Earth, Moon and Planets (2005)
DOI 10.1007/s11038-005-9033-y

SPECTROSCOPY OF A GEMINID FIREBALL: ITS SIMILARITY TO COMETARY METEOROIDS AND THE NATURE OF ITS PARENT BODY

J. M. TRIGO-RODRÍGUEZ
Institute of Geophysics and Planetary Physics, University of California, Los Angeles (UCLA), 90095-1567 California, USA
(E-mail: jtrigor@ucla.edu)

J. LLORCA
Departament Química Inorgànica, Universitat de Barcelona, Martí i Franquès 1–11, Barcelona, 08028 Spain and Institut d'Estudis Espacials de Catalunya, Gran Capità 2–4, Barcelona, 08034 Spain

J. BOROVIČKA
Astronomical Institute, Academy of Sciences, Ondrejov Observatory, Ondrejov, 25165 Czech Republic

J. FABREGAT
Observatori Astronòmic, Universitat de València, Paterna, València, 46980 Spain

(Received 13 October 2004; Accepted 30 May 2005)

Abstract. A detailed analysis of a photographic spectrum of a Geminid fireball obtained in December 14, 1961 at the Ondrejov Observatory is presented. We have computed a synthetic spectrum for the fireball and compared it with the observed spectrum assuming chemical equilibrium in the meteor head. In this way we have determined relative chemical abundances in meteor vapors. Comparing the relative chemical abundances of this Geminid meteoroid with those obtained from meteoroids associated with comets 55P/Tempel-Tuttle and 109P/Swift-Tuttle we found no significant chemical differences in main rock-forming elements. Despite of this similarity, the deepest penetration of the Geminid meteoroids and their ability to reach high rotation rates in space without fragmentation suggest that thermal processing is affecting their physical properties. We suggest that as consequence of space weathering a high-strength envelope is produced around these particles. In this picture, heating processes of the mineral phases could result in the peculiar properties observed during atmospheric entry of the Geminid meteoroids, especially their strength, which is evidenced by its resistance to ablation. Finally, although one meteoroid cannot be obviously considered as representative of the composition of its parent body, we conclude that 3200 Phaethon is able to produce millimetre-size debris nearly chondritic in composition, but the measured slight overabundance of Na would support a cometary origin for this body.

Keywords: Asteroid 3200 Phaethon, fireball, Geminid, meteor spectrum, meteoroid

1. Introduction

3200 Phaethon was discovered by the Infrared Astronomical Satellite (IRAS) in 1983 (Green, 1983). Since then, the nature of this Apollo object has been debated vigorously: is it an extinct comet or an asteroid? Initially, some authors classified 3200 Phaethon as a S-type asteroid in basis to reflectance spectroscopy (Cochran and Baker, 1984; Belton et al., 1985). However Veeder et al. (1984) did not confirm these first results, and remarked that the object was extremely blue. Higher resolution spectra obtained with the near-infrared spectrograph KSPEC revealed a dust continuum similar to the reported for several comets like 2060 Chiron and P/Schwassmann-Wachmann 1 (Dumas et al., 1998), and no evidence of cometary degassing has been obtained up to now (Chamberlin et al., 1996; Campins et al., 1999). The surface properties of minor bodies can be modified by space weathering and/or due to the presence of regolith. Both effects make extremely difficult the detection of extinct cometary nuclei although the possible cometary nature of some asteroids has been suggested and is currently debated (Flynn, 1989; Lodders and Osborne, 1999). The presence of a dense meteoroid shower associated clearly with Phaethon has been seen as a good example of how Meteor Science can bring interesting information about Solar System bodies (Whipple, 1983; Hunt et al., 1985; Williams and Wu, 1993). In fact the extraordinary similarity between Phaethon's orbit and Geminid meteoroids is difficult to controvert (Williams and Wu, 1993), being the densest known annual meteoroid stream intercepting the Earth. Phaethon's meteoroids intercept the Earth's orbit in December and their radiant is projected on the constellation of Gemini. The Geminid meteor shower reaches a maximum zenith hourly rate in excess of 100 around December 13 each year. Usually this shower displays activity during 10 days having the unusual property that the peak activity occurs only a day or so from the end of the display. Gustafson (1989) concluded that the conditions for meteoroid transference from Phaethon to the Geminid stream are those expected from cometary activity. Later Williams and Wu (1993) deduced that meteoroids ejected from Phaethon more than 1000 years ago could have evolved under planetary perturbations and radiation pressure into Earth-crossing orbits. They confirmed that Phaethon is the largest remnant of the parent body of the Geminid stream, but they were unable to shed light on whether Phaethon released these meteoroids under a cometary or asteroidal behaviour. Despite this, cometary ejection seems a better approximation when comparing the model and the observed orbital and physical properties of the meteoroids (Halliday, 1988). The Geminid meteoroid stream is rather unusual in having a short orbital period of 1.57 years and a semimajor axis of only 1.35 A.U. These orbital characteristics confer on this stream a relative stability, free from important gravitational effects from the outer planets. We analyse here one grating spectrum of a Geminid fireball registered in the Ondrejov Observatory (Czech Republic) in 1961. Meteor spectra from this stream are rare because the amount of meteoroids with masses producing luminous meteors to be imaged by spectrographs is more restricted that in the case of other meteor showers. Using the method developed by Borovička (1993) we have derived the relative chemical abundances from the meteor column in order to compare this meteoroid to others coming from streams associated to comets. Some interesting similitudes with cometary meteor spectra are found, thus supporting the cometary nature for 3200 Phaethon.

2. Observations and Data Reduction

The Geminid spectrum (GEM) was obtained on 14 December 1961 at the Ondrejov Observatory (Czech Republic) at 2h47m34s UTC. The trajectory data and orbital elements compared to the average Geminid stream and the Phaethon parent body are given in Tables I and II. The dispersing element used was a diffraction grating with 600 grooves/mm. The camera focal length was 360 mm and the focal ratio 1:4.5. The spectrograph was equipped with a 18 × 24 cm AGFA 100 photographic plate. The original spectral plate was measured in detail, dividing the fireball in different scanning paths for a same height on the atmosphere, using a two-axis microdensitometer at the Ondrejov Observatory. The camera plate was also scanned along the diffraction hyperbola since long meteor paths can be out of the optical axis of the camera (Ceplecha, 1961). In order to obtain such detailed scanning, the microdensitometer included a rotation slit for keeping the measured signal

TABLE I
Trajectory of the Geminid fireball

Trajectory data	
Beginning height (km)	96.3
Ending height (km)	56.7
Absolute panchromatic magnitude	(−5.1)
Initial velocity (km/s)	37.8
Ending velocity (km/s)	26.8
Geocentric Radiant (1950.00)	$\alpha = 113.82 \pm 0.28°$
	$\delta + 33.54 \pm 0.11°$
Zenithal angle (z_R)	24.4°

TABLE II

Main orbital elements of the meteoroid that produced the GEM fireball compared with the averaged Geminid stream and the 1983TB Phaethon parent body

Orbital elements (1950.00)	GEM	Geminids	(3200) Phaethon
Semimajor axis (A.U)	1.674 ± 0.036	1.36	1.27133
Eccentricity	0.9168 ± 0.0020	0.896	0.890156
Perihelion distance (U.A)	0.1394 ± 0.0022	0.142	0.139844
Argument of perihelion (°)	322.63 ± 0.39	324.3	321.8207
Longitude of the Ascending Node (°)	262.7347 ± 0.0007	261.0	265.5874
Inclination (°)	28.51 ± 0.44	23.6	22.102

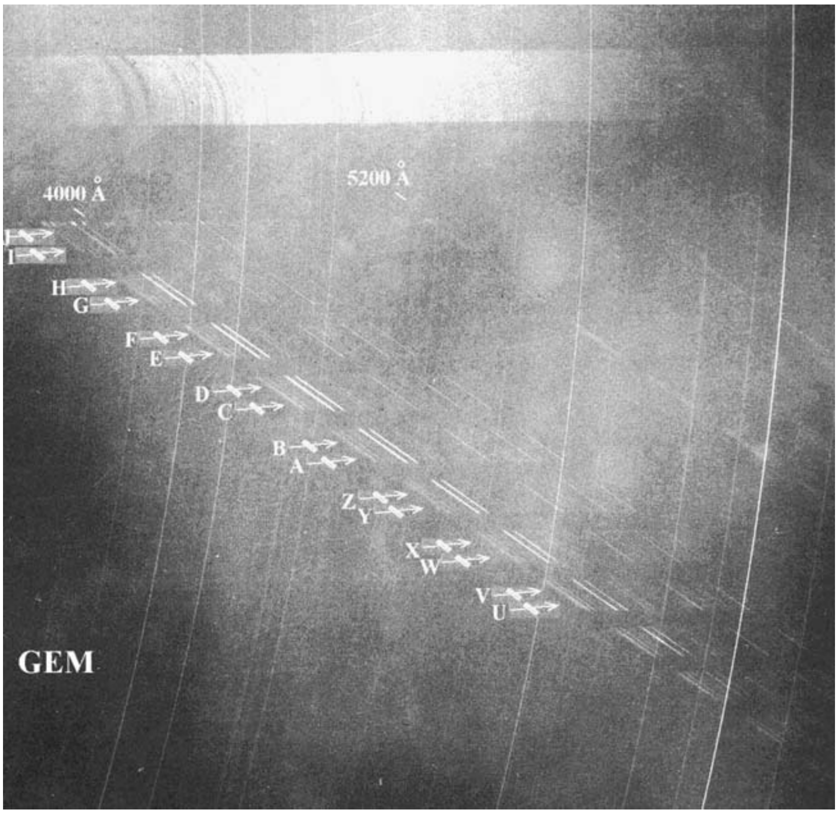

Figure 1. The original spectrograph contained the spectrum of the Polaris star (on top in the second order). The Geminid spectrum appears below showing the different scanned paths (segments) taken in order to determine the physical parameters and chemical abundances along the path.

window parallel to the meteor path. The slit dimensions were adapted to the apparent size of the brightest lines. The spectrum was scanned twice per segment. The exact location of the scans was marked on photographs as it is shown in the GEM spectrum (Figure 1). Letters named in growing and decreasing order designed scans. All the spectral analyses and scans are available in Trigo-Rodríguez (2002). The photometric signal was carefully calibrated according to the relative spectral sensitivity of the spectrograph. The wavelength scale for each spectrum was determined by means of known lines in the spectrum (Borovička, 1993). Plate sensitivity at each wavelength was obtained by studying the bright and detailed spectra of the Polaris star that was recorded in the same plate as the spectrum GEM as was previously described in Trigo-Rodriguez et al. (2003). Briefly, the linear part of the characteristic curve of the plate GEM was constructed by scanning the zero order spectra of all stars recorded, excluding the red and variable stars. Then the first and second order of the Polaris spectrum was scanned. The wavelengths scale was determined by means of known emission and absorption lines in the stellar spectrum. In order to relate the instrumental lengths to wavelengths, a polynomial adjust of degree 3 was used. The real energy distribution of the Polaris spectrum was calculated using the Kurucz (1991)

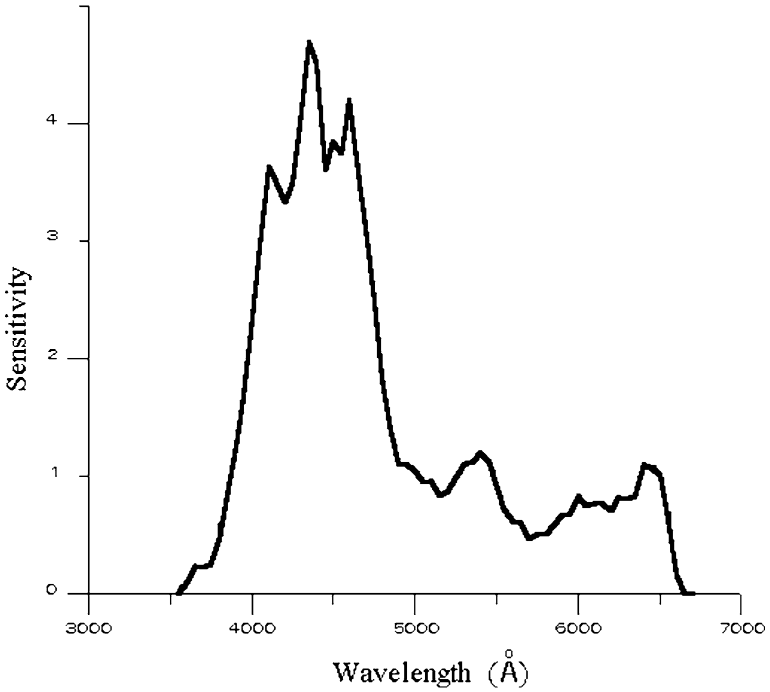

Figure 2. Spectral sensitivity of the AGFA 100 photographic plate. Adapted from Trigo-Rodríguez et al. (2003).

atmosphere models implemented within the DIPSO package of the Starlink software collection (Howart et al., 1996) such as is described in more details in Trigo-Rodríguez (2002) and Trigo-Rodríguez et al., (2003). Such spectrum model of Polaris was compared with the first and second order spectra recorded on the original plate, and transformed into the relative spectral flux by means of the characteristic curve. The ratio of both yielded the relative spectral sensitivity function that provides us the plate response for each wavelength (Figure 2).

The GEM spectrum has a resolution of 78 Å/mm although the low luminosity of the fireball (approximately $M_{\mathrm{p}}=-5.1$ at the maximum light) makes difficult to identify lines of minor chemical elements on the plate. Despite of this, the analysis allowed us to determine the relative abundance of Ca, Mn, Fe, Mg, Na and Cr.

3. Physical Analysis and Relative Chemical Abundances

The GEM spectrum was analysed at the scanning paths marked in Figure 1. To obtain the relative chemical composition of the Geminid meteoroid we used the geometrical model of the meteor developed by Borovička (1993). The radiating volume is treated as a prism with square base and elongated in the direction of the meteor flight following the procedure described in Trigo-Rodríguez et al. (2003). Assuming thermal equilibrium, the brightness of the spectral lines is computed by adjusting four parameters: temperature (T), the column density of atoms (N), the damping constant (γ) and the surface area (P). We used the software developed by Borovička (1993) that uses the least square method in order to reconstruct a synthetic spectrum by direct comparison with the Geminid spectrum in the different scanned segments of the trajectory (see e.g. Figure 3). When the best fit is reached, the determination of the four previously mentioned physical parameters is completed. As most lines in the spectrum are of neutral iron, consequently Fe I is taken as a reference element to adjust the intensity of lines and temperature. One time T, γ and P have been estimated the software allows changing the column density (N) of any element. In order to obtain the chemical composition in the meteor column is fundamental to consider the degree of ionization of the different elements, taking into account the ratio of neutral, singly and doubly ionized atoms given by the Saha equation (Borovička, 1993; 1994a, b). Following this procedure the effective excitation temperature of the main component gas was determined with an estimated precision of ± 100 K. The high temperature component of the spectrum was weak, but can be adjusted to a temperature of 9500 ± 500 K.

The temperature of the main component was found to be typically between 4200 and 4300 K, but a short peak in J and L segments was reached

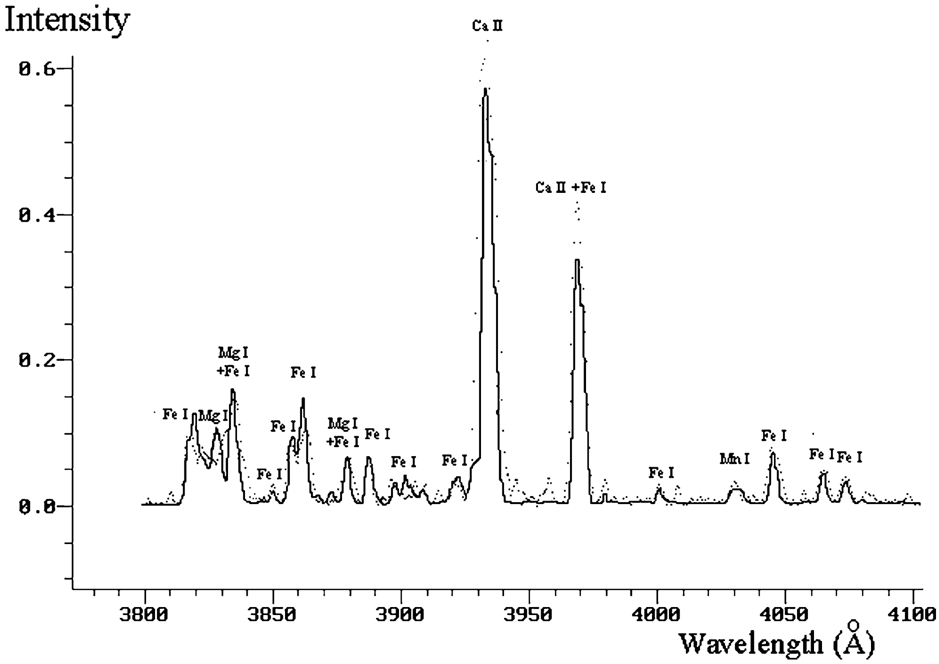

Figure 3. Observed spectrum (dotted line) and the synthetic one (continuous line) obtained from the determination of physical parameters following the method explained in the text. This spectrum corresponds to segment d in the interval of wavelength 3800–4100 Å where the main elements contributing to the lines are identified. The synthetic spectrum is the sum of lines coming from the main and the second component, respectively at 4200 and 9500 K.

with a maximum of 4500 K. Such range of temperatures is below the associated with the ablation column of higher velocity meteors such as Perseid and Leonid (Borovička and Betlem, 1997; Borovička and Jenniskens, 2000). The main differences between a Perseid and the Geminid spectrum are shown in Figure 4. In the brightest scanned segments (I, J and LL) the ratio of the mass ablation products involved in the production of both spectral components was estimated. In order to do this, we estimated the ratio of the number of iron atoms contributing to both components. We obtained in the brightest segments the mass ratio between the main component and the high temperature component to be 20. The contribution of the second component is lower in the beginning of the meteor where $m_1/m_2 \approx 50-100$. It can be easily explained because the amount of ionised Fe is lower when the meteoroid goes trough atmospheric layers where the density is lower and, consequently, the probability of a collision producing ionised products is also lower.

The temperature and chemical abundances relative to Fe for the different scanned segments are given in Table III. The abundance of Mg is between the expected for Interplanetary Dust Particles (IDPs) and for CI chondrites

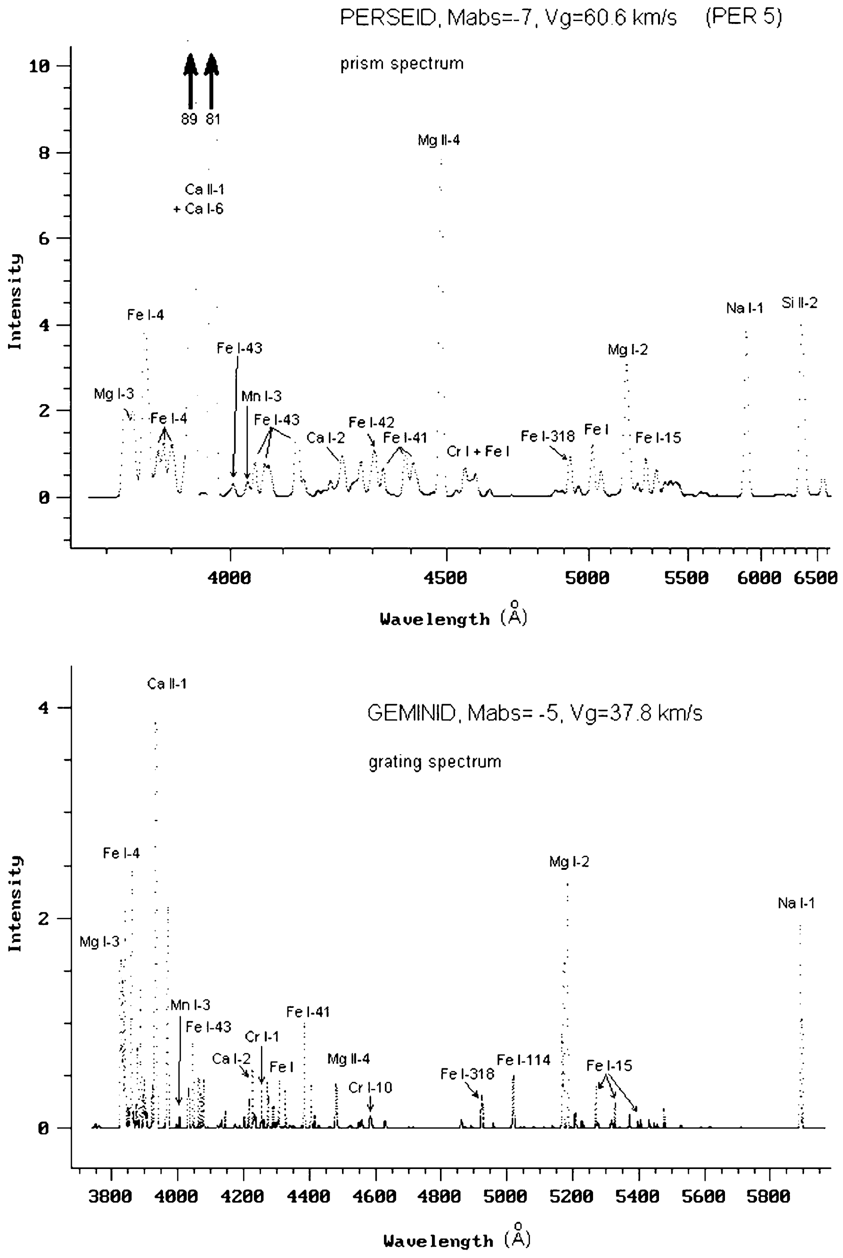

Figure 4. Comparison between the intensity of spectral lines of a Perseid fireball (PER 5) with the exhibited by the Geminid fireball in segment B. The lines belonging to the high temperature component are weak in the Geminid spectrum as a consequence of its lower geocentric velocity. Both spectra were analysed in (Trigo-Rodríguez, 2002).

TABLE III

Relative chemical abundances relative to Fe for the different segments analysed of the Geminid spectrum

Segment	Magnitude ±1	$T \pm 100$ (K)	Ca ($\times 10^{-3}$)	Mn ($\times 10^{-4}$)	Mg	Na	Cr ($\times 10^{-4}$)
A	−4.6 ± 1.0	4200	22	78	1.21	0.09	43
B	−4.8	4200	25	76	1.06	0.10	100
C	−4.3	4200	34	47	1.07	0.13	53
D	−4.3	4200	7	31	1.21	0.07	52
E	−4.8	4200	6	46	1.05	0.07	50
F	−5.0	4200	7	16	0.94	0.14	55
G	−5.0	4300	26	63	1.09	0.09	106
H	−4.9	4300	8	34	1.29	0.13	121
I	−5.1	4300	21	49	0.96	0.13	112
J	−5.1	4500	33	82	1.16	0.12	166
Z	−4.9	4200	6	75	0.90	0.14	97
X	−4.7	4200	14	47	0.62	0.10	53
W	−4.3	4200	18	62	0.90	0.07	98
M	−5.0	4300	13	75	1.08	0.09	51
LL	−5.1	4300	15	50	1.14	0.21	59
L	−5.0	4400	28	83	1.16	0.16	115
Average	–	–	18 ± 9	49 ± 18	1.05 ± 0.16	0.12 ± 0.04	83 ± 36
CI	–	–	68	100	1.2	0.07	144
IDPs	–	–	76	238	1.35	0.08	190
P/Halley dust	–	–	120	95	1.92	0.19	170

For more details on the scanned segments see Figure 1. For comparison are given the typical abundances for CI chondrites, Interplanetary Dust Particles (IDPs) and 1P/Halley dust calculated relative to Fe from the original Rietmeijer and Nuth III (2000) data relative to Si.

(Table III). Mn and Cr are little below the expected for chondritic composition probably suggesting that both elements are not contributing completely to meteor light. Differences with 1P/Halley dust are easily explained because Giotto mass spectrometers detected only tiny particles that are not chondritic in composition (see e.g. Rietmeijer, 2002). The Ca abundance change along the trajectory, but its contribution to the meteor light is higher when the temperature increases. Finally, the measured Na abundance is similar to the obtained for other cometary meteoroids producing fireballs recorded with the same type of spectrograph than the present Geminid (Trigo-Rodríguez et al., 2003). In general, the Geminid meteoroid has abundances similar to other cometary meteoroids inside the range of chondritic meteorites and IDPs.

In this Geminid spectrum there is not evidence for FeO or other molecular bands contributing to meteor light. In any case other authors calculated that the contribution of these molecular bands can be important (Alexander and Love, 2001; Alexander et al., 2001; Flynn, 1991; McNeil et al., 2002; Murad, 2001). FeO has also been observed in persistent trails (Jenniskens et al., 2000). Future studies on the contribution of these molecular bands in the determination of chemical abundances are required.

4. Discussion

The mass of the meteoroid producing the GEM spectrum was estimated to be about 4 g (Trigo-Rodríguez et al., 2003). Assuming a chondritic density, this corresponds to a diameter of about 3 mm. Despite of this small size, the observed chemical abundances are typically chondritic (Table III).

The Ca behaviour along the trajectory deserves special discussion. The contribution of Ca to the meteor light increases as function of the temperature as is shown in Table III for the brightest segments (from G to LL). Trigo-Rodríguez et al. (2003) found a clear dependence between the Ca contribution to meteor spectra and the geocentric velocity. Ca is only moderately volatilised in high velocity meteoroids where the temperatures reached are higher than in GEM. The reason is that Ca is present in refractory mineral phases with highest resistance to volatilisation. Assuming that the GEM meteoroid had a chondritic abundance, less of a 25% of the Ca content would be contributing to produce light.

The derived Na abundance suggests that the particle's size is able to preserve mineral phases associated with this volatile element inside the meteoroid. In fact Trigo-Rodríguez et al. (2004) reported recently from meteor spectroscopy that cometary particles producing fireballs are overabundant in Na. Borovička et al. (1999) pointed out that small cometary particles suffer depletion in the Na content. Due to their higher surface-area/volume ratio, sodium-rich phases are more easily exposed to solar radiation heating and solar wind bombardment. Future spectroscopic observations of Geminid meteors and other cometary meteoroids may get insight into the importance of this depletion as function of meteoroid's size.

Cometary particles suffer degradation mainly by three processes: thermal, radiative and collisional (Stern, 2003). The averaged temperature for the Geminid meteoroids along their entire orbit is 226 K, being the highest of any known meteoroid stream intercepting the Earth (Beech et al., 2003). The deepest penetration of the Geminid meteoroids (Halliday, 1988) and their ability to reach high rotation rates without fragmentation suggest that thermal processing is affecting the physical properties of the Geminid meteoroids (Beech et al., 2003).

If the Geminid have a special ablation behaviour, but the chemical composition of the main chemical elements is similar to other cometary meteoroids, perhaps the different behaviour would be explained by the presence of an envelop surrounding the particles. There is no evidence to relate this wrap to organics but if this hypothesis is true, the study of Geminid meteors using high-sensitivity cameras working in the UV and IR would be an interesting astrobiological target. Other possibility would be that space weathering produced such envelope. It would happen from interaction of the particles by solar photons, by particles of the solar wind or by impacts with micrometeoroids. The degradation by radiation induced by photons and by the bombardment of charged particles of the solar wind is expected to be intense in the Geminid orbit. Especially solar and interstellar ultraviolet ($h\nu > 3$ eV) radiation is able to break bonds and induce substantially chemical alteration in cometary surfaces. This kind of radiation can produce significant degradation of the composition of cometary surfaces, promoting surface darkening and devolatilization progressively more severe with dosage, directly proportional to the Sun proximity (Greenberg, 1982; Thompson et al., 1987; Hudson and Moore, 2001). Because of their close proximity to the Sun, 3200 Phaethon experiences a high UV and solar cosmic ray surface dose. The effect of this radiation probably lead to the gradual conversion of the original water-dominated ice matrix to a complex dark surface by formation of long-chain organic polymers (Stern, 2003). In consequence, the higher strength observed in the surface of these meteoroids would be "delaying" the meteoroid ablation until such envelope disappear at the beginning of the trajectory. The main difference with the Na-rich matrix proposed for other cometary meteoroids (Trigo-Rodríguez and Llorca, 2004) is that, due to the particular orbit of the Geminid stream, thermal processing has removed the presence of volatile elements as Na in the processed outer region.

5. Conclusions

From the analysis of the Geminid fireball spectrum, we conclude the following:

(i) The Geminid meteoroid had in general chondritic chemical abundances, but exhibiting a high content in Na characteristic of cometary meteoroids (Trigo-Rodríguez et al., 2004). Despite that Geminid meteoroids are affected by high temperatures in their orbits around the Sun, the analysed spectrum shows that volatile elements as Na can be still preserved inside millimetre-sized meteoroids.

(ii) The depletion of Na and other volatile elements is clearly dependent of the particle's mass. Borovička et al. (1999) remarked that submillimeter cometary particles producing meteors in the video range suffer depletion in the Na content. Due to their higher surface-area/volume ratio, Na-rich phases are more easily exposed to solar radiation heating and solar wind bombardment, being the volatile phases depleted more efficiently.

(iii) To explain the deepest penetration of the Geminid meteoroids and their ability to reach high rotation rates without fragmentation, Beech et al. (2003) suggested that thermal processing is affecting the physical properties of the Geminid meteoroids. If it is true, according to the chemical similitude between GEM and cometary meteoroids, we propose that an envelope compacted by space weathering would be covering the particles. Due to the presence of this high-strength outer region the ablation will occur little bit deeper in the atmosphere than the expected for lower-strength cometary particles.

(iv) Although one meteoroid cannot be obviously considered as representative of the composition of its parent body, the chemical abundances deduced for the Geminid meteoroid support a chemical composition similar to that expected for cometary meteoroids. 3200 Phaethon is able to produce millimetre-size debris nearly chondritic in composition, but the slight Na overabundance would support a cometary origin for this body.

Acknowledgements

The Ondrejov Observatory of Czech Republic provided the meteor spectra and software for data reduction. The authors are grateful for helpful discussions with Dr. Frans J.M. Rietmeijer (University of New Mexico). J.M.T-R. would like to thank the Spanish State Secretary of Education and Universities for a Postdoctoral grant. J.Ll. is grateful to MCYT for a Ramon y Cajal Research Program grant and DURSI (Generalitat de Catalunya).

References

Alexander, C. M. O. D., Boss, A. P., and Carlson, R. W.: 2001, *Science* **293**, 64–68.

Alexander, C. M. O. D. and Love, S. G.: 2001. *LPSC XXXII abstract # 1935*, Lunar & Planetary Institute, Houston TX.

Beech, M., Illingworth, A., and Murray, I. S.: 2003, *Meteorit. Planet. Sci.* **38**, 1045–1051.

Belton, M. J. S., Spinrad, H., Wehinger, P. A., and Wycroff, S.: 1985. *IAU Circ.* **4029**.

Borovička, J.: 1993, *A&A* **279**, 627–645.

Borovička, J.: 1994a, *Planet. Space Sci.* **42**, 145–150.

Borovička, J.: 1994b, *A&A Supl. Ser.* **103**, 83–96.

Borovička, J. and Betlem, H.: 1997, *Planet. Space Sci.* **45**, 563–575.

Borovička, J. and Jenniskens, P.: 2000, *Earth, Moon, Planets* **82–83**, 399–428.

Borovička, J., Stork, R., and Bocek, J.: 1999, *Meteorit. Planet. Sci.* **34**, 987–994.

Campins, H., McCarthy, D., Kern S., Weaver, H. A., and Brown R. H.: 1999, *AAS DPS Meeting* 31, abstract no. 3005.

Ceplecha, Z.: 1961, *Bull. Astr. Inst. Czech.* **12**, 246–250.

Chamberlin, A. B., McFadden, L. A., Schulz, R., Scheleider, D. G., and Bus, S. J.: 1996, *Icarus* **119**, 173–181.

Cochran, A. L. and Baker, E. S.: 1984, *Icarus* **59**, 296–300.

Dumas, C., Owen, T., and Barucci, M. A.: 1998, *Icarus* **133**, 221–232.

Flynn, G. J.: 1989, *Icarus* **77**, 287–310.

Flynn, G. J.: 1991, in A. W. Harris and E. Bowell (eds.), *Asteroids, Comets, and Meteors*, Lunar and Planetary Institute, Houston, TX.

Green, S.: 1983, *IAU Circ.* **3878**.

Greenberg, J. M.: 1982, in L. L. Wilkening (ed.), *Comets*. Univ. Arizona Press, pp. 131–164..

Gustafson, B. A. S.: 1989, *A&A* **225**, 533.

Halliday, I.: 1988, *Icarus* **76**, 279–294.

Howart, I. D., Murray, J., Mills, D., and Berry, D. S.: 1996, Rutherford Appleton Laboratory Publication.

Hudson, R. L. and Moore, M. H.: 2001, *J. Geophys. Res.* **106**, 33381–33386.

Hunt, J., Kox, K., and Williams, I. P.: 1985, in C.-I. Lagerkvist et al. (eds.), *Asteroids, Comets, Meteors II*, Uppsala University, pp. 549–553.

Jenniskens, P., Lacey, M., Allan, B. J., Self, D. E., and Plane, J. M. C.: 2000, *Earth, Moon, Planets* **82–83**, 429–438.

Kurucz, R. L.: 1991, in D. Philip, L. Upgren and L. Janes (eds.), *Precision photometry Astrophysics of the Galaxy*, Davis Press, Schenectady, EUA.

Lodders, K. and Osborne, R.: 1999, *Space Sci. Rev.* **90**, 289–297.

McNeil, W. J., Murad, E., and Plane, J. M. C.: 2002, in E. Murad and I. P. Williams (eds.), *Models of meteoric metals in the atmosphereMeteors in the Earth's Atmosphere*, Cambridge University Press, Cambridge, UK, pp. 265–287.

Murad, E.: 2001, *Meteoritics Planet. Sci.* **36**, 1217–1224.

Rietmeijer, F. J. M.: 2002, *Chemie der Erde* **62–1**, 1–45.

Rietmeijer, F. J. M. and Nuth, J. A. III: 2000, *Earth Moon Planets* **82–83**, 325–350.

Stern, S. A.: 2003, *Nature* **424**, 639–642.

Thompson, W. R., Murray, B. G. J. P. T., Khare, B. N., and Sagan, C.: 1987, *J. Geophys. Res.* **92**, 14933–14947.

Trigo-Rodríguez, J. M.: 2002. *Spectroscopic Analysis of Cometary and Asteroidal Fragments during their Entry into the Terrestrial Atmosphere*, University of Valencia, Spain, PhD thesis (in Spanish) .

Trigo-Rodríguez, J. M. and Llorca, J.: 2004, *Adv. Space Res.* (submitted).

Trigo-Rodríguez, J. M., Llorca, J., Borovička, J., and Fabregat, J.: 2003, *Meteorit. Planet. Sci.* **38**, 1283–1294.

Trigo-Rodríguez, J. M., Llorca, J., and Fabregat, J.: 2004, *Mon. Not. Royal Astron. Soc.* **348**, 802–810.

Veeder, G. J., Kowal, C., and Matson, D. L.: 1984, *Lunar and Planetary Science XV* abstract 878–879.

Whipple, F. L.: 1983, *IAU Circ.* **3881**, 1.

Williams, I. P. and Wu, Z.: 1993, *Mon. Not. R. Astr. Soc.* **262**, 231–248.