteoroid is deemed destroyed by a collision with the planet or by ablation within its atmosphere. The planetary data used is listed in Table 1.

If the particle does not collide with the planet, scattering proceeds. A matrix M effecting a rotation by an angle γ around the axis defined by a unit vector along the pole $\vec{u} = (u_x, u_y, u_z) = \vec{U}/|\vec{U}|$ and following the right-hand rule is given by

$$M = \begin{bmatrix} c+(1-c)u_x^2 & (1-c)u_y u_x - s u_z & (1-c)u_z u_x + s u_y \\ (1-c)u_x u_y + s u_z & c+(1-c)u_y^2 & (1-c)u_z u_y - s u_x \\ (1-c)u_x u_z - s u_y & (1-c)u_y u_z + s u_x & c+(1-c)u_z^2 \end{bmatrix} \tag{12}$$

where $c = \cos\gamma$ and $s = \sin\gamma$, though alternate formulations exist Frazer et al. (1955, 2001, chap. 8 and 5 resp.). This matrix is used to rotate the initial planetocentric velocity through an angle γ to produce the post-scatter planetocentric velocity $\vec{V}_f$.

The planet's velocity $\vec{v}_p$ is then added back to $\vec{V}_f$ to yield the final heliocentric velocity $\vec{v}_f$. The particle is taken to leave the Hill sphere of the planet at a position R_f corresponding to a rotation of R_i around $\vec{U}$ by an angle $\pi + \gamma$.

After the final heliocentric position and velocity are calculated, the meteoroid is then assumed to follow a two-body orbit around the Sun. The usual orbital elements can be calculated, and the bound or unbound nature of the orbit assessed as well as whether or not it will reach the Earth's orbit and at what speed.

This technique for calculating the scattering of a meteoroid by a planet is approximate, and breaks down where the motion of the planet deviates appreciably from a straight line (*i.e.* where scattering takes a long time, or equivalently where the approach velocity is low). However this is a minor issue for this study, as we will see that hyperbolic scattering occurs almost exclusively for meteoroids that are already moving near the hyperbolic limit; thus the encounters are rapid and the straight-line approximation to the planet's velocity is valid.

Table 1
Planetary data used in this study. Masses are from Standish (1998). The planetary radius r_p used is the sum of the usual planetary radius r plus the height of the atmosphere r_{atm} to a density of 10^{-6} kg m^{-3} and is derived from Lodders and Fegley (1998).

Planet	$1/M_p(M_\odot)$	a (AU)	r (km)	r_{atm} (km)	r_p (km)
Mercury	6023600.0	0.387	2437.6	0	2437.6
Venus	408523.71	0.723	6051.84	110	6161.84
Mars	3098708	1.523	3389.92	50	3439.92
Jupiter	1047.3	5.202	71,492	200	71,692
Saturn	3497.898	9.514	60,268	600	60,868
Uranus	22902.98	19.22	25,559	350	25,909
Neptune	19412.24	30.185	24,764	250	25,014

2.2. The flux of hyperbolics at Earth

The scattering algorithm of Section 2.1 provides some information on whether or not a given planet can produce hyperbolic meteoroids at the Earth. What one would really like to know is the absolute flux of such meteoroids at Earth to determine whether they arrive in significant numbers, especially with respect to the flux of interstellar particles.

The primary difficulty here lies in determining the flux of meteoroids as a function of velocity and approach direction near the scattering planet. Given the highly heterogeneous flux of meteoroids at the Earth, we would expect a similarly complex meteoroid environment around the other planets. Since no detailed measurements of the meteoroid environments near other planets currently exist, we will address the question first assuming one of two idealized meteoroid environments, and then a third modelled environment.

1. Each planet's Hill sphere is bombarded uniformly by meteoroids from all directions at all speeds compatible with the meteoroids being initially bound to the Sun.
2. Each planet's Hill sphere is bombarded by meteoroids travelling at all bound speeds but with their velocity vectors parallel to the planet's orbital plane. The meteoroids travel parallel to but not necessarily in the planet's orbital plane: they may enter the Hill sphere at positions above or below it. This mimics a scenario where meteoroids are concentrated in the ecliptic plane.
3. The sporadic meteor model at Earth of Wiegert et al. (2009) is used to extract model meteoroid environments for the planets.

In the first case, 10^{10} initial conditions are selected each with an initial heliocentric speed drawn from a uniform random distribution ranging from 0 to $\sqrt{2}v_p$, where we note that our upper limit is the maximum heliocentric speed that a meteoroid bound to the Solar System can have. The initial approach directions are drawn uniformly on a sphere. The meteoroid enters the Hill sphere at a point (x_{tp}, y_{tp}) on the target plane where each coordinate is drawn from a uniform random distribution ranging from $+H$ to $-H$. After scattering, we tabulate those meteoroids which are unbound (hyperbolic) relative to the Sun and in particular those which reach the Earth.

A hyperbolic meteoroid scattered off an outer planet is considered to be detectable at the Earth if the meteoroid is travelling inward on the post-scatter leg of its orbit, has a perihelion $q < 1.1$ AU and either (i) its inclination to the ecliptic plane is less than (3°) or (ii) it has a node within 0.1 AU of the Earth's orbit. Hyperbolic meteoroids scattering from the inner planets inevitably reach 1 AU and so only the conditions on the inclination and/or node are applied to them. Note that we ignore any possible gravitational focusing (*e.g.* Jones and Poole, 2007) due to the Earth's gravity, which would be small for fast-moving particles anyway.

The results for the first case are shown in Fig. 2. The excess velocity v_+ is the velocity above the hyperbolic limit *as it would be measured at the Earth*; Venus and Saturn are both able to produce velocities at Earth reaching $v_+ \approx 2\ \mathrm{km\,s^{-1}}$. Jupiter creates the broadest distribution of v_+, exceeding $6\ \mathrm{km\,s^{-1}}$. We see the result first reported by Wiegert (2011) that excess velocities comparable to those expected of interstellar meteoroids (*i.e.* a few $\mathrm{km\,s^{-1}}$) can be generated by scattering off the planets. Mars, Uranus and Neptune contribute much less and at excess velocities mostly below $100\ \mathrm{m\,s^{-1}}$. Mercury contributes much more than these last three, though the distribution drops off sharply at $v_+ \approx 400\ \mathrm{m\,s^{-1}}$.

The second case, where the particle paths are concentrated in the ecliptic is shown in Fig. 3. The planets scatter more efficiently in this case and the numbers at Earth are increased, but the same qualitative trends that were noted for case 1 apply here. Venus and Mercury are the most prolific producers of unbound particles at the Earth though these are almost exclusively at $v_+ < 1\ \mathrm{km\,s^{-1}}$. while the largest v_+ are produced by Jupiter, again reaching over $6\ \mathrm{km\,s^{-1}}$.

Note that the maximum v_+ described above do not represent true physical maxima to these quantities, but reflect in part the finite number of Monte Carlo trials. The largest excess velocities are associated with meteoroids which pass very near to the surface (or top of the atmosphere) of the planets, a very narrow window or 'keyhole' which may not be well sampled by our Monte Carlo simulations. Thus the possibility of even higher excess velocities than those described here certainly exists.

To examine the size of the 'keyholes' involved in some cases, plots were created of the target plane, that is the x_{tp}–y_{tp} plane. An example is shown for the largest v_+ seen at the Earth via scattering from Uranus, which has $v_i = 1.345340 v_p$, $\phi = 77.°833635$ and $\psi = 0°$. Given that v_i is not particularly close to $\sqrt{2} v_p \approx 1.4142 v_p$, a strong scattering to Earth might seem unlikely (as indeed it is). But a check of the target plane shows that this scattering is correctly calculated.

Fig. 4 shows the part of the target plane where this particular case occurs, revealing that it is the result of a near-collision with the planet (red region). However the resolution of Fig. 4a is insufficient to reveal the true outcome. Magnifying the portion of the target plane in question (Fig. 4b), a small arc only a few thousand kilometres across appears wherein hyperbolic velocities at Earth can be obtained (yellow and orange region). The case is produced by a small keyhole that is not evident in coarse-grained examinations of the target plane.

In fact, though the case we are examining produces a $v_+ \sim 1\ \mathrm{km\,s^{-1}}$, the largest v_+ in the orange region shown in Fig. 4 reaches over $1.5\ \mathrm{km\,s^{-1}}$; increasing the resolution by a factor of five in each dimension reveals cases of $v_+ > 1.6\ \mathrm{km\,s^{-1}}$. The reason such values do not appear in our earlier figures is that the number of trials in our Monte Carlo simulations (10^{10} per planet) is not sufficient to sample all these tiny regions well. Further examination of this and many other keyholes found would be necessary to determine the maximum v_+ that could be produced: this is not attempted here since we are more interested in typical values than the maxima. However, the largest simulated v_+ values for each planet are examined by means of target plane plots like those of Fig. 4 and all are found to be real high-v_+ scattering events and not numerical or other errors.

The computations involve a large number of orbits near the parabolic limit ($e \sim 1$) and so provide a data set which challenges most orbital element calculation algorithms. We have avoided the use of the orbital elements in the scattering calculations, expressing the transformations in terms of rotations and additions of velocity vectors to avoid such issues. A second potential numerical issue involves scatterings with very small impact parameters $B \sim 0$ or planetocentric velocities $|\vec{V}_i|^2 \sim 0$. In these cases, γ (Eq. (8)) is ill-defined. However, these correspond to collisions with the planet rather than scattering events and are treated correctly here (that is, they are discarded).

Since we have constructed an analytic patched-conic model of the scattering process, could we not determine the most efficient scattering conditions analytically as well? It can be shown that that maximum v_f possible is $v_f = v_i + 2v_p$, a gain of twice the orbital velocity of the planet. This may occur when the particle's velocity is opposite that of the planet in the limit of a head-on collision ($B \to 0$) if we idealize the planet as a point mass ($r_p \to 0$). In this case, $\gamma = 180°$, and the particle is 'reflected' elastically off the pla-

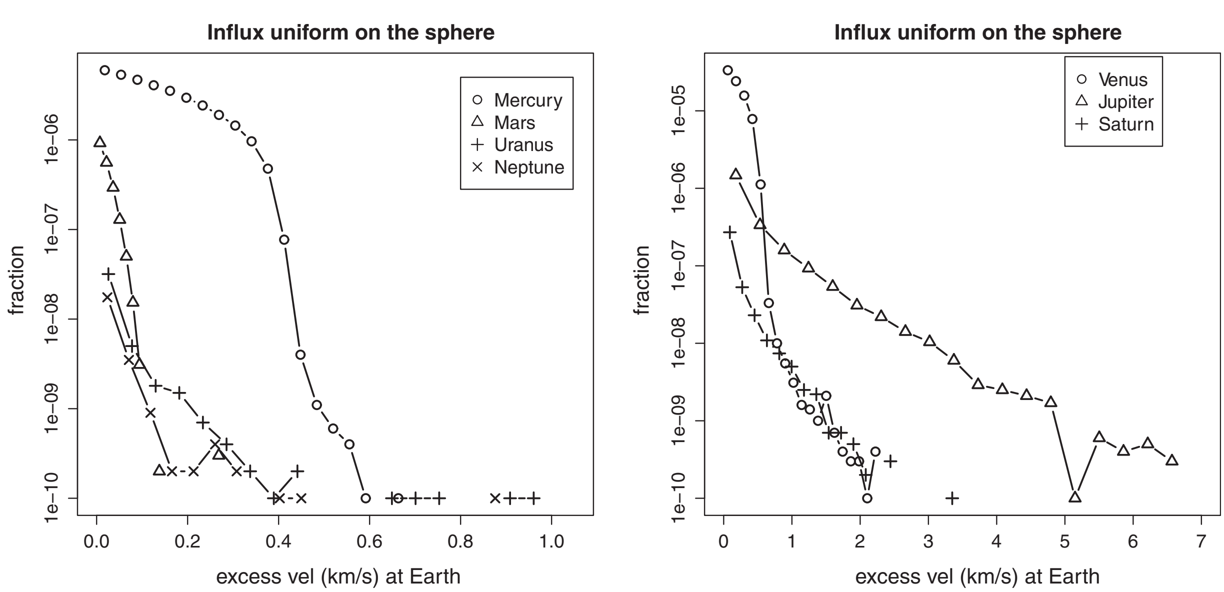

Fig. 2. The excess velocity with which a meteoroid reaches the Earth's orbit in the case of the planet being uniformly bombarded by particles from all directions.

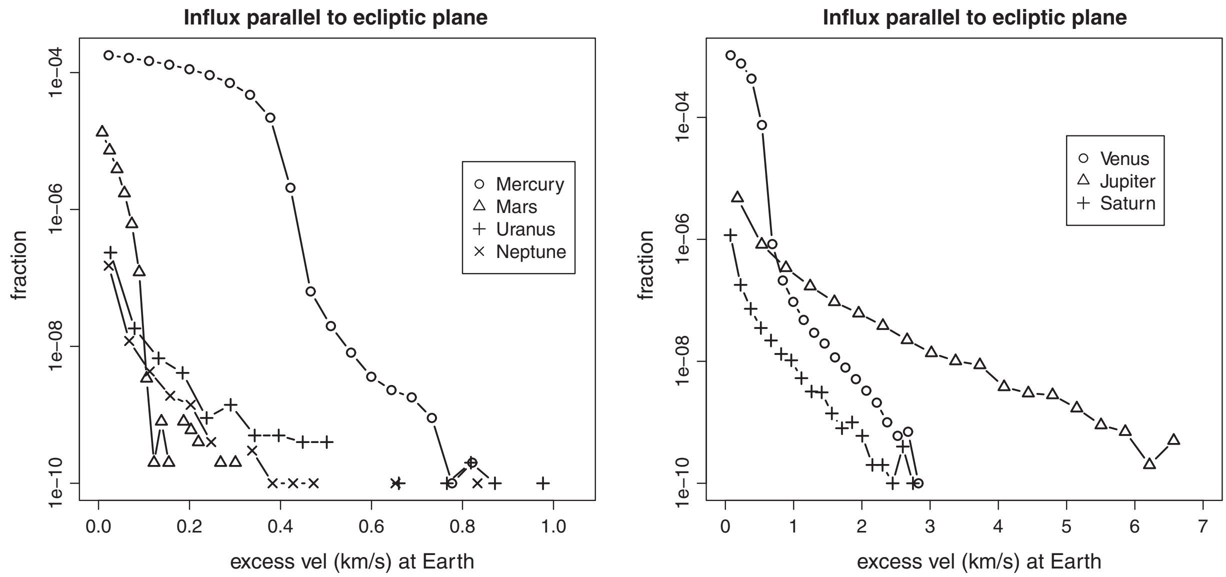

Fig. 3. The excess velocity with which a meteoroid reaches the Earth's orbit in the case of the planet being bombarded by particles travelling parallel to the planet's orbital plane.

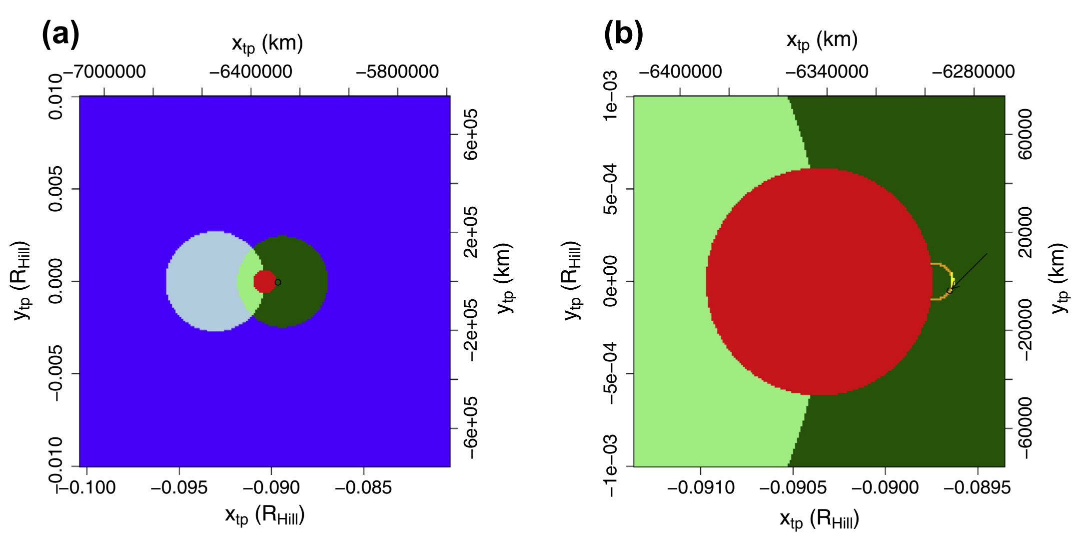

Fig. 4. (a) A portion of the target plane near the largest v_+ simulated for Uranus. (b) The target planet at even higher magnification. The *x* and *y* target plane coordinates of the meteoroid with the largest excess velocity seen at Earth from this planet in the Monte Carlo simulations is indicated by an arrow. The outcomes are coded by colour; the reader may wish to consult the on-line figures. Red indicates collision with the planet; white indicates that the initial conditions of the particle recede from the planet or miss the Hill sphere; dark and light blue indicate bound heliocentric orbits moving inwards and outwards respectively; dark and light green indicate unbound orbits moving inwards or outwards respectively but that do not intercept Earth's orbit; yellow and orange indicate post-scattering orbits that are unbound and intercept the Earth's orbit with v_+ less than or greater than 1 km s^{-1} respectively. Not all colours appear on this plot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

net. However this provides only a loose upper limit to our study of v_+. The restrictions due to the planet's non-zero size together with the necessity of a post-scattering intersection with the Earth's orbit complicate an analytical approach. Thus we have not attempted to calculate the maximum possible speed: the intent of this study is only to present the general characteristics of the post-scattering population of hyperbolic meteoroids, and to show that interstellar speeds are possible.

3. Expected fluxes of scattered sporadic meteors at Earth

Cases 1 and 2 provide some idea of the range of possible scattering events but the actual component of scattered hyperbolics in our Solar System depends strongly on the meteoroid environment of the scatterer.

To address the question of the expected flux of hyperbolics at Earth, we use a theoretical model for the sporadic meteoroid flux at the planets as the input to our scattering model. Wiegert et al. (2009) numerically simulated dust released from a variety of comets and asteroids and compared the results with radar observations of meteors at the Earth. This allowed the primary contributors to the sporadic meteors at the Earth to be determined and provides a broad-strokes description of our planet's meteoroid environment. Using the data from the same dynamical simulations, we are able to extract the meteoroid environments for any of the planets and feed them into the scattering model.

The results are presented in Fig. 5. In this case, only 10^8 Monte Carlo trials were performed due to the more involved calculations and hence slower execution speeds; each planet required in excess of 10 CPU-days to complete. Only the planets Mercury, Venus and

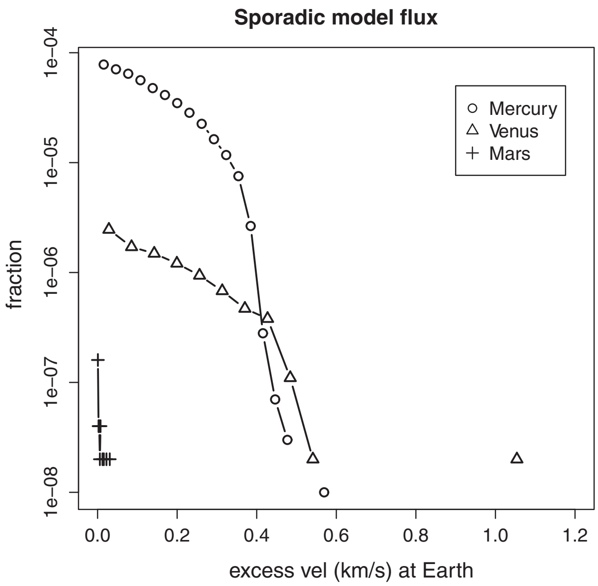

Fig. 5. The excess velocity with which a meteoroid reaches the Earth's orbit in the case of the planet being bombarded by a particle distribution derived from the sporadic model of Wiegert et al. (2009). Here the *y*-axis is the fraction of the total sporadic flux of meteoroids onto the planet's target plane that are accelerated to hyperbolic speeds.

Mars produced any hyperbolic meteors at the Earth. Mercury is perhaps unexpectedly the largest contributor. Though not able to scatter to high excess velocities, it is a relatively effective scatterer (with a surface escape speed of 4.2 km s^{-1}) and its environment is rich in nearly-unbound meteoroids. Mercury's maximum simulated v_+ was 580 m s^{-1} while the mean and median values were 125 and 110 m s^{-1}. Venus' maximum $v_+ \approx 1080$ m s^{-1}, with a mean and median of 160 and 130 m s^{-1} respectively. Mars scattered Earth-intercepting hyperbolics only to a maximum of $v_+ \approx 30$ m s^{-1} with mean and median values of only a few metres per second, scarcely detectable.

The outer planets do produce hyperbolics, and they scatter meteoroids onto paths that eventually reach Earth, but none that fit into both categories. This results in part from the much lower average meteor velocity in the outer Solar System than in the inner, though the geometry of encounter also plays a role. Thus in our Solar System, the least massive planets are the chief contributors to the high-velocity scattered meteoroid population near Earth, though the excess velocities do not reach values comparable to those expected of interstellar meteoroids. We conclude that the sample of interstellar meteors may be contaminated at excess velocities below 0.5 km s^{-1} but not at higher v_+.

Can we estimate the absolute flux of contaminating scattered hyperbolics? By extracting the number of meteors intersecting each planet's Hill sphere per unit time from the model of Wiegert et al. (2009), and multiplying by the fraction scattered on to Earth-crossing hyperbolic orbits (here 'Earth-crossing' refers to the same conditions as were described in Section 2.2), we can estimate the number of such hyperbolics created by each planet per unit time. Relatively large numbers of such meteors are produced, but the number that reach the Earth is reduced by a factor related to the probability that any individual scattered meteor will encounter our planet as it passes its orbit. Travelling near the escape velocity (42 km s^{-1}) as they pass 1 AU, such particles have a probability p of encountering the Earth given roughly by the time needed to cross a torus the width of the Earth ($t_{cross} = 2R_{Earth}/v$) divided by Earth's orbital period so that

$$p \sim \frac{2 \cdot 6378 \text{ km}}{42 \text{ km s}^{-1} \cdot 3.15 \times 10^7 \text{ s}} \sim 10^{-5} \tag{13}$$

The end result is that the average rate of Mercury-scattered hyperbolics arriving at Earth is only 10^{-4} the usual sporadic meteor background. This fraction drops to 2×10^{-5} for Venus and 5×10^{-6} for Mars. This implies that observational sample sizes of $\sim 10^5$ meteors would be needed before significant numbers would be observed. We do not expect many yet to have been seen. Because of the restrictions of the geometry of scattering to Earth, these scattered hyperbolics do not arrive uniformly in time but peak at intervals of the scatterer's synodic period, and so the rates may vary by an order of magnitude or more with time.

Though small in number, the arrival times and directions of these scattered hyperbolics are correlated. The radiants observed at the Earth (Figs. 6 and 7) are concentrated near the Sun for the inner planets, and near the antapex for Mars. Thus there should be 'hyperbolic meteor showers' with distinct radiants which reoccur with the synodic period of the scatterer: 116 days for Mercury, 584 days for Venus, 778 days for Mars.

Accounting for the travel time of the particles from the scatterer to Earth, we can estimate when in the synodic cycle of the scatterer that the hyperbolic radiant should occur. The travel time from Earth to Mercury for simulated hyperbolics is 20–50 days with peaks near 27 and 40 days; for Venus, 10–70 days with a peak near 33 days and for Mars, 40–100 days peaking at 68 days. From this we can estimate that a hyperbolic shower should occur whenever Mercury is 30–60° ahead of the Earth in its orbit, near its largest western elongation. For Venus, the shower should occur when that planet is within 10° of inferior conjunction. For Mars, when it is 30° past opposition, though there is considerable scatter for this planet. Searches for the appearance of such radiants should be conducted near these times, which are readily available from astronomical almanacs.

The radiants produced by the inner planets are located near the Sun (see Fig. 7) and thus will be buried in the helion sporadic meteor source. For Mercury, the radiants are on the ecliptic at a Sun-centered longitude of 350° with relative velocities (far from Earth) of 33–40 km s^{-1}; and for Venus, on low latitude radiants centered more or less on the Sun at relative velocities of 24–30 km s^{-1}. These radiants might not be easily observed optically because they are in the daytime sky, but should be detectable by modern radar meteor observatories. For Mars, the few hyperbolic meteoroids are concentrated in the antapex direction (see Fig. 6) with relative velocities of 12–15 km s^{-1}.

Have any of these radiants already been seen? First, one might ask if any reported hyperbolic meteors had radiants near the Sun or the antapex. On the radar side, AMOR (Baggaley, 1999) hyperbolics were observed at a wide range of inclinations, while the hyperbolic showers mentioned above would be concentrated at low inclinations. A CMOR search (Weryk and Brown, 2004) collected data from 2002–2004 and so may contain some, but they do not present enough information to determine whether that was the case. Arecibo data (Meisel et al., 2002a) were collected over 1997–1998 and could contain such detections: many of them are at low ecliptic latitude. Janches et al. (2001) indicate that many of these originate in the Mercury–Venus zone, but there is no way to determine for sure from the information as presented there.

As far as optical detections go, none of the most likely hyperbolic meteors of Jones and Sarma (1985) have inclinations in the ecliptic. The two optical meteors of Hawkes and Woodworth (1997) also did not have low inclinations. Musci et al. (2012) do present a plot of their image-intensified camera radiants in Sun-centered ecliptic coordinates but none of their 22 possible interstellar meteoroids have radiants near the antapex or the Sun.

The current largest collection of meteor orbits, from the Canadian Meteor Orbit Radar (CMOR) in London Canada, has several million orbits (Jones et al., 2005) so we might expect to already have such detections among them. Though at least part of the data

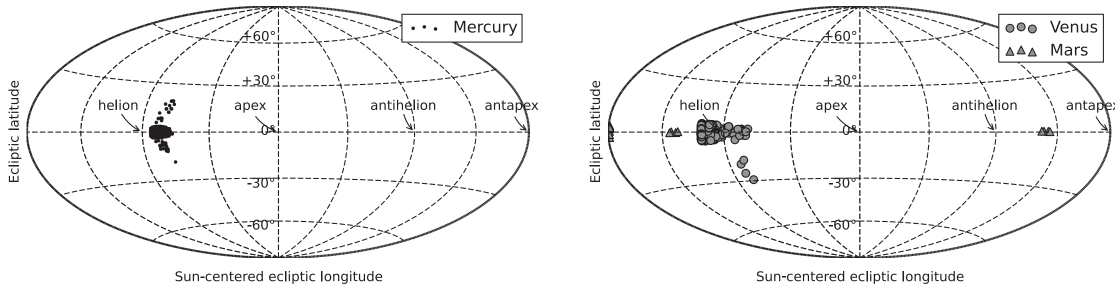

Fig. 6. The hyperbolic radiants at Earth produced by the planets in a Sun-centered ecliptic coordinate system.

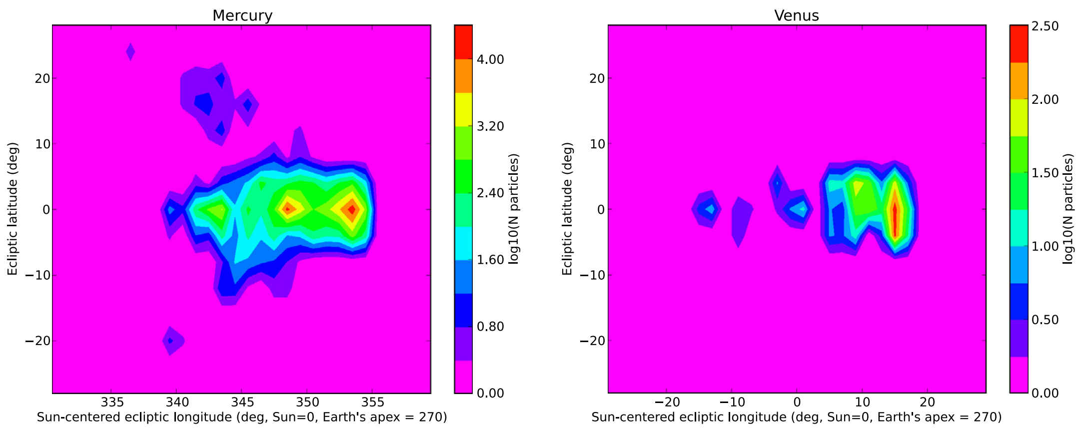

Fig. 7. Magnified view of hyperbolic radiants at Earth produced by Mercury and Venus.

has been searched for interstellar meteors, no such hyperbolic radiants have been reported. However, their analysis was probably not designed to reveal the presence of radiants as described here. The examination of CMOR data for interstellar meteors by Weryk and Brown (2004) examined 1,556,384 individual detections and found fewer than 12 and 40 were 3 and 2σ above the hyperbolic limit respectively. Our theoretical result here might have predicted ~ 100 hyperbolics from Mercury alone in this sample. However, the stringent detection limits of Weryk and Brown (2004) required that the velocity errors, about 15% in the 2σ case, be small enough that any excess velocity could be clearly assigned to the detection itself and not to observational error. Since a typical speed for their sample was 56–68 km s^{-1}, a 15% error amounts to several km s^{-1}, and would far exceed the small excess velocity predicted to be produced by Mercury, Venus or Mars. The CMOR radar may not currently have the accuracy necessary to detect planet-scattered hyperbolics as unambiguously unbound, but a search of the database specifically for such meteors is planned for future work.

We conclude that these hyperbolic meteor showers have not yet been detected; nonetheless we look forward to ever-improving detection methods and new sensors with a hope that soon the existence of meteoroids arriving at Earth directly from near-planet environments can be confirmed or falsified.

4. Scattered shower meteors at Earth

One aspect that the model above does not consider is the contribution from meteoroid streams, as the sporadic model of Wiegert et al. (2009) specifically excludes showers. A well-populated debris stream that crosses a planet orbit would provide a fresh set of particles to scatter each time the planet passed through it and so could be an important if erratic source. To include the possible contributions from showers, we examine those comets which have nodes near a planet, and ask if meteoroids travelling on orbits like that of their parent can be scattered onto hyperbolic orbits that take them to Earth.

All comets in the JPL comet catalogue downloaded from JPL Horizons on 25 February 2013 were examined for nodes within a Hill radius of one of the seven planets (excluding Earth). To this list, the asteroidal parents of two well-known streams 3200 Phaethon and 2003 EH_1 were added for completeness. If a node near a planet was found, then a simulation is run where the entire Hill sphere is populated with meteoroids travelling parallel to the trajectory that the parent would have as it passed the planet in question's orbit, and the results of the gravitational scattering are analyzed. This approximates the case of a meteoroid stream produced by the parent being scattered by the planet.

Periodic comets are likely to have substantial dust trails associated with them, but few are found to produce significant hyperbolics. An exception is 2P/Encke. Dust from comet Encke is scattered quite efficiently by Mercury. Though the post-scatter trajectories do not take them to Earth, scattered particles reach eccentricities above 1.1 corresponding to $v_+ = 3$ km s^{-1} at 1 AU, and thus 2P may be a source of hyperbolic meteoroids at other locations in our Solar System. The only other periodic comet found to produce hyperbolic meteoroids (though they do not reach Earth) is 177P/Barnard: scattering by Mars produces eccentricities up to 1.02 in our simulations. Jupiter-family comets are abundant and do often have a node near Jupiter but do not appear here, because the scattering geometry as well as the low relative speeds are not favourable to producing hyperbolics.

Appreciable hyperbolic meteoroids could be produced by comets on nearly-unbound orbits. In practice, few of these produce meteoroids at Earth's orbit but many could contribute to a broader population within our Solar System. About one-third of the long-period comets with nodes near one of the outer planets have a geometry favourable to producing hyperbolic meteoroids of some description, though most of these do not reach the Earth.

In the case of a long-period comet, the assumption of a well-populated meteoroid stream in the vicinity of the parent's orbit is unjustified. As a result, further checks are needed to determine if the parent comet's trail did indeed pass near the scattering planet in question, and whether or not the Earth would have been in the correct location to intercept the scattered meteoroids. The necessity of both the scattering planet and the Earth being in the correct locations in their orbit in order that a hyperbolic meteoroid be detectable at the Earth considerably reduces the number of cases of interest. Overall this process is not likely to contribute significantly to the flux of hyperbolic meteoroids at the Earth except perhaps during brief intervals. A few cases are discussed below.

Comet 1976/D1 Bradfield passed near Jupiter in 1974 as it approached the Sun. Just above 4% of the target plane scattered by this comet could have produced hyperbolic meteoroids at Earth's orbit with v_+ up to 0.6 km s^{-1}. However the encounter conditions were such that the comet arrived at Jupiter's orbit just after the planet had passed, and so no scattering could have taken place.

Almost 90% of the target planet Comet 1991 T2 Shoemaker-Levy with Saturn would have produced hyperbolic meteoroids at Earth's orbit with $v_+ \lesssim 0.3$ km s^{-1}. However that planet would not have passed through the debris stream from this long-period comet until 2000 (seven years after the parent had passed that location) and thus it is unlikely that there were any meteoroids present to scatter.

Perhaps the most interesting case is that of comet Hale–Bopp. On its pre-perihelion leg in 1996, comet 1995 O1 Hale–Bopp passed just ahead of Jupiter. In this case, the possibility of the planet encountering some portion of the meteoroid stream is substantial. Fifteen percent of the target plane would have scattered hyperbolic meteoroids to Earth's orbit, and at v_+ of up to 1 km s^{-1} (see Fig. 8). To determine whether or not scattered meteoroids would have been directed to Earth would require a full investigation of this event along with numerical simulations of the dust trail and its interactions with Jupiter. While very interesting, this is not addressed here. In particular, a careful calculation of the time for the scattered particles to travel to the Earth's orbit would be required to determine whether or not such meteors might have reached our planet and been observed. Though the Earth did not pass through the debris stream from this spectacular comet, it may have nonetheless have encountered particles originating from this parent but arriving via a non-traditional route.

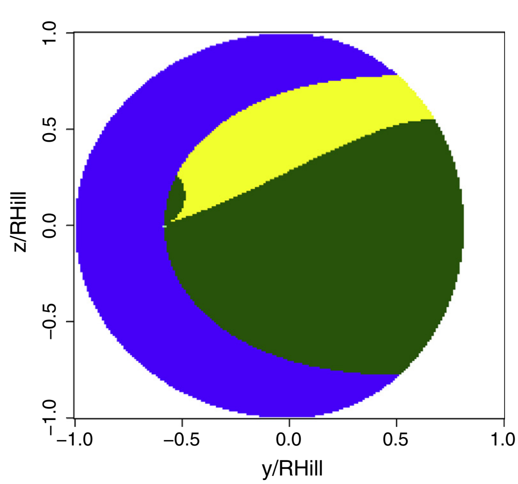

Fig. 8. The target plane of the encounter of C/1995 O1 Hale–Bopp with Jupiter. The outcomes are coded by colour; the reader may wish to consult the on-line figures. Yellow indicates unbound orbits moving inwards and intercepting Earth's orbit; dark green are inward-moving hyperbolics which do not reach our planet's orbit, and dark blue are inward-moving bound orbits. See the caption of Fig. 4 for more details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Given the absence of automated meteor observing systems at the time of Hale–Bopp's passage, it is unlikely that any such meteors would have been recorded, though the European Fireball Network (Oberst et al., 1998) and the Advanced Meteor Orbit Radar (AMOR) (Baggaley et al., 1994) were operating at this time. Note that interstellar meteors reported by AMOR (Baggaley, 2000) were collected in the 1995–1998 time frame and so may contain some contamination from this source. The hyperbolic meteors reported by Hawkes and Woodworth (1997) were observed in June 1995 – before Hale–Bopp passed Jupiter – and so those meteors could not have been associated with this scattering event.

5. Conclusions

The number of hyperbolic meteors observed at Earth that might be produced by gravitational scattering by the planets is calculated: overall the numbers are small, certainly compared to the background rate of bound meteors. According to Campbell-Brown and Braid (2011), the sporadic flux of video meteors at Earth is 0.18 ± 0.04 meteoroids km^{-2} h^{-1} while for the interstellar flux Musci et al. (2012) give an upper limit of 2×10^{-4} meteoroids km^{-2} h^{-1} at optical sizes, so current limits from optical systems put the flux of interstellars at 1 in 1000 at most. Our work here predicts 1 meteor in 10^4 at Earth will be a hyperbolic originating in a scattering event at Mercury. As a result, the contamination of a sample of interstellar meteors in this size range is expected to be at least at the 10% level and possibly higher and so needs to be addressed. The problem is mitigated by the fact that the contamination is primarily at low v_+, much smaller than those expected of true interstellars. At radar sizes, CMOR (Weryk and Brown, 2004) sees perhaps 1 in 10^5 meteors as hyperbolic. Our work here still predicts 1 in 10^4 internally-generated hyperbolics at these sizes, but again their excess velocities are too low to constitute a significant source of confusion in current samples.

We conclude that hyperbolic particles can in principle be generated wholly within our Solar System and at speeds which rival those expected of interstellar meteors. However, the properties of the meteoroid environment of our planetary system are not conducive to scattering large numbers of them onto Earth-intercepting orbits. Though selecting a sample of presumed-interstellar meteors solely on the basis of their heliocentric velocity is likely to produce a substantially contaminated sample, the internally-generated hyperbolics are relatively easy to account for, as their excess velocities at the Earth are expected to be only about 100 m s^{-1} in most cases. Higher v_+ may occur in exceptional cases or when a planet encounters a freshly-deposited debris stream from a comet. However, in all such cases a sufficiently precise velocity determination followed by a careful examination of the pre-atmospheric trajectory can determine whether such a scattering event occurred. Thus while the search for interstellar meteors is complicated by planetary scattering, continuing improvements in detection methods mean that the phenomenon is not likely to prove a substantial obstacle to the study of interstellar meteoroids.

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