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A telescopic search for large Perseid meteoroids

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ABSTRACT

A search for metre-sized and larger exo-atmosphere Perseid meteoroids via their surface reflected sunlight has been made with the 1.2-m Elginfield Telescope. A total survey time of 9.66 h was accumulated during the nights of 2002 August 10, 11 and 12. To a limiting apparent magnitude of +17, we made no distinct detection of any large exo-atmosphere Perseid meteoroids. Our telescopic survey results constrain the upper limit to the spatial number density of metre-sized and larger Perseid meteoroids to be less than $\sim 3 \times 10^{-3}$ per 10^9 km^3. We have also analysed a data set of possible in-atmosphere Perseid fireball events detected by space-based optical and infrared sensors. Operating at a detection threshold of magnitude −17, the space-based sensors have detected eight possible Perseid fireballs in the 15-d window, centred on the time of shower maximum, over the cumulative time interval from 1978 August to 2000 August. The space-based sensor data yield a spatial number density of $\sim 7 \times 10^{-8}$ per 10^9 km^3 for metre-sized and larger Perseid meteoroids.

Key words: comets: general – comets: individual: 109P/Swift-Tuttle – meteors, meteoroids.

1 INTRODUCTION

The annual Perseid meteor shower is one of the most prolific and well studied of meteor showers (Brown & Rendtel 1996; Lindblad 2000). Historically, it was the first meteor shower to be concatenated to a parent comet, 109P/Swift-Tuttle, and the yearly consistency of its activity profile (meteor hourly rate versus time) is indicative of it being a well-established and ‘old’ meteoroid stream (Hughes 1995; Brown & Jones 1998).

The size distribution of meteoroids within a cometary stream will vary from a well-defined minimum, set according to the stream’s orbital characteristics and the meteoroid interaction with the Sun’s radiation field (Williams 2002), to a presently only poorly defined maximum. It is the possible detection and corresponding annotation of the largest meteoroids that might exist within the Perseid stream that motivates this particular study. As will be discussed below, meteoroids of the order of centimetres across certainly do exist within the Perseid stream, but at sizes of a metre and larger there is no clear consensus between survey results.

Whipple (1951) and Hughes (2000) have determined upper limits to the size of a meteoroid that might be ejected from a cometary nucleus through coupling to the gas outflow resulting from the sublimation of surface ices. The upper limits that they derive, however, are sensitive to the physical approximations that must inevitably be employed in the description of the ejection process. In addition, the upper limits derived by the two authors also suffer from an incomplete knowledge of such basic physical quantities as the appropriate densities to apply to the cometary nucleus and to the ejected meteoroids. By way of illustrating the range of possibilities, the largest meteoroid that might be ejected from a cometary nucleus of, say, radius 2.5 km, at a heliocentric distance of 1 au, will have a diameter of the order of 0.2 m according to Whipple’s equation (10) and a diameter of the order of 50 m according to equation (15) of Hughes. Our point here is not to discuss which prediction might be correct, but rather to illuminate the position that the size of the largest meteoroid that might be ejected from a cometary nucleus via gas outflow coupling is still, very much, a quantity that is open to investigation and debate. In addition to the possibility of coupling to the sublimation-driven gas outflow, large meteoroids might also be placed into a stream through the action of cometary outbursts, nuclear fragmentation and surface mantle ejection events (Hughes 1990; Hughes & McBride 1992). Rather than being a process that operates during each and every active perihelion passage, the outburst placement of large meteoroids into a stream will probably occur only intermittently.

We shall briefly discuss the observational situation with respect to the detection of large, 10 m to kilometre-sized secondary components within cometary streams in Section 2. In Section 3 we shall review the statistics of in-atmosphere Perseid fireball observations. In Section 4 we consider the possibility of detecting the faint, reflected sunlight from large Perseid meteoroids outside of the Earth’s atmosphere. We also review in Section 4 our recent attempts to detect exo-atmosphere Perseid meteoroids with the 1.2-m Elginfield Telescope. A discussion of our observations is given in Section 5.

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2 SEARCH RATIONALE

Daniel Kirkwood, as long ago as 1861, made the suggestion that meteoroid streams were produced via a continuous fragmentation process, and that the components in a meteoroid stream varied continuously in size from a few large objects to a multitude of smaller ones (Kirkwood 1861). While Kirkwood's fragmentation hypothesis no longer provides an acceptable mechanism for producing meteoroid streams, the idea that there is likely more to a stream than a single kilometric component (the cometary nucleus) and a multitude of small, visible meteor-producing meteoroids, is worthy of further exploration.

Some data already exist with respect to the detection of multiple large fragments within cometary streams. Historically, the Andromedid meteoroid stream has contained at least two large components, the components being formed through the fragmentation of comet 3D/Biela. It is presently not clear if these two components still exist, but they were observed to endure for at least two perihelion passages (Yeomans 1991). More recently comet D/Shoemaker-Levy 9 was found to have fragmented into large 100 m to kilometre-sized components (Sekanina 1993), and comet C/1992 B2 Hyakutake has been observed to shed ∼10 m sized fragments (Desvoivres et al. 1999). Also, in recent times, it has been suggested that the nucleus of comet C/1995 O1 Hale-Bopp might, in fact, be a gravitationally bound double nucleus (Marchis et al. 1999). Further, the recent fragmentation episodes of comets C/1999 S4 (LINEAR) and C/2001 A2 (LINEAR) have provided some evidence for the existence of 10 m to 100 m sized objects being shed by their parent nuclei (see e.g. Weaver et al. 2001; Sekanina et al. 2002). As a final example from recent times, comet 57P/du Toit-Neujimin-Delporte has been observed to split into numerous 10 m to 100 m sized fragments following its perihelion passage in 2002 July. Additional evidence also comes from fireball observations, where numerous examples of very large (that is, at least metre sized) meteoroids with clear orbital connections to a parent cometary body have been observed entering the Earth's atmosphere (Nemtchinov et al. 1999; Napier 2001). The fact, therefore, that cometary nuclei do fragment and can shed large subnuclei suggests that, even if a given meteoroid stream has no known parent comet, it may still contain more than just the myriad submillimetre meteoroids that produce visual meteors.

We do not know if the nucleus of comet 109P/Swift-Tuttle has ever undergone an outburst or fragmentation event. Chen & Jewitt (1994), however, have argued that short-period comets may undergo outbursts every few perihelion passages, and if comet 109P/Swift-Tuttle prescribes to this scenario we might well expect there to be at least intermittently 1 m to 10 m sized fragments within the Perseid stream. Beech & Nikolova (2001) have investigated the lifetime of water ice fragments against sublimation in various meteoroid streams. For spherical water ice fragments in the Perseid stream, a change of ∼1 m in radius per orbit was found. Hence, for example, a water ice fragment initially 50 m across could survive within the Perseid stream for some 25 perihelion passages (a lifetime equivalent to ∼3600 yr). Since cometary fragments will be composed of 'dirty' ice and may possibly be insulated by a surface layer of refractory grains, we would expect the lifetime against sublimation to be longer than that set by the pure water ice limit.

3 LARGE PERSEID SURVEYS: THE FIREBALL DATA

Large Perseid meteoroids will inevitably produce bright fireballs in the Earth's atmosphere. This follows directly from their large mass and from their high atmospheric encounter speed of 59 km s^{-1}. The population index, defined as the ratio $r = \Phi(m+1)/\Phi(m)$, where $\Phi(m)$ is the total number of observed meteors brighter than magnitude m, for visually observed Perseids is $r = 2.0$ (Brown & Rendtel 1996). Given that of the order of 100 meteors brighter than magnitude +6.0 are recorded per hour at the time of the Perseid shower maximum, under ideal observing conditions, then a single observer might expect to see one Perseid fireball brighter than magnitude −4 during a nighttime's observing session lasting 6 h. A single observer, watching for 6 h per night over a 15-d time interval centred on the night of shower maximum, might further hope to see one Perseid fireball brighter than magnitude −6. It is important to note that the predictions just presented assume that the population index of Perseid meteors is constant into the fireball-producing range of meteors. The constancy of the population index is certainly questionable, and indeed there is some indication that the population index increases beyond magnitude −3 to −4 (Hughes 1995; Beech & Illingworth 2001). As the population index increases, so too does the time interval required for a given observer to actually witness a fireball brighter than a specified magnitude threshold.

We may estimate the size of fireball-producing Perseid meteoroids from the relationship between mass and maximum visual magnitude m_V derived by Verniani (1973). In this manner we construct, for illustrative purposes only, a relationship between diameter D (m), maximum magnitude and meteoroid density ρ(kg m^{-3}), for Perseid meteors, and find

$$\log[D(\mathrm{m})] = -1.378 - 13\log[\rho(\mathrm{kg\ m^{-3}})] - m_V/7.5. \quad (1)$$

From equation (1) we determine that for likely meteoroid densities falling between 500 and 1000 kg m^{-3}, the implied size of a magnitude −6 fireball-producing Perseid meteoroid is some 0.03 m. In addition, large-scale, long-running photographic surveys, such as the European Fireball Network of cameras, have yielded data on Perseid fireballs as bright as magnitude −10 (see e.g. Spurny 1995). Such fireballs, according to equation (1), are derived from Perseid meteoroids with diameters of the order of 0.1 m.

Using fireball data gathered during the 2001 Perseid display, Beech & Illingworth (2001) estimate that the spatial number density of 10^{-4} kg and larger Perseid meteoroids is of the order of 0.1 meteoroids per 10^9 km^3. This number density corresponds to those Perseid meteoroids with diameters $>8 \times 10^{-3}$ m (assuming a meteoroid density of 750 kg m^{-3}) which produce meteors brighter than magnitude −2. We also note, for reference purposes, that it takes the Earth about 15 min to sweep out a volume of space equal to 10^9 km^3. A survey conducted by Beech & Nikolova (1999), in which electrophonic emissions were monitored during the peak nights of the 1998 Perseid display, concluded that the spatial number density of Perseid meteoroids with diameters greater than 1 m was $<3.3 \times 10^{-4}$ meteoroids per 10^9 km^3.

A further constraint upon the arrival rate of large Perseid meteoroids at the Earth's orbit may be obtained from space-based sensor observations. For the past several decades, the United States Department of Defense (DoD) and Department of Energy (DoE) have used space-based optical and infrared sensors, placed into geostationary orbit, to monitor the Earth's atmosphere for the signatures of nuclear explosions (Rawcliffe et al. 1974; Tagliaferri et al. 1994; Ceplecha et al. 1998; Brown et al. 2002). The characteristics and operation of the detectors on board the satellite systems is classified information, but the limiting brightness for fireball detection is estimated to be of the order of magnitude −17. Equation (1) indicates, therefore, that, for typical meteoroid densities falling between 500 and 1000 kg m^{-3}, the satellite systems might potentially detect fireballs derived from Perseid meteoroids with diameters in excess of ∼1 m.

Owing to the nature of the operational directives, the total number of fireballs detected by the satellite systems is not available for 'public' analysis. We have been able to establish, however, that, in the time interval from 1978 August to 2000 August, a total of eight satellite-detected events were recorded on days between August 6 and 20 at times and locations where the Perseid radiant would have been above the local horizon. In light of the time and radiant conditions imposed, as a working hypothesis, we take these eight events to be candidate Perseid fireballs. We adopt the specified time window, representing a 15-d time interval centred on the night of the Perseid shower maximum (August 13), since it is the time period over which the hourly rate of visually observed Perseid meteors exceeds that of the sporadic background (Rendtel, Arlt & McBeath 1995). While low-level Perseid activity continues to either side of our specified window, e.g. from at least mid-July to the end of August, it does cover the time interval over which the more densely populated 'core' of the Perseid stream is sampled. If one extends the time window to encompass the entire month of August, then between the years 1978 and 2000 some 22 satellite-detected events were recorded at times and locations when the Perseid radiant was above the local horizon. The total number of reported events for August, irrespective of the Perseid radiant altitude, is 29. We note here, however, two important points with respect to the satellite data. First, given the complete lack of published orbital information we cannot be certain that any of the eight satellite-detected fireball events were actually Perseids. Secondly, given the incomplete reporting history associated with the satellite programme, it is possible that more than the eight potential Perseid events were detected in our specified time window. All the above being said, the distribution of satellite-observed fireballs in our August 6 to 20 window is such that six fireballs are reported before the time of shower maximum and two are reported after the time of maximum.

Using the entire 23-yr time interval of available satellite observations (i.e. 1978 August to 2000 August), we determine the spatial number density of potential satellite-detected Perseids to be $\sim 7 \times 10^{-8}$ meteoroids per 10^9 km^3. Since we cannot be certain of either Perseid stream candidacy, or the background rate of satellite-detected fireballs, we are not able to express any meaningful formal error on the spatial number density just derived.

4 TELESCOPIC SURVEY: SEARCH TECHNIQUE AND ANALYSIS

In addition to monitoring in-atmosphere fireball activity, the existence of large Perseid meteoroids could be validated through the detection of their surface reflected sunlight while they pass by outside of the Earth's atmosphere. Such exo-atmosphere Perseids would appear as faint streaks in a charge-coupled device (CCD) image of an appropriately chosen star field. In this fashion, our survey has proceeded by obtaining multiple images of predesignated sky locations, with the various image sets being temporally stacked at regular intervals and 'blinked' one after the other to reveal moving (that is, streaked) objects. Barabanov et al. (1996) and Smirnov & Barabanov (1997) have previously employed such a search technique and have specifically gathered observations with the Simeiz 1-m telescope at the time of the 1995 Perseid maximum. Indeed, they report the detection of four objects in the 5 m to 50 m diameter range that they believe to be members of the Perseid stream.

The basic geometry that we have exploited in our survey is shown in Fig. 1. Essentially we arrange for our search areas to be in regions

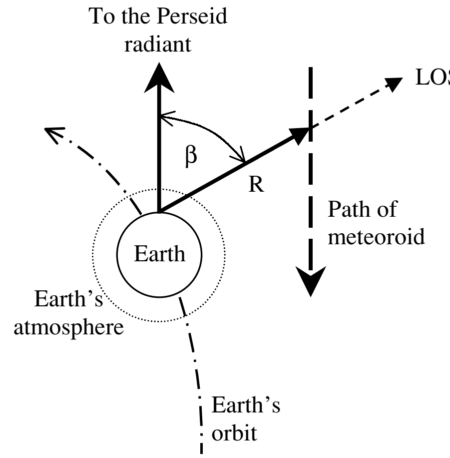

Figure 1. Schematic viewing geometry for the detection of an exo-atmosphere meteoroid. The angle β corresponds to the radiant offset angle to the line of sight (LOS); R is the range at which the meteoroid is detected as it passes through the telescopes field of view.

slightly offset from the apparent Perseid radiant location. In this manner, any Perseid meteoroid passing through a given search area will produce a trailed image. Given an offset angle β and meteoroid range R (km), the apparent angular velocity of the meteoroid will be

$$\omega(\text{deg s}^{-1}) = 57.3(V_{\mathrm{G}} \sin\beta)/R, \tag{2}$$

where V_{G} is the meteoroid's geocentric velocity in km s^{-1}. Clearly, for a zero offset angle the angular velocity will be zero and the meteoroid image will be that of a point source. For a given exposure time and range, however, the image trail length will increase with increasing offset angle, a maximum trail length being achieved for an offset angle of $\beta = \pi/2$. Since, however, the field of view (FOV) for the Elginfield telescope is $\times$ 9 arcmin^2, we are primarily interested in small offset angles. Table 1 provides a sample of anticipated trail length values according to range and angle of offset.

As might well be expected, the potential trail lengths will constitute a small fraction of the FOV when the offset angle is a few arcminutes and the range is in excess of several thousand kilometres. For ranges less than a few thousand kilometres, the expected trail lengths will typically exceed that of the FOV, when the offset angle is more than a few arcminutes.

The expected brightness of an exo-atmosphere meteoroid will depend upon its physical size, range from the Earth, solar elongation angle and surface albedo. Following Jackson et al. (1994), the range R(km) to which a spherical meteoroid of diameter D(m) might

Table 1. Characteristic trail lengths in arcminutes for a selection of ranges and offset angles. Here we have assumed a 1-min exposure time and take the geocentric velocity of Perseid meteoroids to be 59 km s^{-1}. Note that, for a given offset angle, the trail length varies directly with the exposure time, but inversely with the range.

β (arcmin)	$R = 2500$ km	$R = 5000$ km	$R = 10\,000$ km
1	1.4	0.7	0.4
5	7.1	3.5	1.8
10	14.2	7.1	3.5
30	42.5	21.2	10.6
60	85.0	42.5	21.2

Table 2. Observing log for our Perseid survey. Column one corresponds to the date, while columns two and three give the central position of the Perseid radiant to be surveyed. Column 4 indicates the number of frames (NOF) obtained and searched for moving objects. The last column is the accumulated time (AT) of observations.

Date	Radiant (RA)	Radiant (Dec.)	NOF	AT (h)
2002/08/10	02 51 30	+57 03 39	192	3.20
2002/08/11	02 57 06	+57 18 36	212	3.53
2002/08/12	03 02 42	+57 33 36	352	2.93

be detected at a solar elongation angle ϕ to a limiting magnitude M_ϕ is

$$R(\mathrm{km}) = (3.19 \times 10^3) 10^{(M_\phi - 7.2)/5} D(\mathrm{m}) \sin(\phi/2)\sqrt{A}, \quad (3)$$

where A is the albedo. Equation (3) is calibrated according to the full Moon having an apparent magnitude $M(\phi = \pi) = -12.7$ and an albedo of 0.11. We estimate, by way of example, therefore, that a 1 m diameter meteoroid with an albedo of 0.04 could be detected at a range of $R = 5.8 \times 10^4$ km (i.e. a distance of nine Earth radii) to a limiting magnitude $M(\phi = \pi) = +17$. Equation (3) indicates that, for a given limiting magnitude, the range will decrease with decreasing solar elongation angle and with decreasing albedo. We cannot be certain what albedo should apply to large Perseid meteoroids, but we would anticipate that it falls somewhere between those derived for cometary nuclei and the minor planets. The nucleus of comet 1P/Halley has a measured albedo of 0.04 (Whipple 1989), while the albedo of 19P/Borrelly showed surface variations from 0.01 to 0.03 (Soderblom et al. 2002). On the other hand, the albedos derived for minor planets 243 Ida and 951 Gaspa are 0.07 (Veverka et al. 1996) and 0.11 (Helfenstein et al. 1994) respectively. Perhaps of more direct relevance to this study, the six extinct cometary nucleus candidate objects studied by Fernandez, Jewitt & Sheppard (2001) reveal an average albedo of 0.027 ± 0.006.

Our observations were gathered with the 1.2-m University of Western Ontario, Elginfield Telescope, situated in Southern Ontario, Canada, over three nights centred on the peak of the 2002 Perseid display. Table 2 is a summary of our observing times and central search locations. The location of the Perseid radiant for each night's observing was derived from the numerical simulations conducted by Brown (1999). Accordingly, the average position of the geocentric radiant, at the time of shower maximum, for meteoroids ejected from comet 109P/Swift-Tuttle over the past 2000 yr is $\alpha = 46.1^\circ \pm 0.1^\circ$ and $\delta = 57.66^\circ \pm 0.05^\circ$. The theoretical radiant derived by Brown (1999) compares favourably with the radiant location derived for the Perseid 'outburst peak' meteors [see e.g. Brown & Rendtel (1996) for a discussion of the outburst feature] by Lindblad & Porubcan (1995): $\alpha = 46.85^\circ \pm 1.8^\circ$ and $\delta = 57.6^\circ \pm 0.99^\circ$.

A 3 × 3 grid of 9 × 9 arcmin^2 image fields centred on the predicted radiant location was surveyed on each night. Four successive images were obtained of each field before moving on to the next grid position. Throughout our observing run a typical exposure time of 1 min was used, yielding a limiting stellar magnitude of the order of +19. Sidereal tracking was used throughout the survey, but a series of experiments were conducted with varying telescope slew rates to simulate and determine the magnitude loss due to object motion. It was found that, at a slew rate of 0.5 arcsec per second, the limiting magnitude was decreased by one magnitude. On this basis we estimate our typical limiting magnitude for potential objects moving in the Perseid stream to be +17.

A total of 9.66 h worth of data was accumulated during our observing run and the images were 'blinked' and visually scanned for faint, trailed objects. While highly overexposed trails, passing through the entire field of view, of meteors ablating in the Earth's atmosphere, were recorded, we found no conclusive evidence for the detection of any large, exo-atmosphere meteoroids.

5 DISCUSSION

Brown & Rendtel (1996) have determined that the spatial number density of Perseid meteoroids more massive than 2.5×10^{-8} kg is 90 ± 16 meteoroids per 10^9 km^3 at the time of shower maximum (i.e. when the Earth cuts through the descending node of the Perseid stream). This number is based upon the visual meteor observations collected by the International Meteor Organization, and refers to meteors brighter than visual magnitude +6.5 which are correspondingly derived from meteoroids larger than 6×10^{-4} m across [from equation (1) assuming a meteoroid density of 750 kg m^{-3}]. Fig. 2 presents a summary of the spatial number densities of various sized Perseid meteoroids as derived by several different surveys. The solid line in Fig. 2 corresponds to the upper limit on the spatial number density set by our Elginfield observations. The volume element for our calculation is determined according to the telescope field of view being 9 × 9 arcmin^2, with the detection range R being set by the meteoroid's diameter and albedo, and the system's limiting magnitude, as given by equation (3). The visual meteor data imply a mass distribution index of $s = 2.0$ for the Perseid stream (Rendtel et al. 1995), and assuming that this is constant all the way to metre-sized meteoroids the extrapolated number density is shown by the dashed line in Fig. 2. Since we have no reason to suppose that the mass distribution index is actually constant over the entire meteoroid mass range, we also include in Fig. 2, for illustrative purposes, the extrapolated number density for $s = 1.5$ corresponding to a population rich in large objects.

Working to a limiting magnitude of +20, Barabanov et al. (1996) report that four 5 m to 50 m sized objects were found within the Perseid stream during the 1995 August display in an accumulated observing time of 25 h. On the basis of this result, it does not seem unreasonable to think that we should have detected one or possibly two moving objects in the accumulated time of our survey. Two of the objects detected by Barabanov et al. (1996), however, are tabulated as being fainter than magnitude +19, which is well below our detection limit. Barabanov et al. (1996) suggest that for the Perseid stream some two or three large objects brighter than magnitude +20 should be detected outside of the Earth's atmosphere per hour in a FOV covering 5 × 7 arcmin^2, at the time of shower maximum.

At this stage our telescopic observations do not independently confirm the existence of metre-sized and larger meteoroids within the Perseid stream. There are, however, a number of reasons why we may not have detected any large objects in the Perseid stream during our survey. First, it is entirely possible that there are no such objects in the stream, but at least we now have some constraint on the upper bound to their spatial number density. It is possible that our albedo assumption is on the high side and consequently any metre-sized objects are much fainter than our limiting magnitude of +17. Repeating this study to a lower limiting magnitude (using a larger aperture telescope) may address this particular issue. It is also possible, and indeed highly probable, that the spatial number density of large Perseid meteoroids is not constant from one year to the next.

Provided that comet 109P/Swift-Tuttle has actually undergone a significant mantle ejection event in the past, the return time

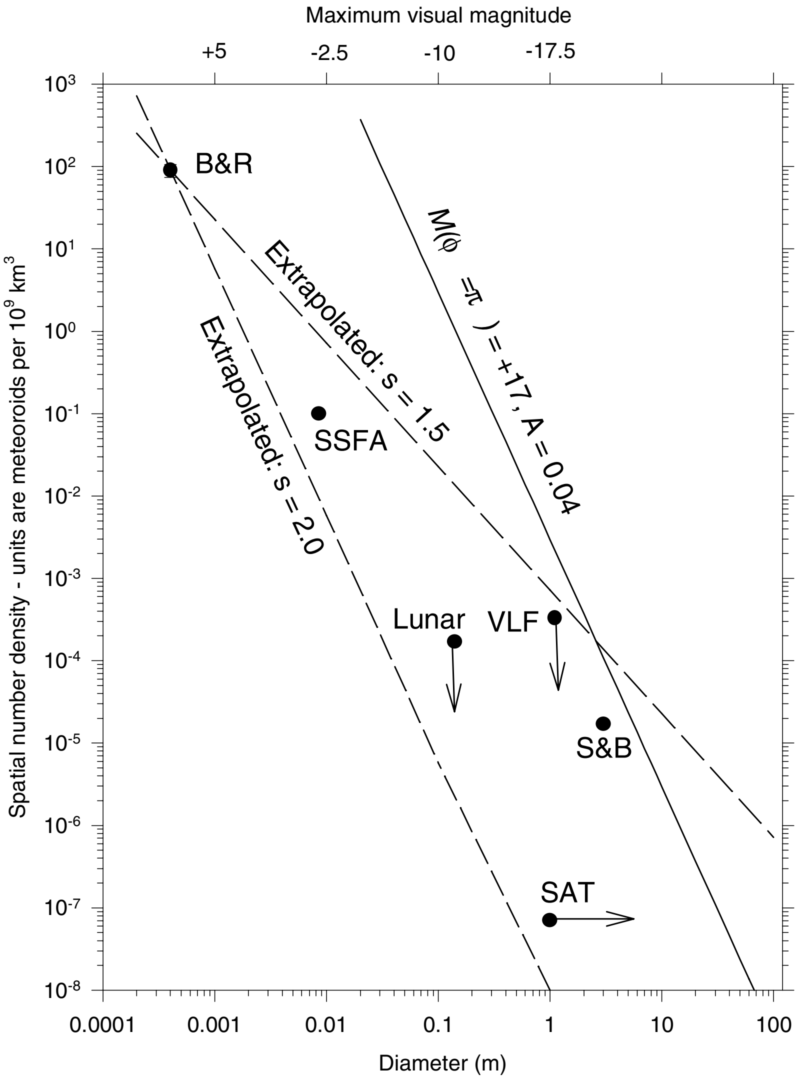

Figure 2. Spatial number density versus meteoroid diameter. The data points correspond to various survey results: B&R is taken from the visual meteor observations analysed by Brown & Rendtel (1996); SSFA is from the fireball study conducted by Beech & Illingworth (2001); Lunar and VLF are from the surveys by Beech & Nikolova (1999); S&B is derived from fig. 2 of Smirnov & Barabanov (1997); and SAT is based upon the US DoD and DoE satellite-observed fireball data (see text for details). The dashed lines correspond to the extrapolated spatial number densities for constant mass indices of $s = 1.5$ and 2.0. The solid line corresponds to the upper limit set by our Elginfield observations assuming a limiting magnitude of +17 and a meteoroid albedo of 0.04. The upper x-axis on the diagram indicates the maximum visual magnitude, according to equation (1), for 10^{-3} m to 1 m sized Perseid meteoroids ablating in the Earth's atmosphere. The arrows attached to the Lunar and VLF data points indicate that they are upper bounds. The arrow attached to the SAT data point indicates that it is probably a lower bound to the size of meteoroids being detected. Given the uncertainty in the reporting history of satellite events, we cannot, at this stage, express any constraint on the SAT data point with respect to it being an upper or lower bound to the spatial number density.

to perihelion for fragments can be estimated via an application of Kepler's third law. For separation occurring at perihelion, the lag time per orbit ΔP for the fragments to return to perihelion will be

$$\frac{\Delta P}{P} = 3\frac{\Delta V}{V}\left(\frac{1+e}{1-e}\right). \tag{4}$$

Here ΔV is the separation velocity between the fragment and the parent nucleus, e is the orbital eccentricity, P is the orbital period and V is the velocity at perihelion. For 109P/Swift-Tuttle we have $P = 132.6$ yr, $e = 0.963$ and $V = 42.5$ km s^{-1}. Sekanina (1982, 1999) finds that the separation velocities of split cometary nuclei (relating, presumably, to objects in the size range of 10 m to 100 m) are typically a few metres per second. Therefore, to accumulate a lag time of 9.7 yr (the time interval between our observations and the most recent perihelion passage of comet 109P/Swift-Tuttle) requires a time interval equivalent to 20 perihelion passages when $\Delta V = 1$ m s^{-1}. The 9.7 yr lag time could be accumulated in a shorter time interval (that is, fewer perihelion passages) if the separation velocity ΔV is larger than 1 m s^{-1}. With $\Delta V = 5$ m s^{-1}, for example, the 9.7 yr lag time can be accumulated in a time interval equivalent to four perihelion passages. It would appear, therefore, that there is no specific dynamical reason why large fragments could not be observed some 9.7 yr on from the time of comet 109P/Swift-Tuttle's last perihelion passage. At this stage, what is crucial, and unfortunately unknown, is whether or not comet 109P/Swift-Tuttle has ever undergone an outburst and, if so, what were the initial fragment sizes and separation velocities.

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