Small Geminids are more fragile than large ones

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The Geminids are a very active annual meteor shower, reaching peak activity in mid-December. It differs from other major meteor showers in that its parent is an active asteroid, 3200 Phaethon. Our research focussed on the mechanical properties of the Geminids. Bright and faint fireballs have been observed by the European Fireball Network since 2018, and were modeled by the semi-empirical fragmentation model coupled with an optimiser based on genetic algorithms. The original sample of very bright fireballs has been extended by meteoroids with smaller initial masses, and ultimately we aim to bridge the gap between fireball and faint meteor observations.

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1 Introduction

Detailed modelling of the fragmentation of meteoroids provides insight into their internal structure and also infer the mechanical strength of the material from which they are made. If we model the fragmentation of meteoroids from a meteor shower for which we know the parent body, then these results also describe the properties of the respective comet or asteroid. Therefore, in the current research we focus on the Geminids, whose parent body is an active asteroid, 3200 Phaethon, a target of the DESTINY$^+$ mission of the Japan Aerospace Exploration Agency (JAXA).

2 Data

We have modelled 14 Geminid fireballs observed by the European Fireball Network (Spurný et al., 2007; Spurný et al., 2017). The instrumentation used and the data reduction procedure are summarised in (Borovička et al., 2022). For the modelling, we used a radiometric light curve, an all-sky image photometric light curve, and the dynamics of the foremost fragment. For one Geminid, we also used data from a dedicated observing campaign taken with a video camera equipped with an image intensifier and a 135-mm lens, and with the MAIA camera (Koten et al., 2011).

3 Fragmentation modelling

The classical meteoroid ablation, deceleration, and radiation equations were used in the model extended by two modes of fragmentation. The meteoroid either fragmented into several regular fragments (gross fragmentation) and into immediately released dust grains, causing a short and bright flare. Or it fragmented into one or a few eroding fragments that released dust grains over a longer period of time, causing a gradual brightening.

Regular fragments were allowed to fragment repeatedly, eroding fragments could not undergo a gross fragmentation. All fragments and dust grains ablated separately. Fragmentation times were determined manually, but were later optimised automatically.

The calculation was stopped when the fragment vanished by ablation or erosion, or when its velocity dropped below $2.5\,\mathrm{km\,s^{-1}}$. We calculated the total brightness of the meteor and the length of the foremost fragment along the trajectory and we compared them with the data.

The data optimisation program FirMpik is based on genetic algorithms. It starts with a population of several tens of random solutions and then evolves them. The value of the fitness function is maximised. We use the inverse value of the reduced χ^2 sum of the model fit to the radiometric and photometric light curves and dynamical data of the foremost fragment. Empirical weights are assigned to each dataset.

In the modelling, we used fixed values for the grain density of $\rho_{\mathrm{grain}} = 3000\,\mathrm{kg\,m^{-3}}$ for Geminids (Ceplecha & McCrosky, 1992; Babadzhanov & Kokhirova, 2009), the product $\Gamma A = 0.8$ and the ablation coefficient $\sigma = 0.005\,\mathrm{kg\,MJ^{-1}}$. For the faintest Geminid fireball we allowed a slight change in the value of the ablation coefficient.

We used two different luminous efficiency functions, one for bright and one for fainter Geminids. For the majority of fireballs, we used the same function as (Borovička et al., 2020), which depends on the mass and the velocity of the meteoroid. For some fainter Geminids, we used the velocity dependent function from (Pecina & Ceplecha, 1983), which predicts smaller values of the luminous efficiency than the previous function. The reason for this was that we could not obtain a reasonable fit to both the radiometric light curve and the dynamics at the same time with the former luminous efficiency function. For our calculations, we applied densities from the NRLMSISE-00 atmosphere model (Picone et al., 2002).

For more details on the physical model of meteoroid fragmentation used in this study see (Borovička et al., 2020), the semi-automatic method of modelling is described in (Henych et al., 2023).

4 Dynamic pressure

The mechanical strength of meteoroids and their fragments is proportional to the dynamic pressure exerted on them just before fragmentation. Dynamic pressure is calculated as

$$p = \Gamma \rho_{\mathrm{a}} v^2, \tag{1}$$

where ρ_{a} is the density of the atmosphere at the fragmentation height, v is the velocity of the meteoroid or fragment at the same height, and Γ is the drag coefficient. For plotting, we always set $\Gamma = 1$ to be able to compare different meteoroids, but the actual value of Γ applied in the model is different. The model uses the constant product of $\Gamma A = 0.8$ (Borovička et al., 2020), where A is the shape coefficient. If we assume spherical fragments, $A \doteq 1.21$ and $\Gamma \doteq 0.66$.

In this study, we derive dynamic pressure values for all fragmentation events during the meteoroid's flight through the atmosphere. We also calculate the median and weighted average dynamic pressure in the volume of the whole meteoroid and the pressure at which 50% of the meteoroid mass is already lost by fragmentation (catastrophic disruption). The calculation procedure for all these mean dynamic pressures is described in detail in (Henych et al., 2024).

5 Preliminary results

Figure 1 shows the pressure statistics for 14 modelled Geminids. It includes a minimum dynamic pressure at which the meteoroid began to fragment, three types of mean dynamic pressure values calculated for all fragmenting parts of the meteoroid, and a maximum dynamic pressure reached by the strongest fragment. This is a lower estimate if the fragment reached the maximum pressure value and did not break apart.

6 Discussion

We emphasize that this is a work in progress and the results are preliminary. In the near future, we will model more fireballs and also include fainter meteors observed with intensified video cameras to check the robustness of the result. We also want to calculate the minimum mass of a Geminid meteoroid, for which mechanical forces still play a key role in its fragmentation.

A possible explanation for the observed trend of increasing dynamic pressure of the first fragmentation with increasing mass of the Geminid meteoroid may be consistent with a theoretical prediction (Čapek & Vokrouhlický, 2011; Čapek & Vokrouhlický, 2012). They simulated the evolution of thermal stresses in Geminid meteoroids with three different sizes of 1 mm, 1 cm, and 1 dm and a distribution of tensile strengths. While the population of the smallest meteoroids remained intact, the centimeter-sized population was partially **fragmented** in weaker members, and the decimeter-sized population was even more **depleted**. It follows, that the largest modelled Geminid ($\sim$ 1 dm in diameter) would represent the strongest surviving material of that size. The smallest modelled Geminid ($\sim$ 1 cm) would then represent the partially **depleted** population of Geminids.

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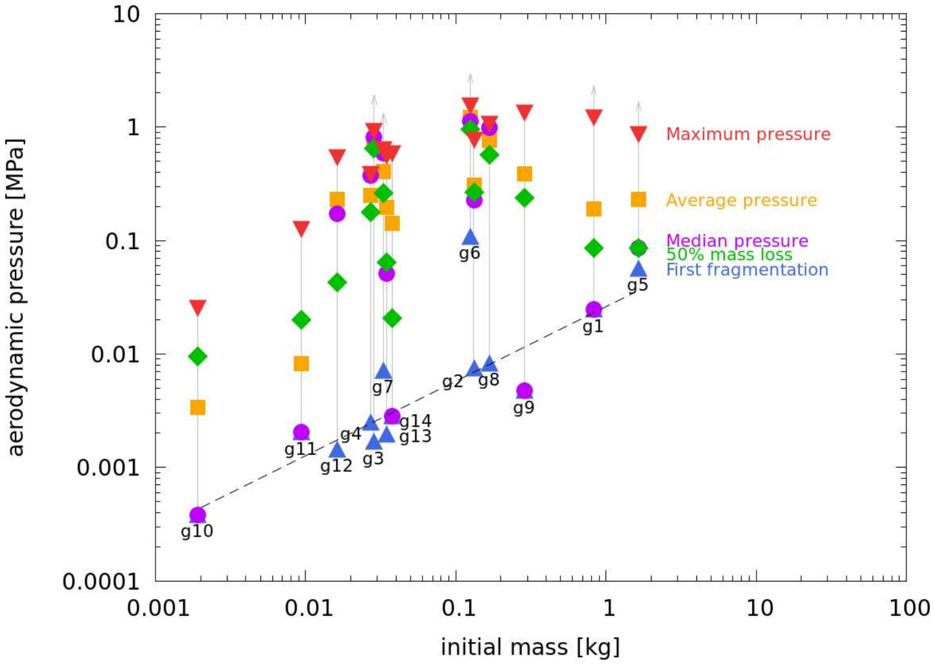

Figure 1 – Dynamic pressure statistics for 14 Geminids versus their initial meteoroid mass. Both axes are logarithmic. The dashed line is a power-law fit to the first fragmentation dynamic pressure. Small gray arrows indicate that the maximum dynamic pressure is a lower limit.