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Fireball flickering: the case for indirect measurement of meteoroid rotation rates

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Abstract

Data collected during the Meteorite Observation and Recovery Program (MORP) indicate that 4% of bright fireballs show a periodic variation or flickering in brightness. The observed flickering frequencies vary from a few Hz to as high as 500 Hz. We interpret the flickering phenomenon in terms of meteoroid rotation. The MORP data does not reveal any apparent correlation between the flickering frequency and the properties of the meteoroid or the atmospheric flow conditions under which ablation is taking place. It is argued that the most likely cause of the flickering phenomenon is the rotational modulation of the cross-section area presented by the meteoroid to the on-coming airflow. A study is made of the Peekskill fireball and it is concluded that the meteoroid was spun-up during its long flight through the Earth's atmosphere, and that its initial brake up was due to rotational bursting. We also argue that the Peekskill event provides the best observational evidence that the flickering phenomenon is truly related to the rotation rate of the impinging meteoroid. We find that the observed rotation rates of the MORP fireballs are clustered just below the allowed limit set by rotational bursting, but argue that this is due to an observational selection effect that mitigates against the detection of low-frequency flickering.

1. Introduction

The light phenomenon associated with meteoroid ablation affords a direct means of studying the physical characteristics of the parent body. The temporal variation of a meteor's brightness (its light-curve), for example, can potentially yield information on the parent meteoroid's mass, density and physical structure.

Meteor light-curves, while morphologically similar, can show some considerable degree of variation (Hoffleit, 1933; Jacchia, 1949). The basic light-curve shape is that of a parabola, skewed about the point of maximum brightness. Superimposed upon this shape are occasionally found flares (sudden and temporally random variations in brightness) that can be associated with fragmentation and meteoroid break-up. The phenomenon that we wish to study here is that of flickering where sustained and periodic variations in a meteor's brightness are seen over a significant portion of its light-curve.

The phenomenon of meteor flickering has been recorded on numerous occasions in the past (e.g., Fisher et al., 1927; Halliday, 1963; Babadzhanov and Konovalova, 1987; Brown et al., 1994), but no systematic survey has ever been published. It is clear that the flickering phenomenon is rare, with perhaps 4–5% of bright fireballs exhibiting the effect in an obvious manner (see Section 2). The deduced flickering frequencies that have been reported in the literature vary from as low as a few Hz to as high as 500 Hz. The key question, of course, is what does the flickering phenomena tell us about the parent meteoroid and the ablation process?

2. The MORP survey and results

The Meteorite Observation and Recovery Program (MORP) constituted a series of 12 multi-camera stations spread across the prairies of Canada. The program was initiated with the hope of recording the passage of meteorite-producing fireball events and indeed, the laudable mettle of the program instigators was roundly proven with the recovery of the Innisfree meteorite in 1977 (Halliday et al., 1981). Operating from 1971 to 1985 more than 750 bright

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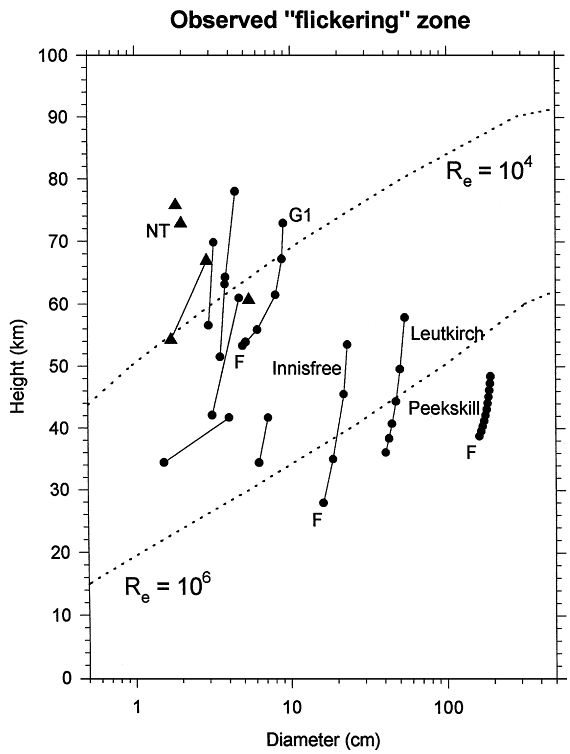

Fig. 1. The observed flickering zone. The onset and end of flickering points of the MORP fireballs are linked together by solid lines. The ● symbol corresponds to type I (stony) MORP fireballs, while the ▲ symbol corresponds to type IIIA (cometary) MORP fireballs. The data point labeled NT is a Northern Taurid fireball. The data points labeled G1 correspond to a Geminid fireball studied by Halliday (1963). The other data sets are labeled according to the event name and are discussed in the text. The diagonal dotted lines correspond to loci of constant Reynolds number — see text for details. F indicates the point at which fragmentation occurred.

fireballs were photographed from well-separated camera stations enabling atmospheric trajectories and parent body orbits to be derived (Halliday et al., 1996).

Halliday (personal communication) has provided us with data pertaining to 11 MORP-recorded fireballs that showed pronounced flickering. In all, some 4% of the unbiased sample of MORP fireballs (259 events) studied by Halliday et al. (1996) exhibited a flickering effect in their light-curves. Using the atmospheric flight data provided by Halliday et al. (1996) we show in Fig. 1 the atmospheric height region in which flickering was observed. Seven of the MORP fireballs that showed flickering are of compositional type I (stony), while four are of compositional type IIIA (cometary). These designations have been ascribed according to the observed initial velocities and meteoroid densities (which were calculated according to the derived photometric and dynamic masses). Only one of the MORP fireballs that displayed flickering can be linked to an annual meteor shower. Specifically, MORP 973 appears to be related to the Northern Taurid stream associated with comet 2P/Encke. For the type I fireballs we adopt a density of 3500 kg/m^3, and for type IIIA fireballs we assume a density of 750 kg/m^3. Meteoroid diameters have been calculated from the tabulated photometric masses (derived according to a constant panchromatic luminous efficiency of 4%) and the adopted compositional-type densities. Characteristically, we discern a flickering zone extending over the altitude range $80 > h(\text{km}) > 25$. There is no obvious distinction between the regions over which the types IIIA and I fireballs exhibit flickering. Included in Fig. 1 are data points for the Peekskill fireball (Brown et al., 1994), the Leutkirch fireball (Ceplecha et al., 1976), the Innisfree fireball (Halliday et al., 1981) and a Geminid fireball (G1) observed on December 12, 1960 (Halliday, 1963). The range of meteoroid diameters sampled varies from some 200 cm to about 1 cm. Also shown in Fig. 1 are the loci corresponding to constant Reynolds numbers of 10^4 and 10^6. The Reynolds numbers, which reflect the ratio of inertial to viscous forces on a body, have been calculated according to the formalism given by ReVelle (1979). We also assume a fixed velocity of 15 km/s in the calculation of the Reynolds number. The turbulence condition, corresponding to $\text{Re} \sim 10^6$, applies to the material that constitutes the meteor trail and delineates in broad terms the regions corresponding to slip flow ($\text{Re} < 10^4$), continuous flow ($10^4 < \text{Re} < 10^6$). At this stage we shall simply use these numbers as a guide to possible interpretations (see Section 5). While the exact details of the flow regime do not concern us here, Keay (1993) has argued, for example, that once the turbulent flow condition has been realized ($\text{Re} > 10^6$) then electrophonic sounds may be produced. In general one will have to perform a detailed analysis based upon meteoroid size and velocity to determine the trail flow conditions.

Figs. 2 and 3 show the atmospheric flight variations derived for the MORP 835 and 886 fireballs. We may see from these two ‘fairly typical’ cases that flickering is only apparent during a small fraction of the atmospheric flight. We also notice that there is no apparent correlation between the onset of flickering and the attainment of maximum fireball brightness (e.g., in 886 the flickering is seen after the time of maximum brightness, while in 835 it is observed before). Also, we find that some fireballs show no apparent change in flickering frequency (e.g., the Leutkirch fireball and MORP 886, Fig. 3), while others show a sharp increase with time (e.g., MORP 835, Fig. 2). One fireball that displayed a particularly dramatic increase in flickering frequency with time was that described by Halliday (1963). The fireball in question was identified as a member of the Geminid meteoroid stream, and its flickering frequency increased from ~ 50 Hz at 73 km altitude to ~ 320 Hz at an altitude of 56 km.

In the cases where light-curve data has been published, the amplitude of brightness variations (ΔM) appears to be remarkably constant, even when the flickering frequency changes. Both the Leutkirch (Ceplecha et al., 1976) and Innisfree (Halliday et al., 1981) fireballs exhibited a near

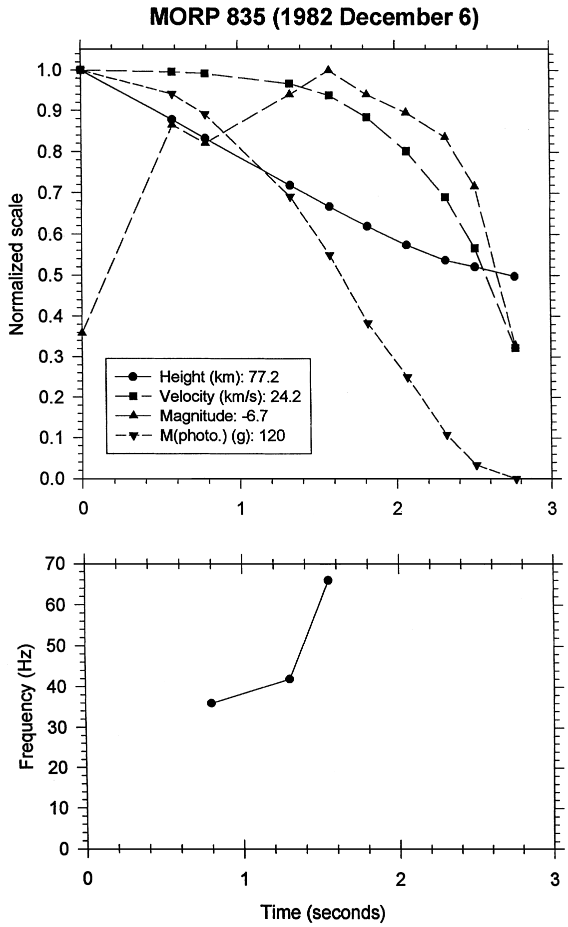

Fig. 2. Atmospheric flight parameters for MORP fireball 835. The top panel shows the normalized data as given by Halliday et al. (1996) with the maximum values being given in the line identification box. The lower panel shows the temporal variation in the observed flickering frequency.

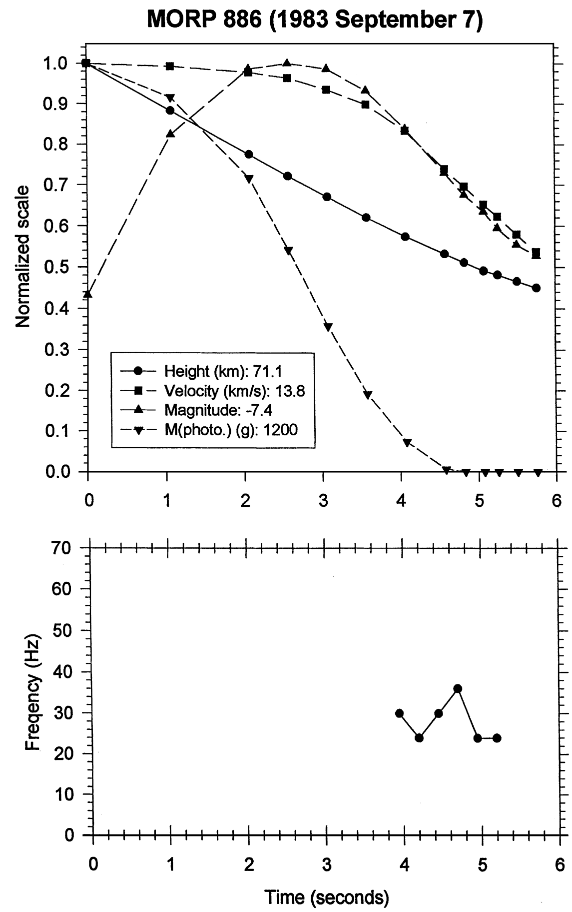

Fig. 3. Atmospheric flight parameters for MORP fireball 886. The top panel shows the normalized data as given by Halliday et al. (1996) with the maximum values being given in the line identification box. The lower panel shows the temporal variation in the observed flickering frequency.

constant variation of $\Delta M \approx 0.5$. Likewise the Geminid fireballs studied by Babadzhanov and Konovalova (1987) showed ΔM variations between 0.5 and 1.0 magnitudes.

With the data at hand we are unable to find any obvious correlation between the flickering frequency, the meteoroid diameter (or photometric mass), the meteoroid velocity, the atmospheric height and/or the atmospheric flow conditions. This would suggest that rather than being the manifestation of some rare ablation-related effect the presence of flickering is probably related to some pre-atmospheric property of the meteoroid. Pre-atmospheric rotation of the parent meteoroid is the most likely parameter that controls the presence, or not, of flickering. Atmospheric interactions and ablation effects may later modify the initial rotation rate.

3. A general survey of fireball flickering

The Peekskill meteorite-dropping event of October 9, 1992 is a recent example of a fireball that exhibited the flickering phenomenon (Brown et al., 1994). The fireball associated with the atmospheric passage of the Peekskill meteoroid is all the more remarkable in that a large number of eyewitnesses were able to capture the event with videotape recorders. Fig. 4 shows the rate of change in the flickering frequency as deduced from two video sequences. The flickering frequency showed a gradual increase from ~ 7 Hz to a maximum of ~ 20 Hz, at which point the parent body began to break apart. Ceplecha et al. (1996) have studied the atmospheric flight of the Peekskill fireball in great detail, and found that the height of the first fragmentation event was anomalously high (41 km) and not consistent with straightforward dynamical crushing. We shall argue below that the first fragmentation event of the Peekskill meteorite's parent body was due to rotational bursting. The rotational bursting limit is reached once the centripetal force per unit area exceeds the tensile strength of the meteoroid body (Paddack, 1969). At the point of fragmentation the Peekskill meteoroid had a radius of about 80 cm (Ceplecha et al., 1996). Adopting an angular velocity of 126 rad/s (corresponding to a

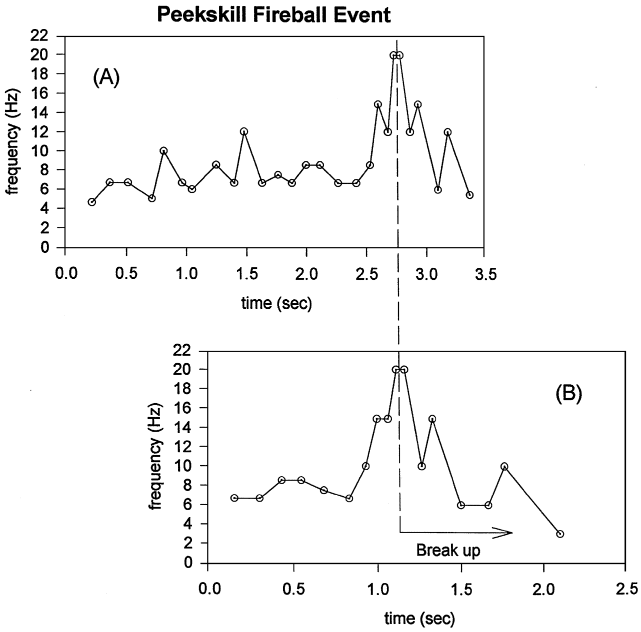

Fig. 4. Temporal variation in the Peekskill flickering frequency. The diagrams have been aligned so as to coincide at the moment of highest flickering frequency. The time axis in each panel is relative to the particular video sequence. The meteoroid began to break apart after the time of frequency maximum. (A) derived from video data recorded by Mr. J. Raspotnik in Saltsburg, PA. (B) derived from video data recorded by Mr. J. Fortney of Station WTAP in Parkersburg, W. VA.

rotational frequency of 20 Hz), the maximum lateral displacement of fragments would be of order 1 km in about 5 s. This displacement is, in fact, consistent with the observed 'spreading' of Peekskill fragments (Beech et al., 1995).

The Peekskill event represents the strongest evidence that flickering is actually related to the instantaneous rotation rate of the parent meteoroid. In particular, we note that the wake of the Peekskill fireball was observed to show "disconnection" events with the same period as the photometric flickering (see Fig. 5). The wake itself is composed of numerous, small and rapidly decelerating grains ablated from the leading surface of the parent body. That the wake disconnection frequency is the same as the photometric flickering frequency indicates that the rate of mass loss from the parent body was varying as a function of time. The simplest explanation for the observed variation in the mass loss rate is that the parent object was rotating as it moved through the Earth's atmosphere.

In Fig. 6 we have gathered together the data on a number of fireballs exhibiting the flickering phenomenon. As before, diameters are calculated according to the derived photometric mass and the density appropriate to the associated compositional type. Rather than plot flickering frequency against diameter in Fig. 6, we have chosen to show the variation in angular velocity. This choice allows us to compare the observed angular velocities with the Opik rotational bursting limit (Opik, 1958). In this manner, we may test the data against the proposition that flickering is due to parent body rotation.

The Opik rotational bursting limit is determined according to the tensile strength, σ, of the parent meteoroid, and is described by the following relationship:

$$\omega < (\sigma/\rho)^{0.5}/r, \qquad (1)$$

where r and ρ are the meteoroid's radius and density, and ω is the angular velocity. The typical tensile strength of a meteoroid is expected to be in the range of 10^6–10^8 Pa (Svetsov et al., 1995). The loci drawn in Fig. 6 correspond to the Opik limit (Eq. (1)) evaluated at three values of σ. We can see that the MORP fireballs all fall below the break-up limit at $\sigma = 10^6$ Pa. Interestingly, we note that the fragmentation points for the Peekskill meteoroid and the December 1960 Geminid meteoroid occur at angular velocity limits consistent with a tensile strength of $1–5 \times 10^7$ Pa. In these two cases, it would appear that the meteoroids are being spun-up as they pass through the Earth's atmosphere, and that rotationaly bursting eventually occurs. This scenario offers an explanation for the anomalously high fragmentation height of the Peekskill meteoroid.

4. Rotation and selection effects

Meteoroid rotation will moderate the ablation process once the spin period, P, is small compared to the characteristic ablation time $T_{ab}=H/V\cos Z$, where H is the atmospheric scale height, V is the meteoroid velocity and Z is the zenith angle. When $P \ll T_{ab}$ the ablation process will be essentially uniform over the meteoroid surface. For characteristic parameters ($V=15$ km/s, $H=7$ km and $Z=45°$) we find $T_{ab} \approx 0.066$ s. and hence rotation becomes important at rotational frequencies greater than ~ 15 Hz.

Within the context of single-body ablation theory, the brightness of a meteor is taken to be some fraction of the kinetic energy lost by the meteoroid per unit interval of time

$$I = \tau(v)[mV\,dV/dt + (V^2/2)\,dm/dt], \qquad (2)$$

where $\tau(v)$ is the instantaneous luminous efficiency (assumed to be a function of the velocity), V is the meteoroid velocity and m is the meteoroid mass. Typically, the first term in Eq. (2) can be ignored since the deceleration of a moderately large meteoroid is small over most of its early trajectory. The derivative in the second term of Eq. (2) can be approximated by relating the energy required to ablate mass δm of meteoroid material to the kinetic energy of the oncoming air flow. Namely,

$$Q\,dm/dt = -(\tfrac{1}{2})C_H\rho V^3 A(t), \qquad (3)$$

where Q is the latent heat of vaporization, C_H is the heat transfer coefficient, ρ is the atmospheric density and A is the cross-sectional area of the meteoroid — here stated to

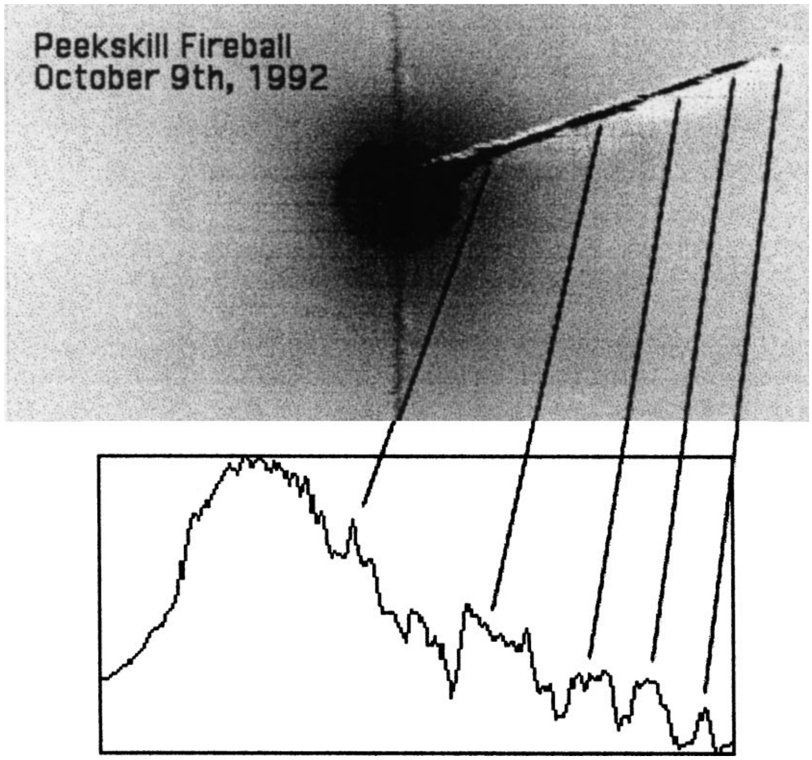

Fig. 5. Wake dissociation events associated with the Peekskill fireball. The upper image shows a single frame from the video data collected by Mr. J. Raspotnik — at least four dissociation events are visible in the image. The lower panel shows the pixel intensity count (in arbitrary units) along an image slice passing through the fireball head and trail. The dark vertical line seen in the top image is due to the column spill over in the camera's CCD.

be a specific function of time. Indeed, the only variable in Eq. (3) that can reasonably modify the intensity term (as described by Eq. (2)) in a periodic fashion is that of the cross-sectional area — all the other terms are either constant or vary monotonically with time, or are likely to vary in a non-periodic fashion. In principal Q and C_{H} may vary with the exposure of different material at the surface of a meteoroid. This effect will not of its own accord, however, produce flickering — it might modulate the amplitude of flickering variations being produced by rotation. A cylindrical meteoroid of length L and diameter D, if rotating around its major axis, will induce a periodic intensity variation of $4L/\pi D$. The Innisfree fireball, for example, showed periodic fluctuations of order $\Delta m \approx 0.5$ magnitudes and assuming a cylindrical profile this implies $L/D \approx 1.2$ for the parent object.

If, as we suppose, the flickering phenomenon is due to meteoroid rotation, the question that naturally arises is; what mechanism is responsible for establishing the spin? In the case of millimeter sized, and smaller, meteoroids the spin-inducing mechanism is probably radiation pressure. The 'windmill' effect first described by Paddack (1969), for example, can spin-up small meteoroids to the bursting point on a time-scale of a few times 10^4 years. One would expect, therefore, that most small meteoroids are rapid rotators. Hawkes and Jones (1978) have argued that rotation rates of order 5×10^3 rad/s are required to account for the initial train radii of faint meteors with masses of order 10^{-6} kg. Olsson-Steel (1987) has further argued that the induced spin rate will decrease as the inverse square of a meteoroid's radius. In this manner we find that a meteoroid of diameter ~ 8.5 cm might obtain an angular velocity of ~ 1 rad/s through interaction with the Sun's radiation field. Meteoroids larger than ~ 10 cm in diameter are not expected to be efficiently spun-up by the 'windmill' mechanism. The data points shown in Fig. 6, however, reveal two important features. Firstly, the centimeter sized meteoroids responsible for the MORP fireballs have characteristic angular velocities of several hundred radians per second, larger than that expected from the 'windmill' effect. And secondly, even the largest meteoroids, such as the Peekskill parent body, have angular velocities of between 15 and 35 rad/s. We would conjecture that the most likely mechanism for producing the rapid spin in centimeter-sized (type I, stony) meteoroids, as well as the meter-sized objects, is collisional fragmentation. Fujiwara and Tsukamoto (1981) and Fujiwara (1987), for example, have studied the rotation rates of spallation fragments produced in the disruption of basaltic spheres. Their experiments reveal a well-defined upper rotational limit at about 1/10th that of the Opik bursting limit (recall Eq. (1)). It would seem, therefore, that the MORP Type I

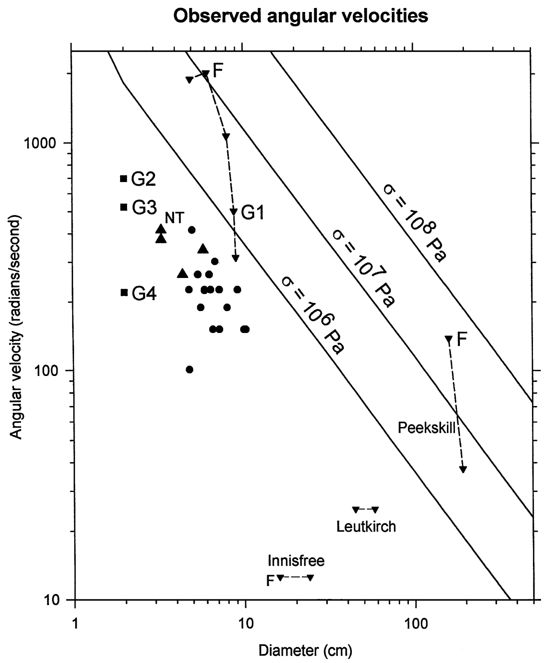

Fig. 6. Observed angular velocity versus meteoroid diameter. The ● symbol corresponds to type I (stony) MORP fireballs, while the ▲ symbol corresponds to type IIIA (cometary) MORP fireballs. The data point labeled NT is a Northern Taurid fireball. The data points labeled G1 relate to the Geminid fireball studied by Halliday (1963). The points labeled G2, G3 and G4 correspond to Geminid fireballs studied by Babadzhanov and Konovalova (1987). F indicates the point at which fragmentation occurred. The other data sets are labeled according to the event name and are discussed in the text. The diagonal lines correspond to rotational bursting limits for three selected values of the tensile strength: $\sigma = 10^6, 10^7$ and 10^8 Pa (see text for details).

(stony) fireballs which show the flickering effect are representative of the fast spallation rotators. It is less clear how type IIIA (cometary) meteoroids might be spun up. The rotation may be pre-atmospheric in origin or it might be due to spin-up in the Earth's atmosphere.

A number of selection effects will act against the detection of low-frequency flickering in fireball light-curves. The field of view of each MORP camera, for example, was occluded every 1/12th of a second by a rotating shutter (this enabled velocity data to be extracted from the film image). This situation dictates that the flickering frequency must be greater than at least ~ 15 Hz in order to be readily seen. This result explains why in Fig. 6 the MORP data is clustered above angular velocities of ~ 100 rad/s. In general, the duration lifetime of a meteoroid against ablation sets a lower limit on the observable flickering frequency. If the duration time of a meteoroid is t_D then the flickering frequency must be greater than, say, $\sim 5/t_D$ to be discernible. The average duration time for MORP fireballs is $t_D \approx 1.9$ s.

There are also a number of selection effects that act against the detection of rapid flickering within meteor light-curves. The smaller meteoroids (diameters less than ~ 5 cm) that might support rapid rotation not only produce less bright meteors, which are not likely to be recorded photographically, but are also short lived, having characteristic ablation lifetimes $t_D < 0.5$ s. Not only this, the finite size of the photosensitive grains within the photographic film will ultimately act against the detection of very rapid variations in light intensity.

5. Discussion

Over the years several mechanisms, other than pure rotation, have been offered as explanations to the flickering phenomenon. Fisher et al. (1927), for example, suggested that flickering might be due to a combination of rotation and non-homogeneous meteoroid composition. In this model, the meteoroids are assumed to be essentially spherical and it is the rotation that periodically exposes regions of varying composition with different ablation characteristics. Likewise, Getman (1993) has suggested that flickering might be due to explosive fragmentation, the result of a meteoroid having both an irregular shape and a non-homogeneous chemical composition. With respect to the varying composition models, however, it seems to us that the straightforward invocation of cross-sectional area modulation is a less contrived and more tractable explanation. In contrast to the rotation hypothesis, Rinehart et al. (1952) have suggested that the flickering is caused by periodic yawing of the meteoroid. In this model a non-spherical meteoroid yaws from one side of the velocity vector to the other, thus exposing a varying cross-section to the on-coming airflow. The interpretation proposed by Rinehart et al., requires that the meteoroid ablates while undergoing orientated atmospheric flight. Interestingly, while most meteorites have near uniform fusion crusts and/or uniformly distributed regmaglipts, some do display the effects of having traversed the atmosphere under orientated conditions. Bronshten (1995) notes that about 5% of all stony meteorite fragments show evidence of orientation (see also Nininger, 1952). The percentage of meteorites displaying evidence of orientated flight is about the same as the percentage of fireballs displaying flickering, and this suggest the periodic yawing method requires further detailed study. We note, however, that orientated flight requires rotation about the axis aligned with the meteoroid entry plane. So, again, it is the initial rotation that is important. More recently, Thuillard (1996) has suggested that fireball flickering is the result of an instability that develops in the airflow around a meteoroid. This model requires the development of a laminar flow above the boundary layer where the ablated material flowing off the meteoroid encounters the impinging airflow. Under these conditions, the so-called, Tollmein–Schlichting (TS) waves can develop, and these are unstable against small perturbations. Thuillard (1996) argues that it is the downstream instabilities caused by unstable TS waves that give rise to the flickering phenomenon. The potential problem with this mechanism, however, is that it has no apparent limitation and all meteoroids that descend low enough into the Earth's atmosphere should show the flickering effect. This is not the case, however. In addition, the Innisfree, Leutkich and Peekskill fireballs showed distinctive flickering when the airflow conditions were apparently turbulent (that is, $R_e > 10^6$ in the meteor trail, see Fig. 1); a situation that is not compatible with the development of TS waves. Again, however, we feel that this mechanism is still worthy of further study especially with respect to the detailed understanding of the laminar-to-turbulent flow transition conditions.

While one of the MORP fireballs showing flickering can be linked to the Northern Taurid stream, the annual meteoroid stream that is most conspicuous in delivering flickering fireballs is that of the Geminids. This is significant in that the parent body associated with the Geminid stream is the minor planet (3200) Phaethon, and in addition the Geminid meteoroids are known to have high bulk densities (Ceplecha and McCrosky, 1991) consistent with an asteroid origin. The low tensile strength of icy-conglomerate structures ($\sigma \approx 10^5$ Pa) would preclude against them being spun-up to the same high rates as type I (Stony) meteoroids. We would expect to find the more fragile cometary meteoroids among the slower rotators — for a given size they suffer rotational bursting at lower rotational velocities.

Farinella et al. (1998) have recently modeled the outcome of including the Yarkovsky effect in the orbital calculations of meteorite producing bodies. This effect depends upon the non-radial emission of thermal radiation (Burns et al., 1979). Petersen (1976) and Farinella et al. (1998) find that the Yarkovsky effect can aid in the delivery of meter-sized bodies within the main asteroid belt to the 3:1 and v_6 resonance channels responsible for 'funneling' meteorites towards Earth-crossing orbits. The Yarkovsky effect is dependent upon the meteoroid size, composition, temperature, spin-rate and obliquity. Depending upon the spin sense, which can change through collisions with time, the Yarkovsky effect results in either an accelerative or a drag force with a magnitude $F_Y \, \alpha P^{0.5}$, where P is the spin rate. In their calculations, Farinella et al. (1998) adopted a spin period to size relationship of $P(\mathrm{h}) = 5\ (D/1\ \mathrm{km})$. This relationship yields spin periods of 18 s at $D = 1$ m and 2 s at $D = 10$ cm. These rates are, in fact, much slower than those observed in the type I (Stony) MORP fireball data. Indeed, the data shown in Fig. 6 are consistent with the approximation formula $P(\mathrm{s}) = 0.5\ (D/1\ \mathrm{m})$. This latter formula really represents, however, an upper limit to the observed spin rate as, as we noted above, observational biases greatly affect detectability at the slow rotational end of the spectrum.

The rubble-pile concept of asteroid structure has gained wide acceptance over the past several years, principally upon the basis of the preponderance of slow rotation rates (see, e.g., Harris, 1996). In contrast to this, the high rotation rates implicated for some of type I (Stony) fireballs observed during the MORP survey suggests that they are cohesive and substantive monolithic structures with tensile strengths of order 5×10^7 Pa.

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