Preliminary Results on the Gravitational Slingshot Effect and the Population of Hyperbolic Meteoroids at Earth

P. A. Wiegert

Abstract Interstellar meteoroids, solid particles arriving from outside our Solar System, are not easily distinguished from local meteoroids. A velocity above the escape velocity of the Sun is often used as an indicator of a possible interstellar origin. We demonstrate that the gravitational slingshot effect, resulting from the passage of local meteoroid near a planet, can produce hyperbolic meteoroids at the Earth's orbit with excess velocities comparable to those expected of interstellar meteoroids.

Keywords meteors · meteoroids · interstellar material · orbital dynamics

1 Introduction

The search for interstellar meteoroids is complicated by contamination of the sample by the abundant meteoroids originating within our own Solar System. Meteoroid velocity is frequently used as a filter to distinguish between these two samples, with velocities above the hyperbolic limit at the Earth's orbit taken as being interstellar in origin. This criterion is based on the assumption that meteoroids on hyperbolic orbits do not originate within our Solar System.

However, there are processes at work in our Solar System that certainly produce unbound meteoroids. One of these is the so-called gravitational slingshot, whereby a meteoroid or other particle passing near a planet can exchange energy and momentum with it. Such interactions should produce hyperbolic meteoroids at the Earth's orbit that are of a purely local origin. In order to distinguish these from true interstellar meteoroids, an understanding of the properties and fluxes of such meteoroids is needed.

Meteoroids ejected from other solar systems are expected to enter the Solar System with excess velocities typical of the velocity dispersion of stars in the solar neighborhood, about 20 km/s. Since energy and not velocity is conserved, they would arrive at Earth with a velocity near $(20^2 + 42^2)^{1/2} \approx 46.5$ km/s where 42 km/s is the escape velocity from the Sun calculated at the Earth's orbit. The presence of this excess velocity has been the traditional hallmark searched for when one looks for extra-solar meteors.

2 Review

Whether of an interstellar nature or not, hyperbolic meteors have been reported in the past, having been observed both in space and at the Earth. Spacecraft dust detectors aboard the Ulysses, Galileo and Helios

P. A. Wiegert (✉)

Dept. of Physics and Astronomy, The University of Western Ontario, London Ontario CANADA. Phone.: +1-519-661-2111 ext. 81327; Fax: +1-519-661-3283; E-mail: pwiegert@uwo.ca

spacecraft (Grün et al 1993; Krüger et al 2007) have detected very small (10^{-18} - 10^{-13} kg) grains moving at speed above the local solar system escape velocity and parallel to the local flow of interstellar gas. These particles are too small to be detected as meteors at the Earth, sizes > 10^{-10} kg may be required for this. These larger particles have also been reported to have a significant hyperbolic component. Between 0.2% and 22% of meteors observed at the Earth by various surveys, optical and radar-based, have shown a hyperbolic component according to a recent review by Baggaley et al (2007). Conversely, other work (Hajduková and Paulech 2007; Hajduková 2008) has shown that many hyperbolic meteors may only appear so as the result of measurement errors. For example, many of the hyperbolic meteors are associated with shower radiants or the ecliptic plane, unlikely associations for interstellar meteors. As a result observations of hyperbolic meteors in the Earth's atmosphere remain somewhat controversial. The problem rests on the velocity, the key signature of an interstellar origin, but which often has an uncertainty (~10%) which is of the same order as the effect one is trying to detect.

The question of the nature of hyperbolic meteors and the possible presence of interstellar meteoroids within our Solar System is an interesting one, but here we address the question of whether or not hyperbolic meteors could be produced within our own Solar System, in particular by the gravitational slingshot effect.

3 Model

In this preliminary work, we simply consider the well-known problem of two-dimensional gravitational scattering of meteoroids off a moving planet. The planets are all considered to be on circular coplanar orbits, with the meteoroids moving within this same plane. A proper treatment relevant to our Solar System will require considering the full three-dimensional scattering problem, but the simple two dimensional problem provides us with initial insight into the broad strokes of the result.

We consider the scenario depicted in Figure 1 below. The planet is moving to the left with a velocity V. The meteoroid arrives with speed v, direction ϕ and impact parameter y, all measured in the heliocentric frame. The arrival velocity is assumed to be less than the local solar escape velocity at the scattering planet. After scattering off the planet, the meteoroid departs with a new velocity v_f and direction ϕ_f. If this final velocity places the meteoroid on an unbound orbit but one which will cross that of the Earth before leaving the Solar System, we conclude that it constitute an observable hyperbolic meteoroid of local origin.
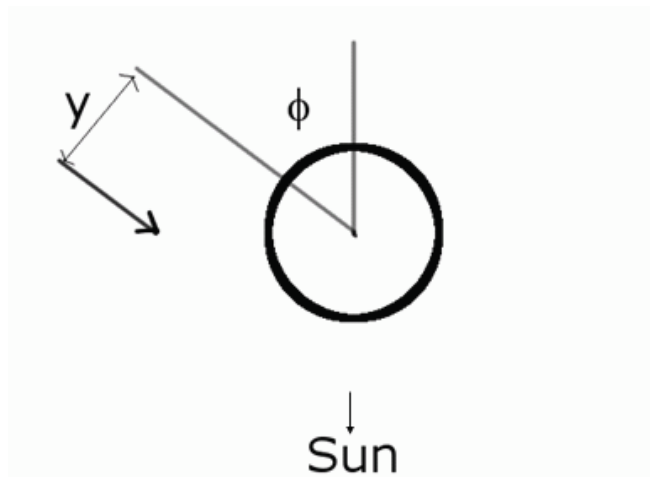

Figure 1. The angle ϕ and the impact parameter y are defined as shown, in the heliocentric frame.

For the purposes of this study, we assume that all the planet are bombarded by meteoroids arriving from all directions, with all possible impact parameters and (bound) velocities, and ask what fraction of these would become observable hyperbolic meteors at the Earth.

The results for meteoroids arriving at a particular planet with a particular speed can be summarized in a single figure displaying the scattering results for a range of arrival direction and impact parameter, here taken on a 100x100 grid. Figure 2, for example, shows the result of meteoroids arriving at Jupiter with a heliocentric velocity of 1.4 times the local circular velocity. A substantial fraction of these objects, indicated by the black area in the figure, leave Jupiter on hyperbolic Earth-crossing orbits. Of course, having arrived at Jupiter on nearly-unbound orbits (the local escape speed is $2^{1/2} \approx 1.414$ times the circular velocity), many of these meteoroids are close to the parabolic limit and thus are relatively easy to scatter onto hyperbolic orbits. Lower arrival velocities (Figures 3 to 5) produce fewer hyperbolic meteoroids, as would be expected.
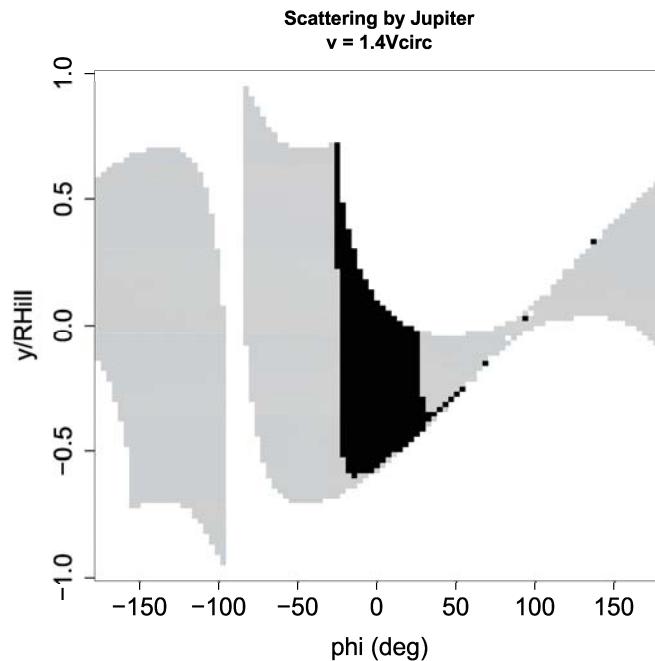

Figure 2. Scattering results for meteoroids arriving at Jupiter with 1.4 times the local circular velocity. Phi is the arrival direction ϕ and y is the impact parameter, as a fraction of the size of the Hill sphere. Grey indicates particles which leave on hyperbolic heliocentric orbits but do not cross the Earth's orbit, black indicates particles scattered onto hyperbolic Earth-crossing orbits.
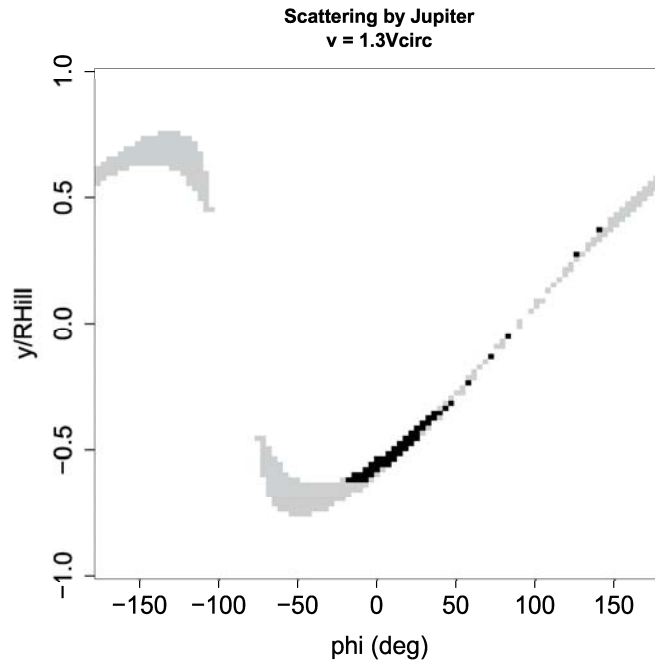
Scattering by Jupiter
v = 1.3Vcirc

Figure 3. Scattering results for meteoroids arriving at Jupiter with 1.3 times the local circular velocity.

Scattering by Jupiter
v = 1.2Vcirc
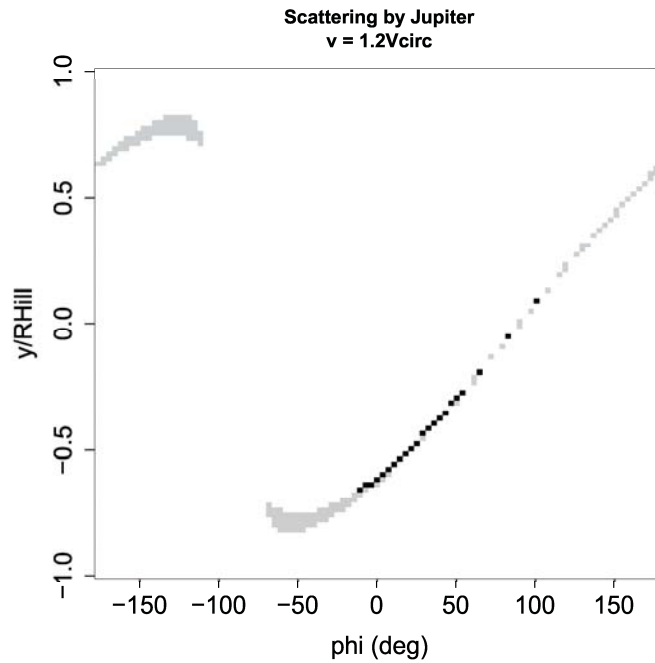
Figure 4. Scattering results for meteoroids arriving at Jupiter with 1.2 times the local circular velocity.

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Scattering by Jupiter
v = 1.1Vcirc
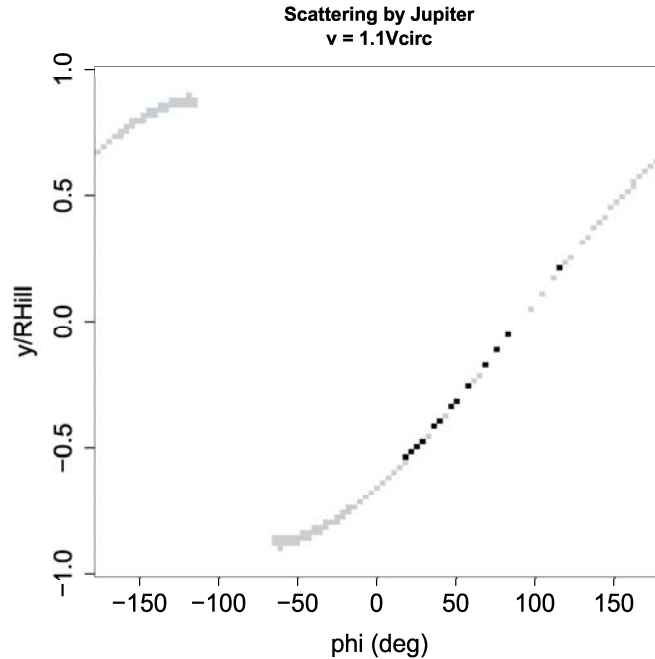
Figure 5. Scattering results for meteoroids arriving at Jupiter with 1.1 times the local circular velocity.

The distribution of velocities that these meteoroids would have measured should they happen to impact the Earth is displayed in Figure 6. This figure collects all the hyperbolic meteoroids produced during the simulations used in the production of Figures 2 to 5, and displays the excess velocity that would be observed at Earth. Most of the hyperbolic meteoroids are just above the hyperbolic limit, but there are some which can reach excess velocities of a few km/s, just what is expected of interstellar meteoroids. Thus we cannot conclude that hyperbolic meteoroids are necessarily of interstellar origin.
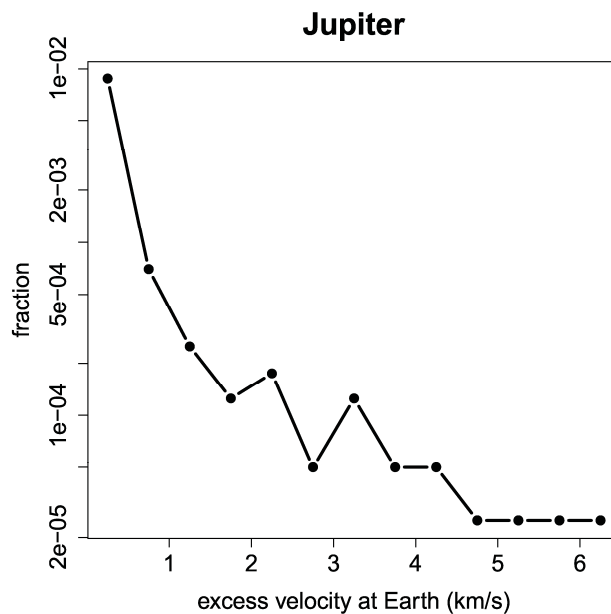
Jupiter

Figure 6. Distribution of excess velocities measured at the Earth for hyperbolic meteoroids of Figures 2 to 5. Fraction is relative to the total number of meteoroids simulated.

The other planets are also capable of producing hyperbolic meteoroids. Mercury and Mars are the least efficient due to their low masses, and are not plotted amongst the following figures, which illustrate the velocity distribution produced from a similar consideration of Saturn (Figure 7), Uranus (Figure 8), Neptune (Figure 9) and Venus (Figure 10). These planets are all much less efficient than Jupiter and produce hyperbolic meteoroids that almost exclusively arrive at Earth with excess velocities below 1 km/s.
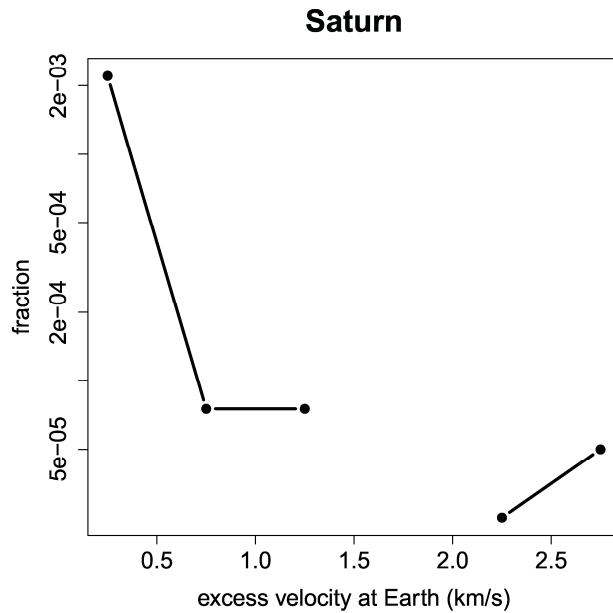
Saturn

Figure 7. Distribution of excess velocities measured at the Earth for the hyperbolic meteoroids scattered by Saturn. Missing points indicate those arrival velocities which are not produced by any of the initial conditions considered.
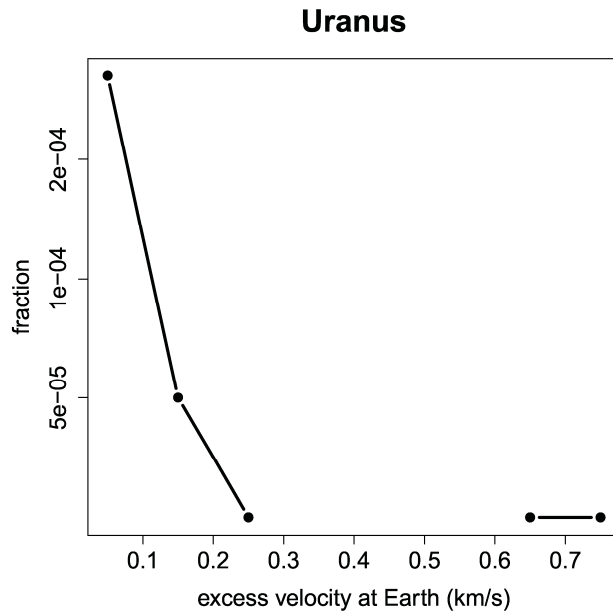
Uranus

Figure 8. Distribution of excess velocities measured at the Earth for the hyperbolic meteoroids scattered by Uranus.
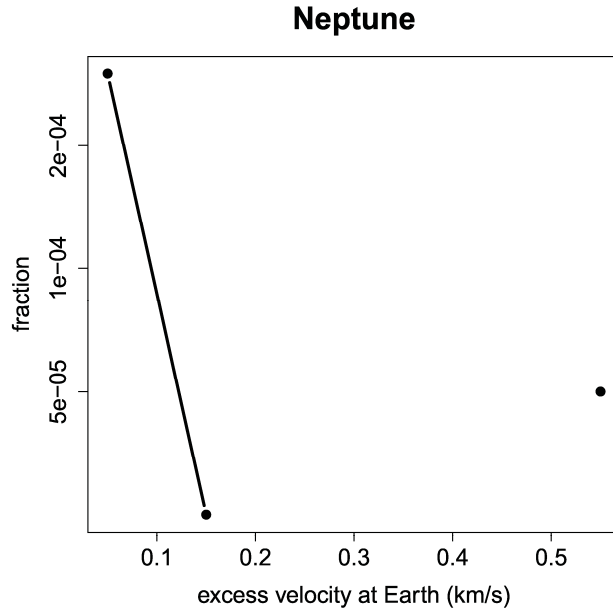
Neptune

Figure 9. Distribution of excess velocities measured at the Earth for the hyperbolic meteoroids scattered by Neptune.
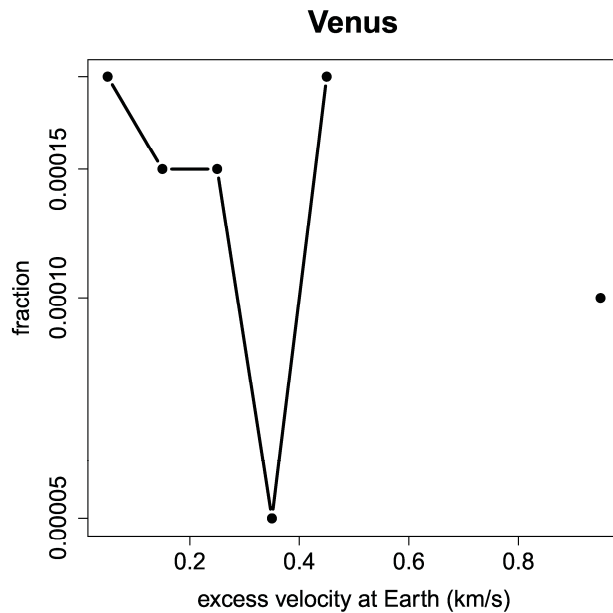
Venus

Figure 10. Distribution of excess velocities measured at the Earth for the hyperbolic meteoroids scattered by Venus.

4 Conclusions

The gravitational slingshot effect can produce meteors with hyperbolic heliocentric velocities measured at Earth that originate wholly within our Solar System. Though our study here is far from exhaustive, we have found that hyperbolic are most easily produced by Jupiter from meteoroids with near-parabolic

orbits. The majority have small (< 1 km/s) excess velocities but some can exceed 5 km/s. Thus we conclude that hyperbolic excess velocities, even of a few km/s, are not unequivocal signatures of an interstellar nature.

Future work would involve extending these results to full three-dimensional scattering, which we are currently undertaking. In addition, estimates of the flux of gravitationally scattered meteoroids at the Earth would be of great value. However, this calculation will require the determination of the meteoroid environments of the planets first, as the production of hyperbolic meteoroids depends sensitively on both the speed and direction with which the meteoroids approach the scattering planet, and the relative populations of such meteoroids is not yet known.

Acknowledgements

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