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Analysis of a "flickering" Geminid fireball

Martin BEECH,[1, 2*] Alison ILLINGWORTH,[1] and Ian S. MURRAY[2]

[1]Campion College, The University of Regina, Regina, SK, Canada S4S 0A2
[2]Department of Physics, The University of Regina, Regina, SK, Canada S4S 0A2
[*]Corresponding author. E-mail: martin.beech@uregina.ca

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Abstract–In the early morning hours of December 13, 2002, a bright Geminid fireball with an absolute magnitude of −9.2 ± 0.5 was observed from Southern Saskatchewan, Canada. The fireball displayed distinct small-scale oscillations in brightness, or flickering, indicative of the parent meteoroid being both non-spherical and rotating. Using the light curve derived from a calibrated radiometer, we determine a photometric mass of 0.429 ± 0.15 kg for the meteoroid, and we estimate from its initial rotation rate of some 6 Hz that the meteoroid was ejected from the parent body (3200) Phaethon some 2500 ± 500 years ago. We find that 70% of Geminid fireballs brighter than magnitude −3 display distinct flickering effects, a value that is in stark contrast to the 18% flickering rate exhibited by sporadic fireballs. The high coincidence of flickering and the deep atmospheric penetration of Geminid fireballs are suggestive of Geminid meteoroids having a highly resilient structure, a consequence, we suggest, of their having suffered a high degree of thermal processing. The possibility of Gemind material surviving atmospheric ablation and being sampled is briefly discussed, but the likelihood of collecting and identifying any such material is admittedly very small.

INTRODUCTION

The annual Geminid meteor shower is not renowned for its production of bright fireball meteors, but bright events are, nonetheless, occasionally reported (Rendtel et al. 1995). One such remarkable Geminid fireball was recently witnessed from Southern Saskatchewan, Canada on December 13, 2002 at 12:25:55 UT. The event generated considerable media attention, with local radio stations and newspapers reporting on numerous eyewitness accounts. The fireball was also detected with an all-sky video camera and radiometer system located at the University of Regina campus.

The video and radiometer system form part of the Southern Saskatchewan Fireball Array (SSFA), which has been in near continuous operation since April of 2000. The all-sky camera system consists of an 18-inch diameter spherical mirror and a downward looking CCD video camera mounted above the mirror's center. The video data is recorded onto standard VHS format videotapes. For objects with altitudes greater than 10 degrees above the horizon' the camera system has a limiting magnitude of about −3. The radiometer is a PC logged system that automatically records the times of background brightness transients. We are able to extract 120 irradiance measurements per second from the radiometer data stream, and these can be used to reconstruct and analyze fireball light curves. Other camera and radiometer systems similar to those used in the SSFA are described by Spurny et al. (2001) and Zinn et al. (1999).

THE LIGHT CURVE

A single mid-flight video image of the Geminid fireball is shown in Fig. 1. The characteristics of the fireball path, as deduced from the observed beginning and end positions of the fireball are summarized in Table 1. The video frames have been digitized with a Scion LG-3 card on a G4 Macintosh computer working at a capture rate of 29.97 frames per second. The digitized frames have been analyzed using NIH Image software (see, e.g., Murray et al. 1999). Although the fireball video sequence lasts some 5 seconds, only 2.4 seconds of data, centered around the time of maximum brightness, could be usefully analyzed with respect to determining the image brightness via a log sum pixel (LSP) count method. The LSP is the logarithm of the sum of pixel intensities for the fireball image minus the local background intensity over a region containing the fireball image. We lose portions of the low luminosity, that is, early rising and late falling segments of the light curve after digitization because of an inability to clearly distinguish the meteor from the background. Hawkes et al. (1993) have shown that for faint meteors, the LSP correlates to apparent stellar magnitude in a linear fashion, but unfortunately for this study, we are not able to perform any

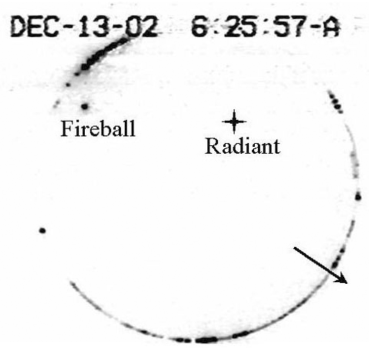

Fig. 1. Mid-flight single frame video image (in negative format) of the December 13, 2002 Geminid fireball. The bounding horizon circle is delineated by campus buildings and access road lights. The arrow indicates north. The cross marks the approximate position of the Geminid radiant at the time of the event.

Table 1. Characteristics of the December 13, 2002 Geminid fireball trail. The initial range is calculated according to the observed angular velocity and known radiant location. The absolute magnitude at maximum is based on the radiometer calibration (Equation 1) and the deduced range.

Beginning (alt., azm.)	= (27.0 ± 2.0, 183.0 ± 2.0)
End (alt., azm.)	= (10.0 ± 2.0, 185.0 ± 2.0)
Duration (sec.)	= ~5 (150 video frames @ 1/30th second each)
Radiant altitude (deg.)	= 48.5 degrees (from time of event)
Initial Range (km)	= 190 ± 20 km (from deduced angular velocity)
Magnitude at maximum	= –9.2 ± 0.5 (from radiometer and range estimation)

such analysis because of the lack of suitable stellar calibration objects. The variation of the LSP count with time, which is a scaled representation of the fireball's light curve, is shown in Fig. 2. The light curve is symmetric about the point of maximum brightness, with the rise and decay times being 1.3 and 1.1 sec, respectively (measured relative to an arbitrary LSP count of 3.4). The light curve also clearly displays a flickering effect, with periodic brightness variations being present throughout the entire digitized sequence. The radiometer light curve (in arbitrary units) for the December 13, 2002 Geminid fireball is also shown in Fig. 2. Since the radiometer's response is linearly with brightness, its light curve looks to be vertically "stretched" in comparison to the LSP count light curve. The brightness flickering is clearly present in the radiometer light curve too, and both light curves show a high degree of correlation, with the prominent "peaks and troughs" being temporally concomitant.

We have calibrated the radiometer output, which varies linearly with irradiance, against apparent magnitude by determining its responses to the moon at various phases and to a calibrated light source. We find that:

$$m = -2.5\log(N) - 1.5 \tag{1}$$

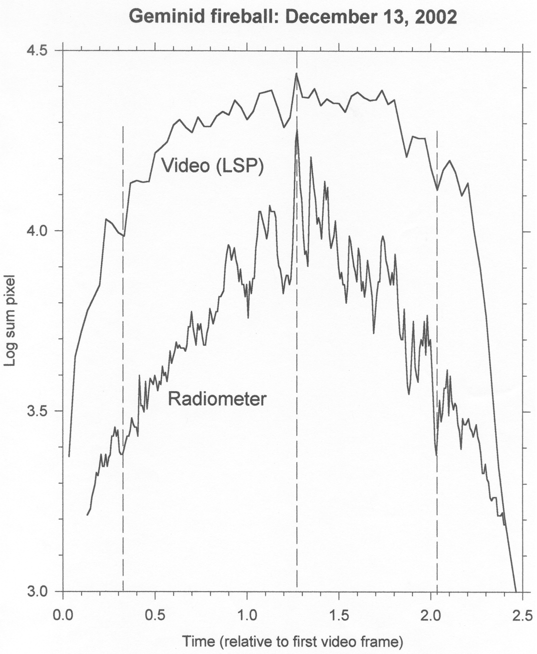

Fig. 2. Light curve of the December 13, 2002 Geminid fireball. The y-axis scale corresponds to the log sum pixel count in the case of the video data but is an arbitrary scale for the radiometer data. The x-axis is time relative to the onset of video analysis. The radiometer data has also been "shifted" on the time axis to achieve temporal agreement between light curve features (as indicated by the three "dotted" vertical lines). A high degree of temporal consistency is in fact evident between the distinctive "peaks and valleys" displayed by the 2 light curves.

where *m* is the apparent magnitude and *N* corresponds to the radiometer measure. The maximum radiometer response to the December 13, 2002 Geminid fireball indicates that it achieved a peak apparent magnitude of −8.3 ± 0.3.

The photometric mass of the December 13, 2002 Geminid meteoroid may be estimated by assuming that the time varying intensity, I(t), as measured by the radiometer, is proportional to the rate of change of the meteoroid's kinetic energy. In this fashion, the mass is proportional to the area under the observed light curve. If we assume that the deceleration of the parent object is negligible (see below), then the mass is related to the intensity through the integral relationship:

$$\mathrm{mass(kg)} = \frac{2}{\tau V^2}\int I(t)dt \tag{2}$$

where V is the meteoroid velocity at the top of the atmosphere and τ is the luminous efficiency. Like Halliday (1988), we take the luminous efficiency to be 0.034 (also see below). Before the mass can be extracted from the data, we convert the radiometer measurements to absolute units. To achieve this, we first note that the energy flux of a zero magnitude A0V star is 3.908×10^{-9} W/m^2 over the wavelength range 6.7

$\times 10^{-7}$ to 3.7×10^{-7} m (Cox 2000). At a range of 100 km, this zero magnitude flux corresponds to a luminosity of L_{100} = 491.09 Watts and, consequently, we have $I(t) = L_{100}\,10^{-0.4M(t)}$, where *M(t)* is the time varying absolute magnitude. The conversion to absolute magnitude is $M = m - 5\mathrm{Log}(R/100)$, where *R* is the range in kilometers. We do not have actual beginning and end heights for the December 13, 2002 fireball. However, since the fireball's angular velocity can be estimated from the video data and because the fireball's angular distance from the Geminid radiant can de deduced from the known time of the event, the initial range may be estimated. A fireball's angular velocity may be expressed as (see, e.g., Gural 1999)

$$\omega(\mathrm{deg./s}) = (57.296)\frac{V\sin(D_{rad})\sin\varphi_B}{H_B} \quad (3)$$

where *V* is the meteoroid's velocity (36 km/s in the case of the Geminids), D_{rad} is the angular displacement of the fireball from the Geminid radiant, φ_B is the fireball's altitude at its beginning point, and H_B is the beginning height. The time of the event fixes the altitude of the Geminid radiant to be 48.5 degrees, and the video data indicate $\omega \sim 4$ deg./s. Hence, the implied beginning height for the onset of video observations is some 85 km, which in turn indicates an initial range of $R = H_B/\sin(\varphi_B)$ = 190 km. The uncertainty in our altitude measurements implies a range error of some ±20 km. Since the fireball is traveling towards the camera as it descends through the atmosphere, the range at the end point is determined to be of the order of 110 ± 20 km. With these estimated ranges, we apply an average correction of −0.9 to the radiometer apparent magnitude data to obtain the absolute magnitude. We may now evaluate the integral in Equation 2 and, consequently, derive a mass of 0.429 kg for the December 13, 2002 meteoroid. Table 2 is a comparison between the characteristics of the December 13, 2002 Geminid and those Geminids of similar duration and maximum brightness analyzed by Halliday (1988). The mass we deduce for the December 13, 2002 Geminid meteoroid is consistent with Halliday's results to within an order of magnitude.

The equation for the mass determination is based on the assumption that the deceleration term, dV/dt, of the meteoroid is negligible. For an object penetrating as deeply into the atmosphere as the December 13, 2002 Geminid, the assumption of zero deceleration is certainly not valid. However, since we have no direct data on range, height, and velocity, we cannot sensibly correct for the deceleration. In addition to the uncertainty in the deceleration term, some uncertainty also exists as to what value of the luminous efficiency term to use. We have adopted the value given by Halliday (1988) but note that luminous efficiency terms in the range of 0.01 to 0.15 have been used by various authours at other times in other studies (see, e.g., Ceplecha et al. 1998 and more recently, Brown et al. 2002). A luminous efficiency of $\tau = 0.034$ for Geminid meteors was presented by Halliday (1988) on the basis that the photometric and dynamic masses of the Geminid fireballs that he studied should be equal. The photometric mass (as evaluated in Equation 2) is inversely proportional to the luminous efficiency, while the dynamical mass, which is derived from measured fireball decelerations, is proportional to the inverse square of the meteoroid density. Halliday's assertion, therefore, not only "sets" the value of the luminous efficiency but also dictates that the density of Geminid meteoroids should be on the order of 1000 kg/m^3. Halliday estimates that a range of $0.02 < \tau < 0.06$ is allowed by the data, and this implies a possible density range of $700 < \rho\ (\mathrm{kg/m^3}) < 1300$ for Geminid meteoroids. Given all of the uncertainty factors, we would suggest that our mass estimate for the December 13, 2002 Geminid is perhaps in error by as much as ±0.15 kg.

Both light curves shown in Fig. 2 display low amplitude brightness modulation or flickering. The calibrated radiometer light curve yields a maximum modulation of about 0.1 magnitudes. The small amplitude oscillations are interpreted in this study as being due to the rotational modulation of the ablation process. Specifically, the periodic variation in the cross-section area presented by an aspherical meteoroid to the on-coming airflow modulates the ablation mass loss (see Beech and Brown 2000).

Although we adopt the interpretation that flickering is due to the rotation of an aspherical meteoroid, other mechanisms for producing the flickering phenomenon have been suggested. Rinehart et al. (1952) have, for example, argued that flickering might result from the periodic, back

Table 2. Comparison between the December 13, 2002 event and the comparable brightness Geminid fireballs studied by Halliday (1988). Column one identifies the specific fireball, with the numbers referring to the MORP catalogue. The second column gives the photometric mass in kilograms, and the fireball duration is given in column three. The fourth and fifth columns provide the zenith distance of the radiant and the absolute magnitude at maximum brightness.

Identification	Mass (kg)	D (sec.)	Z_R (deg.)	M
Dec. 13, 2002	0.429	2.3	41.5	−9.2
#271	0.180	2.2	58.6	−8.0
#274	0.310	1.6	21.5	−9.4
#524	0.120	1.8	22.8	−8.0
#638	0.600	1.8	18.0	−9.9
#841	0.750	3.36	66.5	−9.5
#985	0.490	1.8	60.0	−9.3

and forth, yawing of a non-spherical meteoroid as it moves through the atmosphere. This mechanism essentially requires that the meteoroid undergoes ablation during orientated flight, and this in turn requires that the meteoroid is spinning. So again, meteoroid rotation is important, but in this case, transverse rotation, as opposed to tumbling rotation, needs to be invoked. About 5% of stone meteorites show evidence for having undergone orientated flight (Bronshten 1995), and the Rinehart et al. (1952) mechanism may well apply to the fireballs associated with such meteorites. Thuillard (1996) has alternately suggested that flickering is the result of a downstream instability developing in the airflow behind a meteoroid. While this mechanism does not invoke rotation per se, it does require that a laminar flow region develop above the boundary layer where the ablated meteoroid material encounters the impinging airflow. One potential problem with this model, however, is that no apparent limiting mechanism exists. All meteoroids that descend low enough into the Earth's atmosphere should display flickering, and this is observationally not the case (see the discussion below as well as Beech and Brown [2000]). Getman (1993) has suggested that flickering might be associated with explosive fragmentation and invokes the rotation of an aspherical, compositionally non-homogeneous meteoroid as the modulating mechanism. A variable fragmentation model in which clusters of very small grains are ejected from the parent object has recently been employed by ReVelle and Ceplecha (2002) to describe the flickering variations recorded for the Innisfree meteorite dropping fireball. But, while they can nicely "reproduce" the Innisfree light curve, ReVelle and Ceplecha offer no physical explanation for the observed 2.5 Hz flickering modulation. To conclude this discussion, clearly, at a basic level, meteoroid rotation is an important part of the flickering phenomenon, but the continued study of other modulating mechanisms is warranted. For the time being, we choose to work with the model in which the flickering is produced via the rotation of an aspherical meteoroid because rotation appears to encapsulate, in a straightforward fashion, the basic physical principles of the phenomenon.

To first order approximation, the flickering amplitude will vary as $\Delta m = 2.5\log(a/b)$, where *a* and *b* are the semi-major and semi-minor axes of the spinning meteoroid (assumed to be ellipsoidal in profile). To produce an amplitude modulation of 0.1 magnitude, as observed for the December 13, 2002 Geminid, an axes ratio of $a/b = 1.1$ is required. In this sense the rotational model suggest that the Geminid meteoroid need not have been greatly elongated to produce the observed flickering modulation. By way of comparison, Beech (2001) found that an axes ratio of $a/b \approx 2$ was required to explain the flickering modulation observed in the light curve of the Innisfree meteorite-dropping fireball. And, likewise, the Geminid fireballs studied by Babadzhanov and Konovalova (1997) showed large 0.5 to 0.75 magnitude flickering variations, indicative of meteoroids with axes ratios on the order of 1.6 and 2.0 respectively.

A discrete Fourier transform analysis of the radiometer light curve has been performed, and the power spectrum is shown in Fig. 3. A number of distinct "peaks" are evident at 2.4, 2.8, 3.7, 4.6, and 6.0 Hz. We find that the first 4 terms account for the light curve's basic profile and that the 6.0 Hz term describes the flickering modulation. A similar analysis of the video image light curve reveals a dominant flickering frequency of 7 Hz. The Fourier analysis confirms the expectation from simply counting the number of flickering oscillations per second as portrayed by the light curves shown in Fig. 2. We conclude, therefore, that in terms of the rotational modulation model, the December 13, 2002 Geminid fireball entered the Earth's atmosphere spinning at a rate of something like 6 rotations per second.

No clear indication exists of any dramatic spin-up of the December 13, 2002 Geminid as it descended to lower altitudes. Some indication exists of a weak 8.5 Hz term in the power spectrum (Fig. 3) suggestive of slight spin-up, but all in all, the flickering frequency appears to have remained remarkably constant. Spin-up has been observed to occur for other Geminids (Halliday 1963; Babadzhanov and Konovalova 1997), and Beech (2002) has argued that this relates to an interaction with the oncoming airflow. This being said, other non-Geminid fireballs have shown a near constant flickering frequency throughout their atmospheric flight (e.g., the 4 Hz, $\Delta M \approx 0.25$ flickering observed in the light curve of the Leutkirch fireball described by Ceplecha et al. [1976]). If spin-up is related to the asphericity of a meteoroid, the near constant

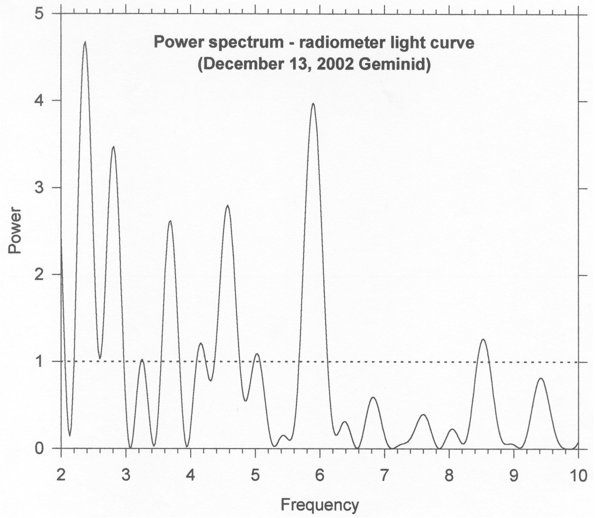

Fig. 3. Power spectrum of the radiometeor light curve. Powers less than unity (as delineated by the horizontal dotted line) are not deemed significant. The strongest peak at 2.4 Hz corresponds to the sampled time of the fireball's light curve. The second strongest peak at 6 Hz identifies the basic flickering frequency. The peaks between 2.4 and 6 Hz identify the frequencies of those additional small-amplitude sine terms required to fully reconstruct the light curve's basic profile.

rotation rate of the December 13, 2002 Geminid might be due to its having a semi-major to semi-minor axes ratio close to unity. The apparently large axes ratio Geminids studied by Babadzhanov and Konovalova (1997) were all eventually spun-up to rotational frequencies on the order of 400 Hz.

The lack of significant high frequency terms appearing in the Fourier transform analysis and the distinct absence of a terminal flare and/or major fragmentation in the video sequence of the December 13, 2002 Geminid indicates that it was not spun-up to its rotational bursting limit. The rotational limit, beyond which the meteoroid will be disrupted, is set according to the centripetal force per unit area being greater than the meteoroid's tensile strength. The 6 Hz flickering frequency we deduce for the December 13, 2002 Geminid is notably smaller than the order of 40 Hz initial flickering frequency derived for the Geminids studied by Halliday (1963) and Babadzhanov and Konovalova (1997). This is not too surprising, however, given that the December 13, 2002 Geminid was some 4 times larger than the Geminids studied by Babadzhanov and Konovalova. Here, we simply assert that under the same prevailing conditions, a small mass (size) meteoroid will be spun-up more rapidly by non-isotropic photon scattering after ejection into space than a large mass (size) meteoroid (see below and Beech [2002]). While the December 13, 2002 Geminid was apparently comparable in size to the Geminid studied by Halliday, the latter object was remarkable for its rapid spin-up and eventual rotational disruption.

DISCUSSION

Video image data on 10 Geminid meteors brighter than apparent magnitude −3 has been gathered with the SSFA over the course of the 2001 and 2002 Geminid displays. Of the 10 observed fireballs, 7 showed distinct brightness oscillations. Only the fireball presently under discussion, however, was bright enough to be detected with the radiometer. The limiting magnitude for detection by the radiometer system is estimated to be an order of magnitude of −7. In the time interval from April 2000 to April 2003, the SSFA camera has detected 28 non-shower fireballs brighter than magnitude −3, and of these, just 5 showed distinct brightness variations. In addition, 60 fireballs were recorded during the 2001 Perseid display (Beech and Illingworth 2001a), but none of these showed any distinct signs of flickering. We did, however, find evidence for brightness variations in 11 out of 251 Leonid fireballs recorded during the 2001 Leonid storm (Beech and Illingworth 2001b). These combined data suggest that Geminid fireballs are noteworthy for their ability to display a flickering effect. The percentage of fireballs brighter than magnitude −3 showing flickering appears from SSFA data to be ~70% for Geminids, ~18% for sporadic fireballs, ~4% for Leonid fireballs, and ~0% for Perseid fireballs. Halliday (1988) has also noted that Geminid fireballs are remarkable for their ability to exhibit the flickering effect. In his study, Halliday analyzed 12 Meteorite Observation and Recovery Program (MORP) (see, e.g., Halliday et al. 1996) observed Geminid fireballs and found "about 50% showed distinct flickering." A review of the overall MORP fireball data by Beech and Brown (2000) revealed that some 4% (11 out of 259 fireball events studied) displayed distinct flickering. All but one of the MORP observed flickering fireballs were considered to be sporadic in origin (one was deemed to be from the Northern Taurid meteor shower associated with comet 2P/Encke). The percentage of SSFA observed sporadic fireballs showing flickering is some four and half times greater than that deduced from the MORP survey. Likely, the insidious "quirks" of low number statistics are partly to blame for the higher SSFA flickering statistics. We also note, however, that due to the characteristics of the rotating shutter used in the MORP camera systems, flickering at frequencies smaller than ~15 Hz would not be readily detected. In this sense, the SSFA may be "picking up" an enhanced population of low frequency flickering fireballs not evident in the MORP data. This being said, continued observations with the SSFA data will, we trust, refine our understanding of the flickering rate among sporadic and shower fireballs.

Beech (2002) has suggested that the age of the Geminid stream might be gauged from the initial, that is pre-atmosphere encounter, rotation rates of Geminid meteoroids. The age estimate of the stream is based on the time required to spin-up a meteoroid via non-isotropic photon scattering (Paddack 1969) while it resides in an orbit corresponding to that of the Geminid stream. Our estimate of the mass of the December 13, 2002 Geminid allows for the initial meteoroid to have had a diameter in the range of $0.05 < D(m) < 0.1$, assuming a range of between $700 < \rho(kg/m^3) < 5000$ for the meteoroid density. The density range employed spans that expected of both cometary and asteroidal material, but as we discussed above, with respect to the luminous efficiency, the observations lean toward the meteoroid having a lower density and, hence, a diameter close to 0.1m. Using Equation 1 of Beech (2002), a Geminid meteoroid in the size range just derived could attain a spin rate on the order of 6 Hz in 2500 ± 500 years. This approximate age of the December 13, 2002 Geminid sits nicely within the range of stream age estimates, of between 1000–5000 years, as derived by Hughes (1986), Jones (1982), Gustafson (1989), and Beech (2002).

The parent object to the Geminid stream has long been identified as the observationally transitional object (3200) Phaethon (Fox et al. 1984; Lupishko and Di Martino 1998). By transitional, we mean that the cometary nature of Phaethon is not apparent through the detection of a distinct cometary tail or coma. So, while Phaethon observationally masquerades as an asteroid, cloaked by a dark insulating mantle, its sibling meteoroids are actually composed of cometary material. The deep penetration of Geminids into the Earth's atmosphere (Halliday 1988) and their remarkable ability to withstand high rotation rates without fragmentation is suggestive, however, of an extraordinary constitution. The exceptional qualities of Geminid meteoroid's, even though they are apparently cometary in origin, are possibly related to the intense thermal processing that they must inevitably endure. The Geminid stream has the smallest semi-major axis and perihelion distance of any known meteor shower-producing stream, and with a perihelion distance q(AU) = 0.143, the peak equilibrium blackbody temperature of Geminid meteoroids will be on the order of $Tq(K) \approx 280/\sqrt{(q)} = 740$. Also, the time averaged temperature of $\langle T(K)\rangle \approx (280/\sqrt{a})(1 - e^2/16 - 45e^4/3072) = 226$ for the orbit of the Geminids (with semi-major axis $a = 1.37$ AU and eccentricity $e = 0.89$) is the highest of any known meteor shower-producing stream. Such extreme temperature characteristics, with perihelion "pulsing" at 1.6 year time intervals, acting for potentially several thousands of years, might conceivably result in the loss of volatile elements via sublimation and the constitutional alteration of the meteoroid's binding matrix. In this sense, we suggest that Geminids are "well-baked" cometary meteoroids. Our assertion here being that the exceptional qualities of Geminid meteoroids are a result of post-ejection matrix alteration, and we point to thermal processing as one possible agent for this alteration. Halliday (1988) suggests an alternative scenario to the one just outlined and argues that since Phaethon is an apparently aged comet, the remarkable properties of Geminid meteoroids might relate to the fact that they are derived directly from its insulating mantle. The basic difference between these two scenarios is essentially one of where and when the meteoroid matrix material becomes "baked."

While we do not consider Geminid meteoroids to be monolithic, if one takes a meteoroid of the mass corresponding to the December 13, 2002 Geminid and performs a classical, single-body ablation analysis, it becomes apparent that the mass lost by ablation is not 100% complete. Indeed, using an ablation coefficient of 8.0×10^{-9} s^2/m^2 (as advocated by Halliday [1988]), a zenith angle of 41.5 degrees, and an initial velocity of 36 km/s, we find a residual mass of 0.003 kg for the December 13, 2002 Geminid. While some 99.4% of the original meteoroid mass might well be destroyed during atmospheric ablation, the "classical" calculation raises the possibility that gram-mass "particulate" residue might survive the atmospheric passage of large Geminid meteoroids. Wetherill (1986) raised this very same point with respect to the Prairie Network observed Geminids, although he argued that perhaps 4% of the original meteoroid mass might survive ablation. Wetherill (1986) adopted an ablation coefficient of $\sigma = 5 \times 10^{-9}$ s^2/m^2, which is 1.8 times smaller than the value we used in our calculation. Padevet and Jakeš (1993), on the other hand, advocate even larger values of the ablation coefficient, suggesting that $\sigma = 10^{-8}$ s^2/m^2 might even be appropriate for Geminid meteoroids. With this latter, larger ablation coefficient, the ablation mass loss is on the order of 99.8% complete.

The possibility of finding and recognizing cometary meteorites has recently been discussed in considerable detail by Campins and Swindle (1998). One object, apparently similar in nature to (3200) Phaethon, which they consider as a possible source for cometary material on Earth, is (4015) Wilson-Harrington. Indeed, Campins and Swindle suggest that MORP fireball #498 may have been derived from (4015) Wilson-Harrington. Interestingly, Halliday et al. (1989) further suggest that MORP #498 may have presaged the fall of a carbonaceous chondrite meteorite in the Allan Hills area of mid-Saskatchewan, Canada. The orbit of Fireball #498 is additionally interesting in that Halliday et al. (1990) find 3 other MORP detected fireballs with similar orbital characteristics, perhaps suggestive of their being part of a "meteorite" steam. We note in passing that the light curve of MORP fireball #886, a putative companion to MORP #498, displayed distinctive flickering at a frequency of ~25 Hz (see Fig. 3 of Beech and Brown [2000]). Suggesting what the defining characteristics of any Wilson-Harrington and/or Geminid residue might be is difficult. Campins and Swindle (1998) argue, however, that cometary meteorites would most likely be weak and porous structures, possibly being achondritic, having near solar abundances, and having CHON and anhydrous silicate inclusions.

While the probability is arguably not zero, it is nonetheless highly unlikely that any large Geminid residue will be sampled on the ground. However, although again highly unlikely, the Geminid residue might possibly be sampled by atmospheric collection. In this latter respect, Messenger (2002) has recently discussed, for example, the possibility of collecting and recognizing dust ejected from comet 26P/Grigg-Skjellerup (and 4 other low eccentricity, low inclination short-period comets). Messenger argues that cometary dust from comet 26P/Grigg-Skjellerup might be recognized on the basis of short space exposure ages, but in the case of the Geminids, one would have to use structural characteristics rather than space exposure age as the identifying discriminant.

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