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Material properties of transition objects 3200 Phaethon and 2003 EH_1

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Abstract. Asteroids 3200 Phaethon and 196256 (2003 EH_1) are connected with two major meteoroid streams, Geminids and Quadrantids, respectively. We have modeled the observed light curves and decelerations of Geminid and Quadrantid meteors and studied their spectra. In both cases, we have found typical bulk densities of about 2600 kg m^{-3}, much larger than in cometary meteoroids. Sodium was partially lost from Geminids and Quadrantids due to solar heating. The Quadrantid material was therefore not hidden deep inside the parent body 1500 years ago, when the perihelion was low enough for sodium loss to occur.

Keywords. meteors, meteoroids; minor planets, asteroids

1. Introduction

The close orbital similarity of asteroids 3200 Phaethon and 196256 (2003 EH_1) with the Geminid and Quadrantid meteoroid streams, respectively, leaves no doubt that there is a genetic relation between the asteroids and the streams (Whipple 1983; Jenniskens 2004). Since 2003 EH_1 is on a Jupiter-family-comet type orbit, it could be more easily considered a dormant comet. Phaethon, on the other hand, is on asteroidal orbit in the inner solar system and the origin of this body and of the Geminid stream has been a subject of considerable debate (e.g. Hsieh & Jewit 2005; Ryabova 2007; Licandro *et al.* 2007; Wiegert *et al.* 2008).

In this work, we studied trajectories, light curves, decelerations and spectra of Geminid and Quadrantid meteors. We estimated the likely mechanical properties (in particular porosity), of Geminid and Quadrantid meteoroids and compared them to meteoroids of clearly cometary origin. We also measured the content of volatile sodium, which is diagnostic of meteoroid thermal history.

2. Data analysis

We used the erosion model, which we recently developed and applied to Draconid meteors (Borovička *et al.* 2007). The model assumes that meteoroids are composed of grains, which are gradually released (eroded) during the atmospheric entry. The most important parameters of the model are the height at which the erosion started, the erosion and ablation coefficients, the size distribution of the grains, and the bulk density of the meteoroid. The grains were assumed to be spherical with the density of 3000 kg m^{-3}. In some cases, we needed two stage erosion to explain the data. In that cases, only certain fraction of meteoroid mass was involved in the initial erosion. The rest continued unaffected until (a part of it) was subject to the second stage erosion starting at a lower height.

In contrast to Draconids, Geminids and Quadrantids proved to be too faint before the start of the erosion to be detected. In consequence, the bulk density of the meteoroid

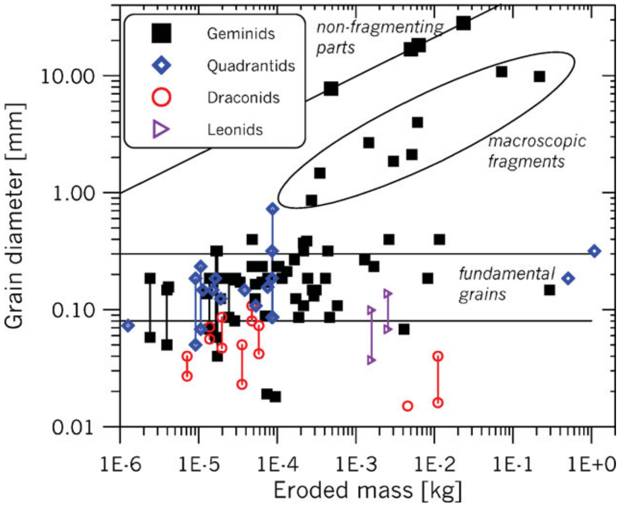

Figure 1. Sizes of grains or fragments in Geminid (full squares), Quadrantid (diamonds), Draconid (circles), and Leonid (triangles) meteoroids.

and the erosion coefficient could not be determined independently from our model. We formally fixed the meteoroid bulk density at 2000 kg m^{-3} and computed the formal erosion coefficient for this value of the bulk density. Since it is reasonable to assume that the energy necessary for the start of the erosion and for grain separation during the erosion is larger for less porous (i.e. more dense) meteoroids, we computed the likely densities of meteoroids (or their parts) from the following empirical formula (calibrated by Draconids):

$$\delta = \delta_{\mathrm{g}} \Big/ \left(1 + 3\,\bar{\eta}\,\frac{10^6}{E_{\mathrm{S}}}\right). \tag{2.1}$$

Here δ_{g} is the grain density, $\bar{\eta}$ is the formal erosion coefficient (units: $\mathrm{s}^2\,\mathrm{km}^{-2} = \mathrm{kg}\,\mathrm{MJ}^{-1}$) for the bulk density fixed at 2000 kg m^{-3}, and E_{S} is the energy received per unit cross-section before the start of erosion ($\mathrm{J\,m}^{-2}$).

We applied the erosion model to 37 Geminid meteors of magnitudes from +4 to −2 observed by image intensified video cameras in 2006. The corresponding meteoroid masses and sizes were 10^{-6} to 10^{-3} kg, and 1 – 10 mm. To extend the analysis to larger bodies, we also analyzed 7 Geminid fireballs (magnitudes −5 to −9, masses 0.01 to 1 kg, sizes 2 – 10 cm) photographed within the scope of the European Fireball Network. For Quadrantids, we used 10 video meteors (+1.5 to −2 mag, 10^{-5} to 10^{-4} kg) and one photographic fireball (−11 mag, 2 kg) observed in 2009. We further analyzed 2 Leonid fireballs observed in 1999, which showed significant deceleration. Draconid data were taken from Borovička *et al.* (2007)

For a majority of video meteors, we also obtained spectra with an additional video camera. The spectra were analyzed for the relative content of magnesium, sodium, and iron in a similar way as we did previously for other meteors (Borovička *et al.* 2005). Spectra were not available for the photographic fireballs.

3. Results

The resulting sizes of grains in various meteoroids are presented in Fig. 1. We tried to fit each meteor data with only one size of grains. If it was not possible, the upper and

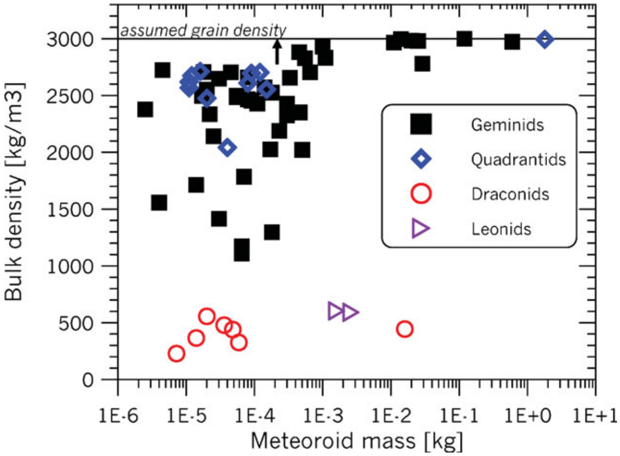

Figure 2. Inferred bulk densities for Geminid (squares), Quadrantid (diamonds), Draconid (circles), and Leonid (triangles) meteoroids. One iron-rich Geminid had much larger density and is not shown.

lower limit of grain sizes, connected with vertical bar, are shown. In cases of two stage erosion, both stages were plotted as independent events.

A majority of grain sizes of Geminids and Quadrantids lies in the range of 80 – 300 μm. This can be considered as the typical size of fundamental grains. Typical grain sizes of Draconids and Leonids are only 20 – 100 μm. In the second stage, some large Geminids did not fragment into grains but into macroscopic pieces of $\sim 1 - 10$ mm. In four cases, a cm-sized parts of the meteoroids did not fragment at all.

The bulk densities, computed according to Eq. (2.1), are plotted in Fig. 2. In cases of two stage erosion, both parts were combined together to compute the density of the whole meteoroid. Typical densities of Geminids smaller than 1 gram is about 2600 kg m^{-3} (porosity 15%), although porous with densities down to 1000 kg m^{-3} ($p = 60\%$) were observed as well. Geminids larger than 1 gram were found to be very compact with bulk densities approaching the grain density. Densities of Quadrantids are similar to Geminid densities, while densities of Draconids and Leonids are much lower, about 500 kg m^{-3}. Babadzhanov & Kokhirova (2009) obtained densities similar to ours for Leonids and Geminids and somewhat lower for Quadrantids.

Sodium was found to be depleted by almost an order of magnitude (relatively to magnesium and chondritic abundances) in Geminids smaller than 10^{-4} kg (Fig. 3). The depletion is lower for 10^{-3} kg Geminids. In Quadrantids, the trend is similar but Na depletion is generally lower than in Geminids.

The Geminid orbit is remarkable by its low perihelion (0.14 AU). The computation of Čapek & Borovička (2009) showed that Na can be lost from Geminids by thermal desorption provided that meteoroids are composed from grains not larger than several hundreds of microns and that the pores between the grains are interconnected. They suggested that variation of Na content in Geminids may be due to varying grain sizes. However, the grain sizes proved to be relatively uniform (Fig. 1). We have found that the Na content in Geminids is correlated with the mean pore size. The smaller pores, the larger content of Na. In cases of two stage erosion, the pore size in the denser part of the meteoroid is important. We have spectra only for two meteors which did not fragment into grains and, expectably, they have high Na content.

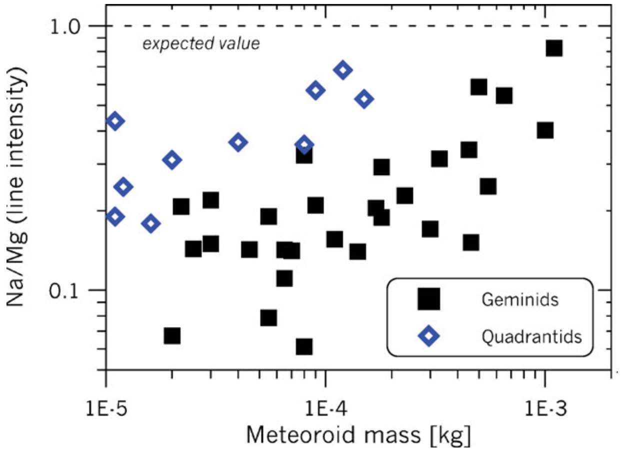

Figure 3. Measured intensity ratio of Na and Mg lines in Geminid (squares) and Quadrantid (diamonds) meteors as a function of meteoroid mass. The expected line intensity ratio for chondritic meteoroid composition is also shown.

The perihelion of Quadrantid orbit is large (0.98 AU) but it was quite small ∼ 1500 years ago (Porubčan & Kornoš 2005). However, the Quadrantid stream can be only 500 years old or even less (Jenniskens 2004; Wiegert & Brown 2005). The fact that there is Na depletion, can be possibly explained by thermal desorption at the surface of the parent body during the low perihelion era.

4. Summary

We have found that Geminid and Quadrantid meteoroids have similar structure. They are composed from grains. The grains are larger than in cometary Draconids. In contrast to Draconids, the porosity is low, typically 10–20%, although it can reach up to 60%. Larger meteoroids (> 1 cm) have macro-porosity lower than 10% and, in case of Geminids, contain compact, non-granular parts. Partial loss of sodium due to solar heating in close vicinity to the Sun occurred in Geminids and, to a lesser extend, in Quadrantids, too. It follows that Quadrantid material was exposed to solar radiation 1500 years ago, i.e. it was not hidden deep inside the parent body at that time.

Acknowledgements

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