Article from Meteorite Quarterly: November 2006, 12(4), 17 – 19

The Problem of Ice Meteorites

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Nothing stimulates the imagination more than the mysterious, and one stimulating mystery, concerning the fall of large blocks of ice to the Earth's surface, has recently been reviewed in this magazine by Saul (2006). The point that I would particularly like to pick-up on, however, relates to Saul's suggestion that, "it now seems more prudent to assume that ice meteorites do exist than that they do not".

That large blocks of ice fall to the ground is evident enough; they are observed to fall and they are collected, but the central question here is did they enter the Earth's atmosphere from interplanetary space? Indeed, it is this latter requirement that must be satisfied, by definition, for such ice remnants to be considered meteorites. In addition, accepting for the moment that ice meteorites might fall to Earth, the question of their origin must also be addressed – literally, where are the ice fragments from. It is certainly true that the solar system contains numerous bodies that have water-ice as a major compositional component. In principle, therefore, one would expect ice meteoroids to exist simply because of the on-going collisional evolution of objects within the solar system. Indeed, it is a certainty that ice-meteoroids exist. The recent outburst of comet 73P/ Schwassmann-Wachmann 3 (figure 1) provides one example of an event that produced icy-nuclei many tens of meters in diameter, and no-doubt smaller icy meteoroids as well.

One of the key factors in determining the delivery of a meteorite to the Earth's surface is the meteoroids initial encounter speed: the lower the encounter speed the better. With respect to known cometary meteoroid streams, the smallest known Earth encounter speed is the 15 km/s of the occasionally active τ-Herculid meteor shower. The next lowest encounter speeds being those for the π-Puppid meteoroids (18 km/s) and the Draconid meteoroids (20 km/s). For the moment I will concentrate on the τ-Herculid shower since this stream is associated with comet 73P/ Schwassmann-Wachmann 3, which is known to have fragmented at least twice: in 1995 and more recently in 2006 [see the excellent study by Wiegert et al, 2005]. I am not suggesting that there will be (or ever have been) any ice-meteorites derived from comet 73P/ Schwassmann-Wachmann 3 and the τ-Herculid stream (see below), but they might be considered the best known candidates for producing such objects.

There are now two questions that I would like to address. Firstly, "what is the lifetime of a pure water-ice fragment in the inner solar system", and second "can water-ice meteoroids survive passage through the Earth's atmosphere"?

Sublimation Lifetimes

While ice-meteoroids must exist within our solar system the more important question at this stage is, how long do they exist for? Once any icy nucleus or ice-meteoroid approaches within about 2.5 AU of the Sun then sublimation will become important. A number of years ago, along with graduate student Simona Nikolova, I looked at the survival times of ice meteoroids moving about the Sun along comet-like orbits [Beech and Nikolova, 2001]. For a spherical ice-meteoroid moving in an orbit similar to, for example, Comet 73P/ Schwassmann-Wachmann 3 the radius would decrease due to sublimation at a rate of about 1.4 meters per orbit (or 0.25 m/yr). In other words, a 10-m diameter ice-block would disappear within about 4 orbits of the Sun – a timescale of about 20 years. The same sized meteoroid in an orbit similar to that of the Earth would disappear on an even more rapid timescale of about 2 years. Comet's that move deep into the outer solar system spend much less time close in towards the Sun, and consequently any ice-meteoroids left in their wake will survive longer. A 10-m diameter ice-block with an orbit similar to that of comet C/1861 G1 (Thatcher), the parent comet to the April Lyrid meteor shower, which has an aphelion distance of about 109 AU, should survive for about 2000 years – but it would encounter the Earth with an initial speed of 48 km/s.

The problem with respect to the production of ice-meteorites therefore is that they must encounter the Earth within just a few years of being ejected from their parent body, and this dynamically speaking is highly unlikely to happen.

Atmospheric passage

The physical characteristics (e.g., the density, specific heat, enthalpy of melting and vaporization) of ice are well known, and consequently the equations that govern the mass loss rate and the deceleration of a meteoroid as it travels through the Earth's atmosphere can be solved in terms of just two in-put parameters: initial mass and initial velocity. What I have done in this study, however, is to solve the meteoroid ablation equations to determine the final mass that hits the ground for two specific initial velocities. The lowest speed that any meteoroid can have at the top of the atmosphere is Earth's escape velocity of 11.2 km/s. So, with this lower limit in mind the two encounter velocities chosen are 11.5 km/s and 15 km/s, with the latter velocity being appropriate to a τ-Herculid ice-meteoroid. Figure 2 shows the results of the ablation calculations.

The calculations leading to figure 2 indicate that when the initial velocity at the top of the atmosphere is 11.5 km/s an ice-meteoroid of mass ~50,000-kg (diameter ≈ 4.8-m) is required to produce a 2-kg meteorite on the ground. When the initial velocity is 15 km/s, however, even a 1,000,000-kg (diameter ≈ 15-m) ice-meteoroid will only produce an ice meteorite of a few grams mass on the ground. Several points must be immediately made. It is clear that no τ-Herculid meteoroid has ever produced an ice-meteorite: Indeed, if the Earth did encounter a τ-Herculid fragment of several tens of meters in diameter it would probably produce an air-burst explosion similar to that of the 1908 Tunguska impact. Catastrophic fragmentation of all large ice-meteoroids in the Earth's upper atmosphere is almost inevitable, in fact, because the ram pressure due to the on-coming air flow will easily exceed the tensile strength of solid-ice or that of a cometary nucleus. The tensile strength of comet D/1993 F2 (Shoemaker-Levy 9) was estimated to be about 1000 Pa [Scotti and Melosh, 1993]; the tensile strength of water-ice falls between 10^6 to 10^7 Pa. My calculations find ram pressures well in excess of 10^7 Pa for the simulations presented in figure 2.

So, can an ice-meteoroid survive atmospheric passage to hit the ground? Well, the answer is perhaps yes – just maybe! If the encounter velocity is not much greater than the Earth's escape velocity then a 5 to 10-m diameter ice-meteoroid might just produce a 1 to 10-kg ice-meteorite at the Earth's surface (provided that the tensile strength of the ice-meteoroid is greater than ~10^7 Pa).

Are there ice meteorites?

With all of the above in place, an attempt to answer John Saul's suggestion, that it might be "more prudent to assume that ice meteorites do exist than that they do not", can be made. I see no reason to doubt the fact that large chunks of ice do fall to the ground under both stormy and clear sky conditions. However, I see every reason to argue that they are not meteorites.

Two main factors argue against ice meteorites. Firstly the velocity restriction requires that the meteoroids must encounter the Earth with very low velocities – certainly less than 12 – 13 km/s. No currently known cometary meteoroid stream, therefore, can produce ice-meteorites. This effectively removes from consideration what might otherwise be considered a good source of material for producing ice-meteorites. Indeed, for an ice-meteoroid belonging to a typical short-period cometary stream, initial sizes in excess of 20 to 50-m across are required to produce an ice-meteorite, and no such objects have been observed. A recent telescopic survey by myself, Peter Brown (University of Western Ontario) and University of Regina undergraduate student Alison Illingworth found no evidence, for example, to support the existence of meteoroids larger than a few tens of centimeters across within the Perseid meteoroid stream [Beech, Brown and Illingworth, 2004].

The second reason why ice meteorites must, at best, be exceptionally rare relates to their survival lifetime in space. To get close to the Earth means that an ice-meteoroid must become heated, and once this happens lifetimes against mass-loss by sublimation are typically just a few tens of years. In other words an ice-meteoroid is 'destroyed' in space long before it might encounter the Earth to produce an ice-meteorite.

In conclusion, from an atmospheric interaction and a solar system dynamics perspective, I would argue that it is not prudent to accept the idea that ice-meteorites exist. The origin of the large ice chunks that have fallen to the ground must lie somewhere within and not beyond the Earth's atmosphere.

A foul smell, a caveat and a weather change

At the risk of confounding one mystery with another, it has been occasionally noted that meteorite falls can precipitate distinct smells; most often described as sulfurous, or 'metallic'. Berczi and Lukacs (1997) have picked-up on this point and suggested that odors of sulphuric and ammonia compounds might in fact be released by 'freshly' fallen ice-meteorites, and indeed they further argue that ice-meteorites might be identified on the Antarctic ice-fields (where their terrestrial lifetime will be long) by their water-ammonia compositional mixtures. To date no candidate objects have been found in Antarctica, but, as ever, there is the caveat: absence of evidence is not evidence of absence.

Perhaps the best current explanation of falling ice blocks is that proposed by Jesús Martinez-Frias and co-workers (2000, 2005). This group of researchers has proposed the term megacryometeors to describe the falling ice blocks (see the web link: http://tierra.rediris.es/megacryometeors/index2.htmlT), and they argue that such objects form under a rare, clear-sky variant of the nucleation process responsible for the production of ordinary hail (Bosch, 2002). The 'meteor' part of megacryometeors, it should be pointed out, relates to the idea that these objects are considered to be meteorological (that is atmospheric) in origin.

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Figure 1: Fragment B and accompanying 'ice-shards', probably several tens to perhaps a few hundred meters across, produced during the 2006 fragmentation event of Comet 73P/ Schwassmann-Wachmann 3. (Hubble Space Telescope image, courtesy NASA)

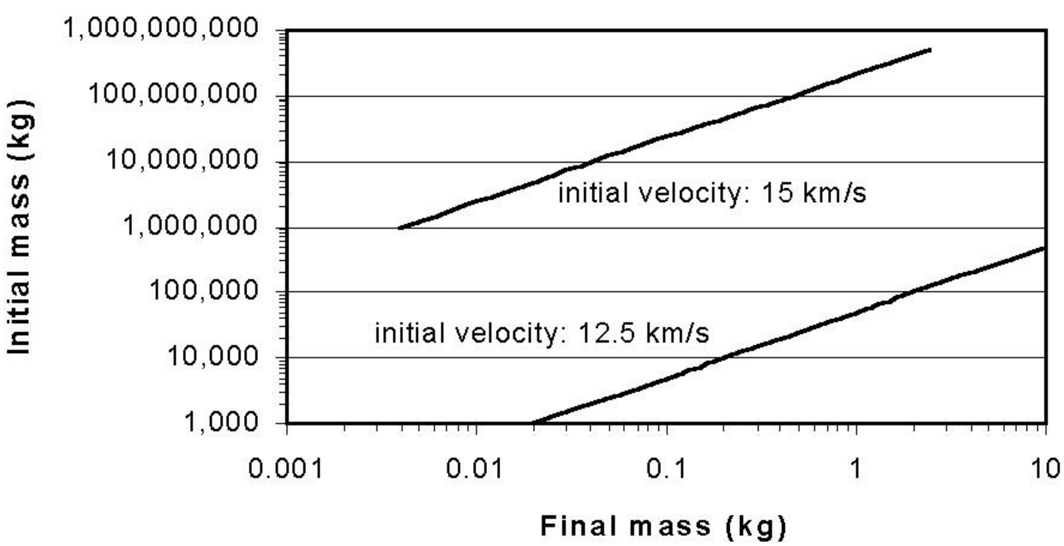

Figure 2: Initial and final mass comparisons for water ice-meteoroids passing through the Earth's atmosphere for the two initial velocities of 11.5 and 15 km/s. [These calculations are based upon an ablation coefficient of $\sigma = 1.67 \times 10^{-7}$ s^2/m^2, a density of 917 kg/m^3, and an entrance angle of 45^o].