Radiants and orbits of Geminids observed by the European Fireball Network

Jiří Borovička[1] & Pavel Spurný[1]

[1] **Astronomical Institute of the Czech Academy of Sciences, 25165 Ondřejov, Czech Republic**
jiri.borovicka@asu.cas.cz

Precise radiants and orbits of bright Geminid meteors observed by the digital cameras of the European Fireball Network in the recent years are presented. When corrected for the radiant motion, most individual radiants fall within an area of a diameter of one degree. The radiants in the east-south-eastern part of that area belong to meteoroids with smaller semimajor axes and larger arguments of perihelia. We can distinguish a core of the stream with semimajor axes between 1.25 AU and 1.30 AU and a wing with semimajor axes up to 1.39 AU. The core is more concentrated in eccentricities and perihelion distances than the wing. Both core and wing meteoroids are encountered during the whole duration of the shower. The wing contains smaller meteoroids on average. Therefore, an opposite trend than expected from the action of the Poynting–Robertson effect, which decreases semimajor axes of small meteoroids, is present in Geminids, as noted already by (Spurný 1993). We hope that our new observations together with a modeling effort will shed light on the formation and evolution of the stream.

1 Introduction

Geminids is currently the most active annual meteor shower (Rendtel 2019). It an unusual meteor shower with short orbital period (∼1.5 yr) and low perihelion distance (0.14 AU). The parent body of the stream, asteroid (3200) Phaethon, was found to be weakly active near perihelion (Jewitt et al. 2013) and a dust trail was detected in its orbit (Arendt 2014; Battams et al. 2022). Nevertheless, neither the current activity nor the dust trail can explain the total mass of the Geminid stream. It is still not clear, if Phaethon is a regular asteroid moved closer to the Sun, an unusual asteroid, or a former comet currently almost inactive. The age and formation mechanism of the Geminid stream also remain open questions.

The European Fireball Network is a long-term project for photographing bright meteors over central Europe. Currently, Digital Autonomous Fireball Observatories are used at stations in Czech Republic and in Slovakia as well as at one station in Austria. Recently, a catalog of 824 fireballs observed in 2017–2018 was prepared (Borovička et al. 2022a). The catalog also includes 38 Geminids. Their radiant and orbits were analyzed, among other fireballs, in an accompanying paper (Borovička et al. 2022b). When plotting eccentricity against semimajor axis, it was found that there is a core and a wing of the stream. The core has a semimajor axis similar to Phaethon and somewhat lower eccentricity and thus larger perihelion distance than Phaethon. The wing extends from the core to larger semimajor axes and somewhat lower perihelion distances (but with larger scatter).

In this work, we extend the analysis to 66 most precise Geminids observed in 2016–2021. One Geminid from (Borovička et al. 2022a) was not included because of large error bars. The weather was mostly cloudy in all years, nevertheless, there were periods of clear sky at some stations enabling us to collect double-station or multi-station data. The methods of data analysis are explained in (Borovička et al. 2022a). We concentrate on Geminid radiants and the relation between the radiant position, meteoroid mass, and orbital elements.

2 The radiants

First, we studied the motion of the radiant in right ascension and declination. The following dependencies were obtained:

$$\alpha = 113.53 + 1.00(\lambda - 261.8) \quad (1)$$
$$\delta = 32.37 - 0.215(\lambda - 261.8), \quad (2)$$

where α is the geocentric right ascension, δ is the geocentric declination of the radiant, and λ is the solar longitude, all in degrees. No dependence of geocentric velocity on solar longitude was found. The mean geocentric velocity was 34.0 km s^{-1} and all values except one lay in the interval 33.5 – 34.5 km s^{-1}. The single deviating value was 33.14 km s^{-1}.

In order to study the scatter of individual radiants, the radiants were moved to the common solar longitude of 261.8° using Equations (1) and (2). The corrected radiants are plotted in Fig. 1. The radiant area is quite compact; 85% of radiants lie within a circle of diameter of one degree. Radiants of meteoroids larger than 10 grams are even more tightly clustered and their right ascensions tend to be larger.

As shown in Fig. 2, there is also a correlation between radiant position and semimajor axis. Meteoroids with

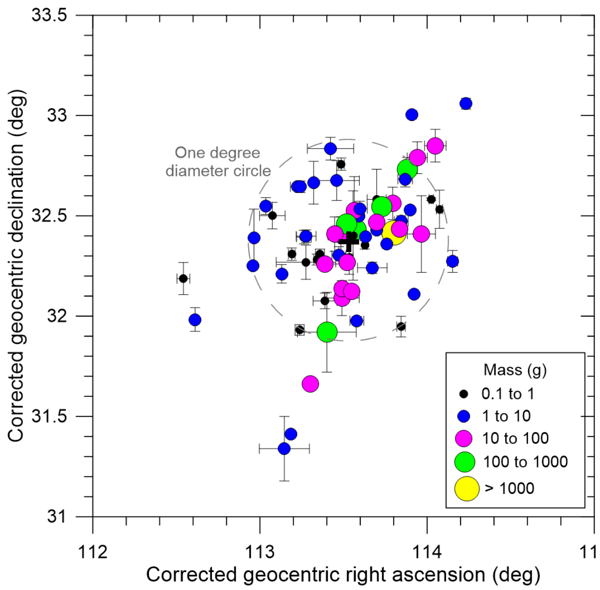

Figure 1 – Geminid radiants corrected for radiant motion to the solar longitude 261.8°. Symbol sizes and colors denote five intervals of meteoroid masses. The dashed circle has a diameter of one degree.

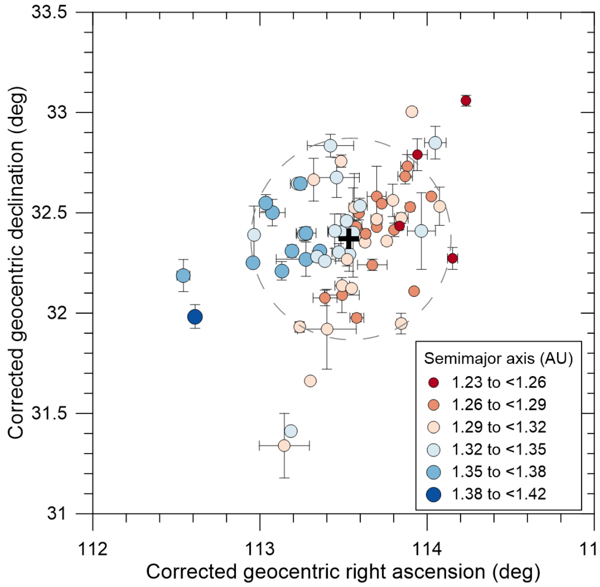

Figure 2 – Geminid radiants corrected for radiant motion to the solar longitude 261.8°. Symbol sizes and colors denote six intervals of semimajor axes. The dashed circle has a diameter of one degree.

lower semimajor axes have larger right ascensions of their radiants, i.e. their radiants are shifted to the east, or perhaps east-south-east, in comparison with meteoroids with larger semimajor axes. This trend was already noted by (Hajduková et al. 2017) in the video data, though the spread of radiants and the extent of semimajor axes was larger in the video data. It was probably caused by a lower precision of the video data, though smaller masses of video-observed meteoroids may also play a role.

There is no obvious trend between radiant position and perihelion distance or eccentricity. Both these quantities occupy a relatively narrow intervals in Geminids. Naturally, similar trend as for semimajor axis is then

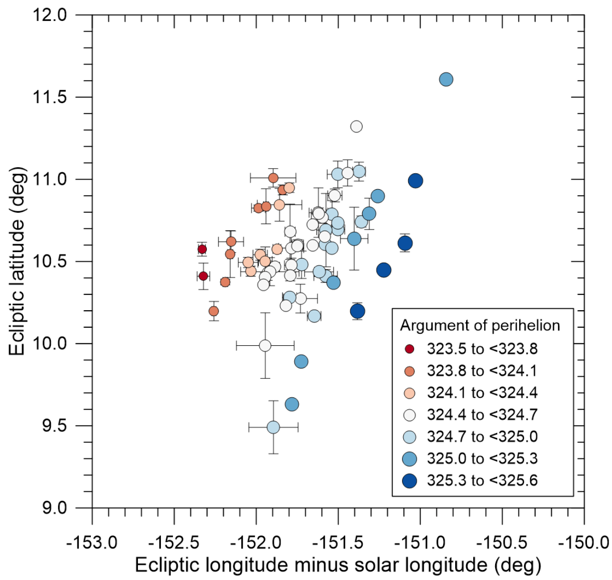

Figure 3 – Geminid geocentric radiants in ecliptic coordinates related to the Sun. Symbol sizes and colors denote seven intervals of arguments of perihelia (in degrees).

observed for the aphelion distance. There is also a trivial correlation between declination of the radiant and inclination of the orbit. Since there is direct proportionality between declination and ecliptic latitude in case of Geminids, radiants with larger declinations belong to orbits with larger inclinations.

It is also possible to plot the radiants directly in Sun-related ecliptic coordinates rather than in corrected right ascension and declination. The plot in Fig. 3 shows correlation between the radiant position and argument of perihelion. As for the semimajor axis, the radiant position in the east-south-eastern direction is correlated with the argument of perihelion. The correlation is even more obvious than in case of semimajor axis. This correlation does not seem to be trivial. The exact meaning of this dependence is, however, not clear at the moment.

Figure 4 shows that the radiant dispersion in ecliptic coordinates is larger before the shower maximum than around the maximum and after the maximum. It must be noted, nevertheless, that while the intervals around and after the maximum cover one day, the interval before maximum is 3.3 days long (our data cover solar longitudes 258.0 – 263.3° and the maximum is supposed to be at 261.8°).

The correlations between radiant position and mass at one side and radiant position and some orbital elements on the other side suggest that there may be a correlation between meteoroid mass and orbital elements. Figure 5 shows the observed values of semimajor axes and arguments of perihelia plotted as a function photometric mass. While small meteoroids occupy wider intervals of orbital elements, the intervals become narrower for larger masses. Large meteoroids have generally smaller semimajor axes and arguments of perihelia near their medium value.

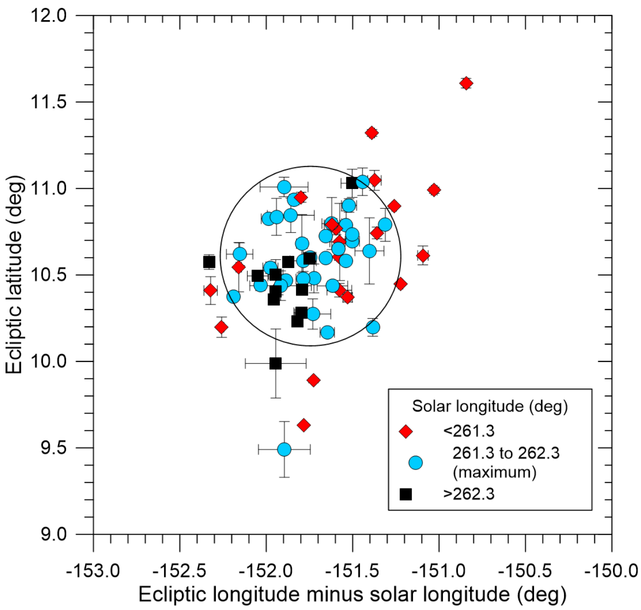

Figure 4 – Geminid geocentric radiants in ecliptic coordinates related to the Sun. Symbol shapes and colors denote three intervals of longitudes of the solar longitude (in degrees). The middle interval corresponds to one day within the shower maximum. The circle has a diameter of one degree.

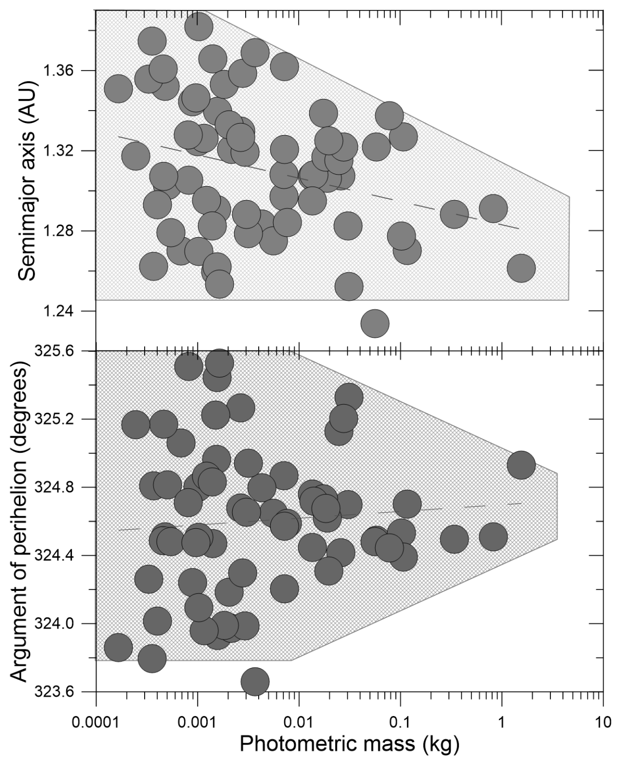

Figure 5 – Semimajor axis and argument of perihelion as a function of photometric mass. The hatched areas shows the decreasing intervals of the values on the vertical axes with increasing mass. The dashed lines are least squares fits to the data.

3 Orbital elements

The plot of eccentricity versus semimajor axis was presented already in (Borovička et al. 2022b). It is repeated here in Fig. 6 with more data. The comparison with model values from (Ryabova 2022) is also provided. (Ryabova 2022) modeled the stream assuming that it

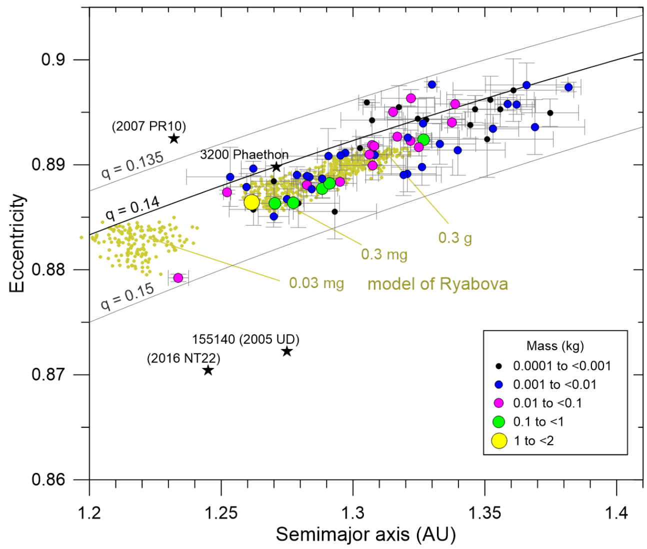

Figure 6 – Eccentricity as a function of semimajor axis. Symbol sizes and colors denote five intervals of meteoroid masses. Model values from (Ryabova 2022) are shown as pale dots with corresponding meteoroid masses labeled. Four near-Earth asteroids, which fall into the displayed range, including Phaethon, are shown as asterisks. Three lines of constant perihelion distance are plotted.

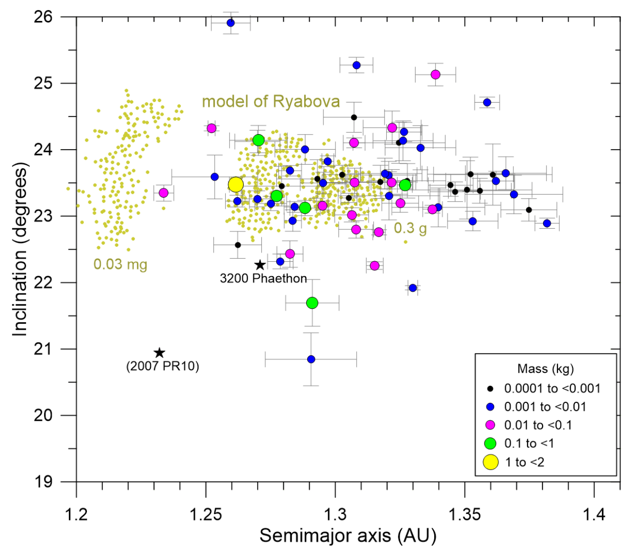

Figure 7 – Inclination as a function of semimajor axis. Symbol sizes and colors denote five intervals of meteoroid masses. Model values from (Ryabova 2022) are shown as pale dots with corresponding meteoroid masses labeled. Two near-Earth asteroids, which fall into the displayed range, including Phaethon, are shown as asterisks.

was formed 2000 years ago by a cometary-like activity of Phaethon during its one orbital revolution. Particles were ejected only from the sunlit hemisphere and the ejection speeds were larger for smaller particles. Only small particles from 3×10^{-5} g to 0.3 g were modeled. That mass range barely overlaps with our mass range (0.2 g – 1.6 kg).

Figure 6 confirms that we can distinguish a core and a wing of the stream. The core meteoroids have semimajor axes in the range 1.25–1.30 AU, similar to that of Phaethon (1.27 AU), and a narrow range of perihelion distances, $\sim 0.143 \pm 0.003$ AU, somewhat larger than that of Phaethon (0.140 AU). The core overlaps well with the model orbits of (Ryabova 2022) for masses 0.3 mg to 0.3 g. The wing meteoroids have larger semimajor axes, up to 1.39 AU, and cover also lower perihelion distances, down to 0.135 AU. The wing consists mostly of meteoroids smaller than 0.1 kg. We stress that the core and the wing are not separated in the longitude of the ascending node. Both core and wing meteoroids are encountered during the whole duration of the shower. The model of (Ryabova 2022) does not reproduce the wing. In particular, no orbits with $a > 1.33$ AU were produced by her model. Moreover, due to Poynting-Robertson drag, the model expects that smaller meteoroids have smaller semimajor axes. But an opposite trend is observed. In this sense, we confirm the observation of (Spurný 1993).

In addition to the core and the wing, we observed one single Geminid with quite small semimajor axis 1.234 AU. Such small semimajor axes were predicted by the model only for the smallest particles of 0.03 mg. But the observed meteoroid had a photometric mass of 56 g.

The plot of inclination versus semimajor axis is in Fig. 7. Most Geminids, both in the core and the wing, have inclinations 23–24.5°, somewhat larger than Phaethon (22.3°) but corresponding with the model of (Ryabova 2022). Larger and smaller inclinations are, nevertheless, encountered as well. The full range is 21–26°.

4 Conclusions

Precise fireball data from the European Fireball Network enabled us to describe previously unresolved or only partly resolved relations among the radiant coordinates and orbital elements of Geminids. It was found that meteoroids with smaller semimajor axes have larger arguments of perihelia and their radiants are shifted to east-south-east in comparison with meteoroids with larger semimajor axes. The orbits with semimajor axes between 1.25 AU and 1.30 AU form what we call the core of the stream. The core is concentrated in perihelion distance and eccentricity, but not in inclination and longitude of the ascending node. The orbits with larger semimajor axes, up to 1.39 AU, form the wing of the stream. The wing is less concentrated in perihelion distance and eccentricity and is not present in the model of the stream. We speculate that it might be formed by an older material. It was also confirmed that in the fireball mass range (10^{-4} to 10^{0} kg), larger meteoroids tend to have smaller semimajor axes. Moreover, the arguments of perihelia of larger meteoroids are closer to the mean value of the stream (324.6°).

The explanation of these facts is currently unknown. Further studies should include obtaining precise orbits of fainter Geminids to extend the observed mass range, modify model assumptions and try to reproduce the observations by modeling, and integrate the most precise orbits backwards to see if they converge at some time in the past.

Acknowledgement

This work was supported by grant No. 19-26232X from GAČR and by Praemium Academiae of the Czech Academy of Sciences.

References

Arendt R.G. (2014). “DIRBE comet trails”. *Astronomical Journal*, 148:135.

Battams K., Gutarra-Leon A.J., Gallagher B.M. et al. (2022). “Continued PSP/WISPR observations of a Phaethon-related dust trail” *Astrophysical Journal*, 936:81.

Borovička J. Spurný P., Shrbený L. et al. (2022a). “Data on 824 fireballs observed by the digital cameras of the European Fireball Network in 2017–2018 I. Description of the network, data reduction procedures, and the catalog”. *Astronomy & Astrophysics*, in press, doi:10.1051/0004-6361/202244184

Borovička J. Spurný P., and Shrbený L. (2022b). “Data on 824 fireballs observed by the digital cameras of the European Fireball Network in 2017–2018 II. Analysis of orbital and physical properties of centimeter-sized meteoroids”. *Astronomy & Astrophysics*, in press, doi:10.1051/0004-6361/202244197

Hajduková Jr. M., Koten P., Kornoš L., and Tóth, J. (2017). “Meteoroid orbits from video meteors. The case of the Geminid stream”. *Planetary and Space Science*, 143, 89-98.

Jewitt D., Li J., and Agarwal J. (2013). “The dust tail of asteroid (3200) Phaethon”. *Astrophysical Journal Letters*, 771:L36.

Rendtel J. (2019). “Geminid activity over a century”. In Rudawska R., et al., editors, Proceedings of the International Meteor Conference, Pezinok-Modra, 30 August – 2 September 2018. IMO, pages 114–117.

Ryabova G.O. (2022). “On mean motion resonances in the Geminid meteoroid stream”. *Planetary and Space Science*, 210:105378.

Spurný P. (1993). “Geminids from photographic records”. In Stohl J. and Williams I.P., editors, Meteoroids and their parent bodies. Astron. Inst. Slovak Acad. Sci., Bratislava, pages 193–196.