Icarus 242 (2014) 112–121

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

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

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ARTICLE INFO

Article history:
Received 8 April 2014
Revised 26 June 2014
Accepted 27 June 2014
Available online 18 July 2014

Keywords:
Meteors
Comets
Interplanetary dust
Earth

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.

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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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http://dx.doi.org/10.1016/j.icarus.2014.06.031
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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 $\mathrm{km\,s^{-1}}$. 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

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