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A summary of the research of Geminid meteoroid stream

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Abstract. A review of observational and theoretical studies of the well-known major meteoroid stream Geminids is presented. We also give a summary of the studies of the relationship between the stream and its parent body, asteroid 3200 Phaethon.

Key words: meteoroid streams – Geminids – parent body – 3200 Phaethon

1. Introduction

In this paper, we give a summary of the past research of the Geminid meteoroid stream and its relationship with asteroid 3200 Phaethon that is regarded as the parent body of the stream. The summary is motivated by the fact that the Geminids have been studied by a relatively large number of researchers and the extent of achieved results and knowledge about the stream is extensive. The numerous studies of the Geminid stream and its parent body have obviously occurred because the Geminids are the second largest shower in the meteor databases and the largest asteroidal meteoroid stream.

In the following sections, we review the observations of the shower performed by various techniques, the studies of stream dynamics as well as physics of the Geminid fireballs. Of course, the numerous studies concerning the stream parent body are also included. We believe that the summarized information will be worth in future studies of this as well as other asteroidal streams, or streams with a similarly small perihelion distance.

2. The first records

As far as we found, the first visual observations of Geminids were reported, in the modern era, in the eighties of the nineteenth century (Sawyer, 1880; 1885; Denning, 1886; Besley, 1898). It is possible that this shower could have been observed even earlier. Connolly & Hoffleit (1991) found a record of a Geminid-shower observation in the autobiography of Miles A. Gilbert, a businessman from Kaskaskia, Missouri, who observed the shower in 1834. His observation was tentatively dated about December 15. And Hasegawa (1999), analyzing the meteors recorded in the Chinese chronicles, reported an observation of one December Monocerotid in 381 and one Geminid in 1077.

3. Visual observations and their results

Especially after the World War I, regular (or quasi regular) reports on the visual observations of Geminids were published by Millman (1934; 1935; 1938; 1939). These observations provided especially the position of radiant and zenithal hourly rates (ZHR, hereinafter), revealing a high numerousity of the stream. The further observations of Geminids (and Leonids) in this period were performed by Burland & Thomson (1940).

The visual observations then went after the World War II. Worley (1955) published the position of the mean radiant in $\alpha = 112.02^o$, $\delta = 32.00^o$ (α and δ are the equatorial coordinates), and the mean solar longitude $\lambda_\odot = 260.6^o$ (all values referred to Eq.1950.0). He noted that the stream was detectable over a 10-day interval and estimated the minimum visual stream-width to be about 2.3×10^7 km.

Grygar & Kohoutek (1958) used the visual observations of Geminids in 1955 to determine the maximum hourly rate of 113.3 ± 6.2 meteors/hour/observer and the average visual magnitude 2.49 ± 0.06. The observational team went on with these observations also in subsequent years (e.g. Grygar et al., 1962).

Meteors, Geminid members including, were observed for several decades at the Skalnaté Pleso Observatory. The observations led to gradual improvements of standard visual parameters. The observations of Geminids were evaluated by, e.g., Porubčan & Štohl (1979) and Porubčan et al. (1980). Zvolánková (1986) employed more than 8000 of these visual records of the Geminids, made over a period of 8 years, to specify the activity of the Geminid shower in the years 1944−1974. She found the maximum ZHR per one observer under undisturbed observational conditions 130 meteors at solar longitude 261.72^o (1950.0) on December 13, 1944. Geminids could be detected over the interval of solar longitude ranging from about 248^o to 266^o.

Further visual observations of Geminids (and Quadrantids) and their evaluation were reported by Rendtel et al. (1985). The observations were performed by the Arbeitskreis Meteore (AKM) during 1979−1984. No evidence for a deformation of the Geminid rate profile was found. The number of bright meteors was shown to increase near the time of maximum activity, when the population index exhibits a maximum. According to Roggemans (1989), global observations on the Geminids in 1988 yielded 14 193 shower members. The averaged activity profile showed a secondary maximum of 50 meteors per hour. The main maximum covered 14 hours with 120 meteors per hour.

Rendtel et al. (1993) presented the results of the 1991 IMO Geminid observing project performed by 163 observers who observed over 32 000 shower meteors in the week-long project, December 11-16, 1991. The peak ZHR rate of

110 was reached at $\lambda_\odot = 262.3^o$. A preceding maximum was clearly defined in the ZHR curve at $\lambda_\odot = 261.35^o$. The ZHR curve was best described as skewed toward pre-maximum nights. The visual ZHR peak coincided with the core of the stream containing most of the larger meteoroids, while smaller particles appeared over a wider region also showing more maximum-like structures before the main peak of number density was reached. A similar conclusion that the rate profile was slightly skew, with a more steep decrease after the peak, was later drawn by Arlt & Rendtel (1994) from the analysis of global data of the 1993 Geminids.

Finally, a couple of analyses of the long-period visual observations of Geminids should be mentioned. In 2004, Rendtel employed the observations collected over 60 years (1944−2003). He concluded that the profiles and values of the population index near the activity peak were rather constant over the entire period and confirmed the strong mass segregation within the stream. The peak activity was characterized by a plateau in the profile with a ZHR between 120 and 130 lasting for about 12 hours between $\lambda_\odot = 261.5^o$ and 262.4^o (J2000). According to him, this is consistent with the age of the Geminid stream of about 6000 years. The position of this plateau was constant. Variations of the ZHR by more than 10% within the peak period were found in data of well-observed returns. In addition, Miskotte et al. (2011) evaluated the 30-year observations (1979−2009) of Geminids performed by the observers of the Dutch Meteor Society. According to the collected data, the activity during the 1980s was less than that in the 1990s and the last decade.

4. Knowledge from the photographical observations

In the 1930s, the photographic meteor networks were installed in North America. The two-station and multi-station records enabled to obtain the geophysical parameters of meteors with an extraordinary high precision. The first two-station Geminid was reported by Millman (1934). In the 1933 season, there were detected 4 Geminids at the Harvard Observatory stations near Cambridge. One of these was -4^m bright, being also detected at the Oak Ridge station. The observation of this Geminid indicated a very small perihelion distance, 0.14 AU, and the orbital period, 1.8 year, of the Geminid stream. Actually, these values were confirmed after the observation of another four two-station Geminids in 1937 (Whipple, 1939).

The comprehensible review of the Geminid meteor shower, based on the visual and photographic observations of the shower, was published by Plavec (1950). Probably the first photographic spectra of Orionids and Geminids were obtained by Millman (1955). Another spectrum of a Geminid meteor was photographed by Russell & Sadoski (1956). Millman went on with acquiring the meteor spectra and his last list of these was published in 1997 (Millman, 1997). On the basis of these observations, Millman also stated a fragmentation to more than 200 meteorites larger than 0.055 kg. Analyzing the spectrum of a significantly non-spherical Geminid bolide, he found a cosmogonic radionuclide implying its single stage exposure history.

In the second half of the 20th century, several small-camera networks were installed in Europe. The photographic observations of Geminids performed by both Super-Schmidt and small cameras were evaluated by Porubčan (1978), who found 153 Geminids in the data. He determined the mean orbital period of photographic Geminids to be 1.66 year. Concerning the results obtained by both types of photographic cameras and concerning Geminids, we should mention the determination of more than 100 Geminid meteor orbits from the 1990 campaign by Jenniskens et al. (1991), or another 1990 data on this shower obtained by Betlem et al. (1993).

Photographic and visual observations of the Geminid meteor shower in 1990 were performed by Evans & Bone (1993a). They determined the ZHR of 89.1 ± 4.2 and noticed that the Geminid meteors were, on average, brighter than the meteors of sporadic background. They also used their photographic and video observations from 1991, 1993, and 1996 Geminids to further improve some parameters (Evans & Bone, 1993b; 1996; and 2001, respectively).

Porubčan & Cevolani (1994) derived the mean orbit and radiant ephemeris of the Geminids on the basis of 191 precise photographic orbits available from the IAU Meteor Data Centre in Lund. Over a time span of 50 years, the semi-major axis, eccentricity and perihelion distance of the stream exhibit variations following the trend of the stream evolution suggested by Williams and Wu (1993; see Sect. 9).

Evans (1997) evaluated the Geminid-stream radiant from photographic observations comparing the data gained during the period 1955−1993. The best-fit position of the radiant was $\alpha = 113.0^o$ and $\delta = +32.7^o$ (2000.0) at solar longitude 262.0^o (2000.0). The spread of the photographic Geminid radiant was found to be small and especially concentrated to the time of the maximum activity.

5. Radar observations and results

After the World War II, a number of meteor radars have been installed in Europe, North America, Australia, as well as in the Asian territory of the former Soviet Union. Using this observational equipment, the researchers, naturally, also observed the Geminid shower.

The radio-echo technique was used many times. In the period from 1952 to 1957, Weiss (1959) observed by this technique the Geminids in Australia and determined the mean radiant having the equatorial coordinates $\alpha = 113.4^o$ and $\delta = 31.4^o$ at solar longitude $\lambda_o = 260.8^o$.

Dudnik et al. (1959) used the radar-echo technique to measure the velocity of meteors. For 226 Geminid meteors, the velocity was found to be in the range from 32.5 to 37.5 km s^{-1}, with the average of 35.9 km s^{-1}. The same technique was used by Kashcheev & Lebedinets (1959) to study the structure of the shower. The central condensation has the measured cross-section over 5.10^5 km and the maximum hourly rate was 945 meteors. The mass distribution of meteor bodies in the Perseid, Geminid, and Quadrantid showers was determined by radar observations by Lazarev et al. (1970). And, some problems of statistic characteristics of the Geminid shower from the results of radar observations were pointed out by Fialko et al. (1971).

Šimek & Zacharov (1973) measured a micrometeoroid flux during the 1970 Geminid shower by radar. A similar measurement was also performed by Hughes (1973). Hajduk et al. (1974), using the data from meteor radars at Ottawa, Canada (14 years), and Ondřejov, the former Czechoslovakia (10 years), examined the distribution of meteoroids around the orbit of the Geminid stream. The data were consistent with a single maximum and minimum in the flux, the ratio being approximately 2:1. The rates for 1958 were anomalously high compared with those observed in other years in the same region of the orbit. The distribution of particles around the mean orbit of Geminids was analyzed, using the radio observations, by McIntosh (1974).

Bel'kovich et al. (1975) observed the interaction of meteor matter with the Earth and estimated the meteor matter influx on our planet and on the Moon. Šimek (1978) went on with the radio observations of the Geminid shower to improve the knowledge of its structure. Among other things, he noticed that the maximum of the shower activity occurred sooner for under-dense echoes, while the bright meteors were concentrated about two days later. The density fluctuation of the falling stream and the index of the meteoroid mass distribution during the period of Geminid activity were determined by Kostylev & Svetashkova (1978).

McIntosh & Šimek (1980) summarized the 20-year (1957−1977) radar observations of the Geminid meteor stream. They found that the mean variation of the meteor number density across the stream is determined for three particle size groups. The time of the maximum meteor flux as a function of the meteor magnitude, M, is given by solar longitude $\lambda_\odot = 261.3^o - 0.135^o M$. The width of the shower at 61% of the maximum varies from 62 hours for faint meteors ($+6^m$) to 31 hours for bright ones (-1.3^m). There are particle number density variations along the orbit, but the orbital period deduced from these cannot be specified more accurately than 1.6 ± 0.1 year.

Andreev et al. (1981) studied the structure of the Geminid meteoroid stream from the radar observations performed in the period 1966−1967 in Dushanbe. The incident flux density of meteoroids Q versus the solar longitude was calculated, whereby the maximal value of Q was equal to 0.017 meteoroids per square kilometer per hour for $\lambda_\odot = 261.1^o$ (1950.0). The meteor matter influx appeared to be up to 1 400 kg for the meteoroid mass larger than 10^{-6} kg and 2 500 kg for the meteoroid mass larger than 10^{-9} kg. It was also found that large particles are concentrated in $\lambda_\odot = 260.15^o - 262.10^o$ and, in this interval, the number of small particles decreases. The small particles are concentrated on either side of this interval. Distribution $Q(\lambda_\odot)$ showed several filaments in the stream.

Bel'kovich et al. (1982) studied the Geminid shower from radar, photographic, and visual observations. They calculated the incident flux density of meteors and the mass index variations as a function of the solar longitude for the periods 1964−1967 and 1969−1971 of radar observations of the shower in Kazan. The flux maximum position and the shower width depend on the minimal registered mass of the meteor bodies. The meteor matter influx on the Earth in the mass interval from 10^{-10} to 10^{2} kg was evaluated as 140 000 kg and 95 000 kg for the total shower period and one day around the activity maximum, respectively.

Šimek et al. (1982) used the radar observations of the Geminid meteor shower, obtained at observatories in Dushanbe, Ondřejov, and Ottawa, to develop a long baseline for extending the observational time to provide 20 hours of observation. The configuration was needed to use a new method of the study of the stream structure. The method gave good shower activity maxima positions but poor amplitudes. The influence of the Poynting-Robertson effect was demonstrated.

Jones & Morton (1982) used a high resolution imaging meteor radar system during the 1980 Geminid shower to record 1013 Geminid echoes. At its peak, the rate of shower meteors was 13 times that of the sporadic meteor background. The *rms* width of the radiant was found to decrease from 1.3^o to 0.8^o over the duration of the shower, while the shower activity increased exponentially before the peak at $\lambda_\odot = 261.3^o$. While finding no evidence for the previously postulated second center of activity near $\alpha = 90.0^o$, $\delta = 32.0^o$, a corrected radiant of $\alpha = 112.3^o$, $\delta = 33.05^o$ was established. The shower, which has an apparent period of detectability in the December 2−15 period, was found to have a mass distribution index mean value which, at 1.69 ± 0.07, corresponds to meteors of $+8.0 \pm 0.5$ mean magnitude.

Isamutdinov & Chebotarev (1984) investigated the Geminid stream with the help of radar observations at Dushanbe, Tadjikistan, in 1971−1979. They showed an irregular distribution of meteor particles in both directions along and across the orbit of the stream. Using the same radar, Babadzhanov et al. (1992) found the mean value of the index of meteoroid mass distribution equal to 1.67.

Porubčan & Cevolani (1994), using the radio observations carried out by the Burdio meteor radar in 1986, reported that Geminids represent a distinct meteor shower with an asymmetric curve of activity. Cevolani et al. (1995) employed the continuous radio-wave monitoring of the Geminid activity in December 1992 and 1993, performed by the forward scatter bistatic radar over the Bologna-Lecce baseline (700 km) in Italy, to reveal some peculiar structural aspects of the stream in terms of signal amplitude-rate and duration-rate dependence. Some reflection properties of Geminids were found to be atypical if compared with echoes from cometary-type showers. They also revealed an asymmetric curve of activity of the Geminids complex, with the peak flux of smaller particles occurring prior to that of larger ones.

Later, Cevolani et al. (1996), using a radio forward-scatter system on the baseline Bologna-Lecce (Italy), revealed that the 1994 Geminid shower exhibited a distinct maximum for overdense echoes of duration larger than 1 s, with the peak rate on December 13, 21–22 UT at solar longitude 261.0^o (1950.0). The maxima of echoes of longer duration (more than 8 s and 32 s) were shifted to solar longitude 261.3^o.

The CLOVAR stratosphere-troposphere radar was used to observe the 1996 Geminid and 1997 Quadrantid showers by Brown et al. (1998). They found the peak flux values to be 0.19 ± 0.02 meteoroid $\mathrm{km}^{-2}\,\mathrm{h}^{-1}$ at $\lambda_{\odot} = 261.82^o \pm 0.2^0$ for the Geminids to a limiting radio magnitude of 7.7.

The fine structure of the Geminid meteor swarm from radar observations in 1988 was described by Karpov et al. (1998). Results of long-term radar observations of Geminids in the period 1958–1997 were presented by Pecina & Šimek (1999). Mean activity profiles along the Earth's passage through the stream showed a systematic change of the peak activity and the width of the stream depending on the distribution of echo durations across the stream. Faint particles were more concentrated in inner orbits, while the large ones dominated in the outer orbits. A skewness of the activity profiles was evident for echo durations longer than or equal to 1 s. The activity levels of individual years showed a moderate scatter over the examined period except for 1995, when low activity of the sporadic background resulted in an apparent high activity of the shower.

The motion of the radio meteor reflection point of Geminids using the ham-band radio observation technique was traced by Ohnishi et al. (2001). This technique is one of the observational techniques for the forward scatter observation of meteors. The authors detected the change of the direction of the reflection point of the meteor radio signal of Geminids in 2000. The reflection point moved from westward to eastward before and after the culmination of the radiant, which was consistent with the formula of the reflection point of meteors. At the same time, they detected the change of the intensity and a trend of the Doppler shift of meteor echoes.

To study the orbit and evolution of the Geminid meteoroid stream, the radio observations were used by Porubčan et al. (2004). The long-term (1996–2007) radio observations of Geminids carried out by the forward-scatter system, this time operating along the Bologna (Italy) – Modra (Slovakia) baseline, were analysed and presented by Zigo et al. (2009). The activity curves indicated a multiple-peak structure of the shower. The global activity curve for overdense echoes of durations larger or equal 1 s and 8 s depicted two peaks at solar longitude 261.7^o, 262.3^o and 261.9^o, 262.3^o, respectively. Larger particles were concentrated more to the centre of the shower and slightly shifted towards the descending branch of the shower activity. The mean mass exponent of Geminids was found to be 1.73.

New meteor radar observations of Geminids were performed by Stober et al. (2010), Webster & Jones (2011), and others to further improve our knowledge about Geminids and other showers.

The results obtained by lidar were published by Nakamura et al. (2010) and Lokanadham et al. (2010). Nakamura et al. tried to measure an enhancement of the metallic atom layer column density due to the Geminid meteor shower. They, however, could not draw any definite conclusion on the effect. Further, they carried out extensive Na temperature lidar observations between 2007 and 2009. They found a significant enhancement of the Na column density: $\sim$3 and $\sim$2.5 times in 2007 and 2008, respectively. Lokanadham et al. measured mesospheric sodium during the night of 12−13 December 2007. The sodium concentration in the atmospheric altitude of $\sim$93 km is estimated to be 2000 per cube centimeter when the meteoric concentration of Geminids was maximum and reduced to around 800 per cube centimeter during non activity of Geminids.

In view of performing the meteor head echo observations in the Martian atmosphere, Schult et al. (2012) used the Middle Atmosphere Alomar Radar System (MAARSY) in December 2010 during the Geminid meteor shower. MAARSY is a new High-Power-Large-Aperture (HPLA) system located close to the Andoya Rocket Range at the northern Norwegian island of Andoya. A total of 26 hours of observations was reached. The authors were able to observe a total of 1560 meteor head echoes from which 118 did originate from the Geminid source radiant and had a velocity of about $35\,\mathrm{km\,s^{-1}}$. Similar observations were performed in 2009 by Espley et al. (2010) to study some effects, obvious in the Earth's atmosphere, in the Martian atmosphere during the activity of Geminids here. However, the expected effects were not detected.

Recently, Abe et al. (2014) studied the orbital evolution of Geminids and Quadrantids by middle and upper atmosphere radar observations. 163 orbits of Geminids were observed in 2009, 310 in 2010, and 513 in 2013 with this technique. Some orbital properties of meteoroids in respect to their parent body were discussed.

6. Video and other observational techniques

The advent of television in the second half of the 20th century led also to utilization of this technique in the meteor observations. Several TV/video meteor networks were established across the world, especially in Europe and Japan. In what follows, we will mention at least some video observations of Geminids and their results.

Ueda & Fujiwara (1993) performed the TV observations of the 1991 Geminid meteor shower and confirmed the deficiency of faint meteors in the stream as compared with sporadic meteors.

In the beginning of the 1990s, the intensified video cameras appeared to be a sufficient tool to observe meteors. Successful observations were largely performed not only by professional, but also amateur astronomers (e.g. de Lignie et al., 1993, who observed the Geminid storm by this technique).

Video observations of the Geminid shower in 1990 were done by Elliott & Bone (1993). Using a low-light video system, they succeeded in recording a total of 132 meteors (126 Geminids and 6 sporadics) in $5^h\ 30^m$ of effective exposure. The video observations of Geminids in 2006 and 2007, from the Croatian Meteor Network, were published by Andreić & Šegon (2008). Jenniskens et al. (2010) and Trigo-Rodríguez et al. (2010) published the observations of 2010 Geminids.

Since 2009, double station meteor observations by the all-sky video cameras of the Slovak Video Meteor Network have been performed (Tóth et al., 2012). Hundreds of orbits of Lyrid 2009, Geminid 2010, and Quadrantid 2011 multi-station meteors during their maxima were observed.

Rudawska et al. (2013) recently presented the results of the 2012 Geminid observation campaign performed by the new video meteor network at the Atlas Golf Marrakesh, Marrakesh, Morocco. It was found that the Geminids duration is generally correlated to their magnitude. Moreover, the authors analysed a Geminid spectrum. It was a normal class spectrum, with a high sodium content.

de Sánchez et al. (2013) performed a video recording from the stratosphere using weather balloons. They found that this is an excellent technique for meteor research. They detected 16 possible Geminids.

7. The parent body

Before the discovery of the actual parent body of the Geminid stream, there was suggested only a single candidate. Specifically, Kresáková (1974) suspected that the Geminid parent could be the periodic comet C/1917 F1 (Mellish), which is now regarded to be the most probable parent of December Monocerotids. According to her analysis, the stream of the comet consists of four filaments, one of which has orbital properties resembling those of Geminids.

In 1983, an asteroid with preliminary designation 1983 TB was discovered (its improved orbital characteristics were published by Gibson & Marsden, 1984). Soon after the determination of its preliminary orbit, Hughes (1983) and Whipple (1983) almost simultaneously reported its possible relationship to the Geminid stream.

Subsequently, there were published several studies proving that this asteroid, which was definitely numbered and named as 3200 Phaethon, is the parent body of Geminids. Specifically, Fox et al. (1984) pointed out that its orbit is very similar to the Geminid stream. They claimed that if this is so then 1983 TB could be the degassed nucleus of the responsible comet, thus establishing a probable evolutionary connection between the two groups of objects. Since its orbit almost intersects the Earth's orbit, close encounters may be expected which will provide good observing conditions for this interesting object. The authors present the orbital calculations determining the future orbital behavior of 1983 TB, highlighting good observing times.

Later, Fox et al. (1985) added information that the Phaethon's orbit crossed over the orbit of Venus about 500 years ago. They traced the history of both the object and the stream through this interaction with Venus and the present interaction with the Earth.

In 1986, Kramer & Shestaka studied the dynamical evolution of Geminids' meteor swarm by the method of a retrospective secular perturbation analysis within 4000 years accounting for the Pointing-Robertson effect. In this work they concluded that a possible genetic relation between the swarm and Phaethon was confirmed. They further estimated that the swarm's age does not exceed 1000 years, and it will remain as compact as it is for another 400 years. In their later works (Kramer & Shestaka, 1991; 1992), the authors, however, drew a different conclusion saying that one cannot explain the ejection of the Geminid swarm from this object.

Licandro et al. (2007) studied the composition of the surface of Phaethon, in order to determine its cometary or asteroidal nature. They used the visible and near infrared spectra covering the $0.35-2.4\,\mu$m spectral range, obtained with the 4.2-meter William Herschel Telescope, the 2.5-meter Nordic Optical Telescope, and the Italian 3.58-meter Telescopio Nazionale Galileo at "El Roque de los Muchachos" Observatory (La Palma, Spain). The authors concluded that the spectral and dynamical properties of Phaethon support an asteroidal nature rather than a cometary one. Phaethon is more likely an "activated" asteroid, similar to the population of activated asteroids in the Main Belt Comets, than an extinct comet.

Ryabova (2008) presented a short review concerning the origin of the Geminid meteoroid stream and its confirmed parent body, Phaethon, but dealt also with another possible candidates for the Phaethon-Geminid complex: asteroids 155 140 (2005 UD) and 1999 YC.

The origin of Phaethon and Geminids was also investigated by de León et al. (2010a; 2010b). They showed that the most likely source of Phaethon and the Geminids is the asteroid 2 Pallas, one of the largest asteroids in the main belt, which is surrounded by a collisional family, containing several Phaethon-sized objects. Pallas' highly inclined orbit and surface composition, also primitive and with evidence of hydration, support this connection. Their analysis revealed a striking similarity between Phaethon's visual spectrum and those of Pallas family members. Moreover, their numerical simulations showed the existence of a robust dynamical pathway, connecting the orbital neighborhood of Pallas with that of Phaethon. In this respect, the Pallas family may constitute a source of primitive NEAs.

8. Physical properties and formation of the stream

After the discovery of Phaethon, there was an effort to confirm the generic relationship of the Geminids to this object also by a similarity of their physical properties. In addition, the researchers attempted to answer the question if Phaethon is an originally asteroidal, or cometary object.

The diffusion effects in the wake spectrum of a Geminid meteor were observed by Halliday (1963). The SEC Vidicon, a low light level closed circuit television system, was used by Millman & Clifton (1975) to obtain 137 spectrographic records of meteors at Mt. Hopkins, Arizona, during the Geminid meteor shower in December 1972. Seven of the best spectra were studied in detail. The near infrared, up to wavelengths near 900.0 nm, was recorded for the first time for Geminids. The spectra, in general, exhibited the elements previously found in photographic records of this shower, but also showed a surprising frequency of occurrence of the forbidden green line of O I at 557.7 nm. This line is normally absent from meteors moving as slowly as Geminids and its presence in these records could be due to the added sensitivity available with the SEC Vidicon. The average green line duration in Geminid meteors with a luminosity near zero absolute visual magnitude was 0.73 s at a mean height of 95 km, 11 km lower than the green line peak in Perseid meteors of the same luminosity.

Hunt et al. (1986) described a model for the formation of the Geminid stream based on a collision between two rock like bodies. It was found that this model could explain two of the major observed characteristics, but had more difficulty in explaining the observed distribution of aphelion distances. The model was based on the preceding observational evidence that Phaethon is not the nucleus of a comet.

Halliday (1988) attempted to infer the properties of Phaethon from twelve long-duration Geminid fireballs observed over western Canada. The luminosity of each of these fireballs was used to obtain a photometric mass that was independent of velocity. For realistic values of an assumed luminous efficiency, the photometric masses agreed for particle densities between 0.7 and 1.3 $\mathrm{g\,cm^{-3}}$. Classification parameters implied the suggestion that, while Geminids are not as 'tough' as meteorites, they are more cohesive than many fireballs and have too low density to justify association with meteorites, or normal asteroids.

Several models for the ejection of particles from the cometary nucleus, in view of explaining the formation of the Geminid stream, were presented by Bel'kovich & Ryabova (1989). Five thousand particles appeared to be sufficient to construct a qualitative map of the cross system of the stream. They also studied the effect of the distribution of the rates of ejection on the structure of the stream.

Gustafson (1989) integrated, backward in time, the motion of twenty Geminid meteoroids to demonstrate the opportunities for their transfer from Phaethon. According to the author, meteoroids could have been ejected under circumstances (location, speed and directions of ejection) that were possible, or even expected, during cometary activity. Phaethon's active period would be no more than 2000 years ago and may have been within the last 600 years. A similar study, with practically the same conclusions, was published by Adolfsson & Gustafson (1991).

Using the photographic observations, Spurný (1993) determined the ablation coefficients of several Geminids, which belonged exclusively to the fireball group I (Ceplecha, 1983).

Interpreting fireball flickering in terms of the rotational modulation of the ablation process, the time since ejection into space of three Geminid meteoroids was determined by Beech (2002). By estimating the time required to spin-up a meteoroid through non-isotropic photon scattering interactions with the solar radiation field, Beech found the meteoroid ages consistent with ejection times some 1000−4000 years ago. There appeared to be some indication that the stream formation process lasted for at least $\sim$1000 years. The tensile strengths of some 3×10^5 Pa was determined. Beech interpreted his results as being supportive of the argument that the parent body to the Geminid stream, Phaethon, is an aged cometary nucleus.

Beech et al. (2003) determined some physical properties of a flickering Geminid fireball, which was observed from Southern Saskatchewan, Canada, in the early morning of December 13, 2002. Its absolute magnitude was -9.2 ± 0.5. The authors determined a photometric mass of 0.429 ± 0.15 kg for the meteoroid. From its initial rotation rate of some 6 Hz they estimated that the meteoroid was ejected from the parent body some 2500 ± 500 years ago. They also found that 70% of Geminid fireballs brighter than magnitude −3 display distinct flickering effects, a value that is in sharp contrast to the 18% flickering rate exhibited by sporadic fireballs. The high coincidence of flickering and the deep atmospheric penetration of Geminid fireballs were suggestive of Geminid meteoroids having a highly resilient structure, which was a consequence of having suffered a high degree of thermal processing. The possibility of Geminid material surviving atmospheric ablation and being sampled was briefly discussed, but the likelihood of collecting and identifying any such material was regarded as very small.

A detailed analysis of a photographic spectrum of a Geminid fireball obtained on December 14, 1961 at the Ondřejov Observatory was presented by Trigo-Rodríguez et al. (2004). They computed a synthetic spectrum for the fireball and compared it with the observed spectrum assuming chemical equilibrium in the meteor head. In this way, they 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, no significant chemical differences in main rock-forming elements were found. 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.

The first result of a Geminid meteor spectrum in the visible-ultraviolet region was published by Kasuga et al. (2005). Wavelengths between 300−600 nm were observed on the meteor which appeared at $17^h41^m24^s$ UT on 2004 December 14, and strong emissions of neutral atoms such as mainly MgI, FeI, CaI and NaI were identified. The results suggest the possibility that the abundances of Geminid meteors are slightly different from solar abundances. Na/Mg $= 0.0036 \pm 0.0005$, which is much lower than other meteor showers. On the other hand, the Ni/Mg ratio is 0.078 ± 0.012, which is larger than solar abundance, and that of meteors of other showers. Extreme Na depletion and, moreover, excess Ni are derived for a Geminid meteor. The excitation temperature of 4640.6 ± 1.5 K is consistent with their moderate velocity.

Chenna et al. (2008) followed the Geminid shower activity in 2003 and 2005 by the Gadanki radar in India. Among other things, the authors were interested in the appearance of echoes of various durations and, therefore, meteors of various masses in order to better understand the filamentary structure of the stream. It was observed that the faint particle flux peaks earlier than that of the larger particles. The mass index profile was found to be U-shaped, with a minimum value near the time of peak activity. The observed minimum values were 1.64 ± 0.05 and 1.65 ± 0.04 in 2003 and 2005, respectively. The activity of the shower indicated the mass segregation of meteoroids inside the stream. Another Indian radar, in Tripura, was used by Guha et al. (2009) to detect day-time 2007 Geminids and provide the dynamic VLF radiation spectra. The VLF emissions lie in the range from 8 kHz to 13 kHz.

Kasuga (2009) dealt with the thermal evolution of Geminids and the Phaethon-Geminid stream complex. According to him, sodium contents of Geminid meteor streams are altered thermally, perhaps during orbital motion in interplanetary space due to the short perihelion distance of the orbit. However, the temperature of meteoroids is less than the sublimation temperature of Na in alkali silicates, suggesting that Phaethon itself might have suffered from the thermal processing. On the other hand, a breakup event on the complex's parent is indicated by the existence of dynamically associated asteroids (Phaethon, 2005 UD, and 1999 YC) sharing pristine features (C, B types). A possible mechanism behind the breakup is the sublimation of ice inside the complex parent due to its thermal evolution.

Following an alert by Battams and Watson, Jewitt & Li (2010) used NASA's STEREO-A spacecraft to image Phaethon near its perihelion, in the period UT 2009 June 17-22, when the heliocentric distance was near 0.14 AU. The resulting photometry showed an unexpected brightening, by a factor of two, starting on UT 2009 June 20.2 ± 0.2, which was interpreted as an impulsive release of dust particles from Phaethon. If the density is close to $2500\,\mathrm{kg\,m^{-3}}$, then the emitted dust particles must have a combined mass of $\sim 2.5 \times 10^8 a_1$ kg, where a_1 is the particle radius in millimeters. Assuming $a_1 = 1$, this was approximately 10^{-4} of the Geminid stream mass and to replenish the stream in steady state within its estimated ∼103-year lifetime would require ∼10 events like the one observed, per orbit. Alternatively, ongoing mass loss may be unrelated to the event which produced the Phaethon-Geminid complex. An impact origin of the dust was highly unlikely. According to the authors, Phaethon is too hot for water ice to survive, rendering the possibility that dust is ejected through gas drag from sublimated ice unlikely. Instead, they suggested that Phaethon is essentially a rock comet, in which the small perihelion distance leads to both the production of dust (through thermal fracture and decomposition cracking of hydrated minerals) and its ejection into interplanetary space (through radiation pressure sweeping and other effects).

Borovička (2010) analyzed 89 spectra of Geminid meteors obtained with image intensified video cameras in 1997-2004. The intensities of lines of Mg, Na, and Fe were studied. Both Fe and Na lines were found to be fainter relatively to Mg than expected for chondritic composition. Moreover, the Na line intensity varied strongly from meteor to meteor. Based on the low Fe/Mg ratio, similar to other cometary meteoroids, he argued that Phaethon is of cometary origin. Severe loss of Na occurred due to solar heating at the small perihelion distance. Varying meteoroid age seems to be the most plausible explanation of varying Na content from meteoroid to meteoroid, although other explanations, such as meteoroid origin in different depths in Phaethon or internal Phaethon's inhomogeneities, are possible as well.

Assuming the asteroidal origin of Geminids, Madiedo et al. (2011) suggested that the Geminid stream could give rise to meteorites. They presented an analysis of a Geminid fireball imaged by the Spanish Meteor Network that supported this idea. The idea of Geminids as a potential meteorite producer was also supported with the analysis of several Geminid fireballs by Madiedo & Trigo-Rodríguez (2011). They analysed the Geminid observations which were made in 2009 and 2010 from several video stations operated by the Spanish Meteor Network.

Čapek & Vokrouhlický (2011) aimed at explaining the unusual mechanical properties of Geminids. According to them, the thermal stress in the solar vicinity may override the material strength and meteoroids begin to crack. This claim seems to be in a contradiction to the conclusion by Beech et al. (2003) about the resilience of the material mentioned above. The destruction of meteoroids begins from the surface and fractured material is removed from the surface, which leads to decrease of a meteoroid size. The thermal stress is, therefore, able to change the initial size distribution of a meteoroid stream with a sufficiently small perihelion. Creating a simplified model and applying it to Geminids, they found that the thermal stress is able to preferentially remove larger and weaker members of the stream. This may explain the higher mechanical strength observed during their passage through the atmosphere and also remove the discrepancy between the result by Čapek & Vokrouhlický and Beech et al.

Arai et al. (2012) performed a mineralogical study of primitive achondrites. This study, in a combination with astronomical observation of the Phaethon-

Geminid-Complex, showed that an incipient partial melting may have occurred in the active Phaethon.

Madiedo et al. (2013) analyzed a Geminid fireball with an absolute magnitude of −13, which was observed over the south of Spain on 2009 December 15. This extraordinarily bright event was imaged from two meteor observing stations operated by the Spanish Meteor Network. It exhibited fast and quasi-periodic variations in brightness, a behavior typically associated with the rotation of the parent meteoroid. The authors inferred a tensile strength of this particle, which was significantly higher than the typical values obtained for Geminid meteoroids. The fireball penetrated the atmosphere down to a final height of about 25 km, and a non-zero terminal mass was calculated at the ending point of the luminous trajectory. In this way, the observational evidence points out the existence of a population of meteoroids at the higher end of the Geminid mass distribution capable of producing meteorites. From the relative chemical abundances inferred from the emission spectrum of this bolide, the authors concluded that the Geminid-forming materials are similar to some primitive carbonaceous chondrite groups. In meteorite collections from cold deserts, capable of preserving meteorites of a few tens of grams, some rare groups of carbonaceous chondrites could, thus, be coming from the Geminid parent body.

9. Stream structure and its dynamical evolution

A lot of studies have concerned the mechanism of the ejection of meteoroids from the parent body and their subsequent dynamical evolution. The modeled structure of the stream has been confronted with the Geminid-shower observations.

Within the analysis of the dispersion of meteors in several major meteor streams, the structure of Geminids, mainly their radiant area, was also analysed by Kresák & Porubčan (1970). The authors used the precise double-station photographic data on 81 Geminids. No significant difference in comparison with the major cometary streams was found.

In 1978, Jones devised a method for analyzing the periodicities from year to year in meteor-shower activity. His approach gave more reproducible results than previously obtained, and the orbital period of Geminid radio meteors was found to be close to 1.49 yr, the value consistent with the decrease in the period of faint meteors and also with the systematic change of solar longitude at maximum shower activity with a decreasing meteoroid size. When interpreted in terms of the Poynting-Robertson effect, these data indicated the stream age of 4700 years, which was sufficiently long to explain a lack of very large concentrations of particles in the stream.

According to Fox et al. (1982), the observations of the Geminid stream over the last 118 years indicate that the ascending node, Ω, is stationary at an Ω-value of $261.38^o \pm 0.11^o$. A theoretical analysis of the effect of a planetaryinduced gravitational perturbation on the stream results in a predicted decrease in the ascending node by 1.57^o per century. The general rule that streams with inclinations greater than 90^o have positive $d\Omega/dt$ values, whereas those with inclinations less than 90^o have negative $d\Omega/dt$, is disobeyed by Geminids. The authors also developed a model for the formation of the Geminid stream and showed that the suggested formation mechanism causes certain features to develop in the model stream which will result in both the rate profile being skew and mass segregation being observable (Fox et al., 1983). Such features are, in fact, observed in the Geminid shower.

Babadzhanov and Obrubov studied the evolution of the orbits and conditions of the encounter of the Geminids and Quadrantids with the Earth (Babadzhanov & Obrubov, 1980; 1984a) and pointed out a certain correlation between the solar longitude in the time of meteor observation and its stellar magnitude as well as the semi-major axis (Babadzhanov & Obrubov, 1984b). Later, these authors found that, depending on the orbit inclination range, the shape of meteoroid showers (under the effect of planetary perturbations) can be two-dimensional or highly three-dimensional (Babadzhanov & Obrubov, 1986). In particular, it was shown that the shape of Geminids is characterized by a thickening of the shower perpendicular to the ecliptic plane.

Jones (1985) studied the gravitational perturbations of the Geminid stream using a very simplified model in which Jupiter causes the only perturbation of an initially very well defined stream. In this way the effects of the gravitational perturbations are not obscured by many other factors that influence the real stream. The extensive calculations of the evolution of the orbits of 71 meteoroids in Geminid-like orbits over a period of 5000 years revealed the complex of orbits lying on the surface of a torus flattened approximately parallel to the plane of the ecliptic. Visual observations of the shower show a strong suggestion of a secondary peak in the meteor activity curve at about 0.8^o in solar longitude after the main shower maximum, which would imply the probable age of about 6000 years for the stream.

Hunt et al. (1985) showed that asteroid 3200 and the Geminid stream are experiencing a very interesting dynamical phase at present with the possibility of close encounters with the Earth and Venus. However, prior to the 14th century, it went through a much more quiescent phase, with no major impulsive perturbations, only secular perturbations from Jupiter, lasting about 3000 yr. During this phase no close approaches to the Earth were made and it seems very unlikely that the fireballs of the 11th century were, therefore, associated with the Geminid stream. The authors also confirmed that, in general, planetary perturbations are not causing any sudden large changes in the major orbital parameters of the stream so that following the evolution of one body does give, even over long time periods, a good insight into the stream behavior.

Jones & Hawkes (1986) extended the theory of Fox, Williams, and Hughes (Fox et al., 1983) for the evolution of the Geminid meteor stream under the perturbing influence of the gravitation attraction of the planets. Whereas the original theory allowed for the planetary perturbations by ascribing to each particle the rates of change of orbital elements appropriate to the mean orbit, we note that the motions of the orbital elements are themselves functions of the orbital energy and angular momentum. Since the ejection velocity from the comet depends on particle mass, the spread in orbital size and shape and, hence, the precession and nutation rates are also mass-dependent. The authors showed that the inclusion of this effect causes the duration of the shower to increase with time, so offering the hope of a reconciliation of theory and observations, and it also predicts a very low apparent rate of retrogression of the ascending node, as observed.

An argument for a bi-modality of the Geminid stream was published by Ryabova (1989, 2001). She also presented a mathematical modeling method to evaluate the influence of the Yarkovsky-Radzievskii effect on the width of the Geminid shower observed at the Earth and the shift of the shower maximum activity as a function of meteoroid mass, i.e. on the mass separation in the stream (Ryabova, 1990). Analyzing the methods for determining the age of a meteoroid stream and applying them to the Geminid stream, she concluded that, most likely, the age of Geminids does not exceed a few thousand years.

Belkovich et al. (1990) dealt with the problem of structure and stability of the Geminid meteor shower, which they regarded to be still a problem.

Four aspects of the Geminid meteor stream were reinvestigated by Williams & Wu (1993). First, a search was conducted through all the observational data held at the IAU Meteor Data Center, in order to obtain the most complete sample of the Geminid meteors and, hence, to obtain refined orbital data. Second, the orbital evolution of Phaethon and the evolution of the mean Geminid orbit were calculated over 17 000 years and found to be very similar. Third, the general features of the stream cross-section were derived for four different formation models and, finally, the effects of planetary perturbations upon some of these models were investigated.

An extraordinary compactness of the Geminid stream was documented by Neslušan et al. (1995). Studying ten major meteor showers, they found the relation between the threshold Southworth-Hawkins D-discriminant, which was well obeyed by nine major cometary showers, but largely disobeyed by asteroidal Geminids (see Fig. 11 in Neslušan et al., 1995). Specifically, the threshold D value for the Geminids appeared to be about 4.75 times smaller than that predicted with the help of the relation valid for cometary showers.

Kalabanov et al. (2002) determined the main area of activity in 1998 Geminids, which appeared to be at most $4^o \times 4^o$. Starting time of shower action was on December 3, its intensity slowly increased by December 12 and very sharply decreased near December 15-17. Near to the radiant area, they found out some small showers with velocities and time of occurrence conterminous with Geminids. The question, if these showers are the filaments of Geminids or originate from another source, remained open.

Kaňuchová & Svoreň (2006; 2008) investigated a fine structure of the Geminid stream on the basis of photographic meteors in the IAU Meteor Data Center database. From the latter, they selected 387 Geminids. As expected, the Geminids seemed to be a relatively compact stream. Only a weak conception of 4 branches of filaments could be found. According to their analysis, two observed maxima of Geminids (Ryabova, 1989, 2001) are the product of activity of two different groups of filaments. These parts of Geminids might appear to be as two different meteor streams, unless the similarity of their orbits was so high.

Probably the last summary of our knowledge about the Geminids and Phaethon were given in the review by Ryabova et al. (2014). Among other things, they said that the activity profile for the Geminid shower has a distinctive shape, the shape that is generated by a cometary model of the stream generation, that is, where ejection persists over a significant fraction of the orbit. The dynamical and spectral properties of Phaethon appear to support the asteroidal nature of the object. Apollo asteroid 2005 UD has a very similar orbit to Phaethon and is a likely candidate, or being akin, to Phaethon and/or the Geminid stream. Another candidate for the Phaethon-Geminid complex is Apollo asteroid 1999 YC, so that a comet progenerator may be responsible for the stream and the three asteroids. The authors studied the dynamics of these objects in order to understand their origin and the mechanism for their decoupling.

10. Concluding remark

The observations and subsequent studies of the Geminids, lasting more than one and three quarters of century, have considerably increased our knowledge of this meteoroid stream and its parent body. It is a short-period asteroidal stream. Its particles approach the Sun to about 0.14 AU, therefore their erosion due to the solar radiation and solar wind can be expected to be relatively large, yet the stream is found to be more concentrated to the mean orbit than the cometary streams of similar numerousity. The Geminids are also distinguishable from a cometary stream by several specific physical properties of meteoroids.

Despite gaining a lot of detailed information about the dynamics of the stream as well as physical properties of its meteoroids, some authors doubted the relationship between the Geminids and Phaethon. The doubts originate in a minute quantitative disagreement between the predicted and actually observed shower properties in the Earth's atmosphere. Although these differences are not large and would likely be well acceptable at cometary streams, they cannot be explained within the corresponding determination errors for compact Geminids. On the other hand, there is no more appropriate alternative parent body. Perhaps, the cause of the differences will be clarified in future studies.

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