Meteoroid Orbits from Video Meteors
The Case of the Geminid Stream

Mária Hajduková Jr.a, Pavel Kotenb, Leonard Kornosc, Juraj Tóthc

aAstronomical Institute of the Slovak Academy of Sciences, Bratislava, Slovakia
bAstronomical Institute of the Czech Academy of Sciences, Ondřejov, Czech Republic
cFaculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia

Abstract
We use the Slovak and Czech video meteor observations, as well as video meteoroid orbits collected in the CAMS, SonotaCo, EDMOND and DMS catalogues, for an analysis of the distribution of meteoroid orbits within the stream of the Geminids and of the dispersion of their radiants. We concentrate on the influence of the measurement errors on the precision of the orbits obtained from the video networks that are based on various meteor-detection software packages and various meteor orbital element softwares.

The Geminids radiant dispersion obtained from the large video catalogues reaches the dispersion of the radio observed Geminids, whereby the diffused marginal regions are affected mostly by meteoroids with extreme values (small or large) of the semi-major axes. Meteoroids of shorter semi-major axes concentrate at the eastern side of the radiant area and those of longer semi-major axes at the western part.

The observed orbital dispersions in the Geminid stream described by the median absolute deviation range from 0.029 to 0.042 AU−1 for the video catalogues. The distribution of the semi-major axes of video meteors in all the databases, except for the Ondřejov (Czech) data, seem to be systematically biased in comparison with the photographic and radio meteors. The determined velocities of the video data are underestimated, probably as a consequence of the methods used for the positional and velocity measurements. The largest shift is observed in the EDMOND and SonotaCo catalogues.

Except for the measurement errors which influence the analyses and their

Email address: Maria.Hajdukov@savba.sk (Mária Hajduková Jr.)
interpretations, we also point out the problem of the uncertainties of the numerical integration procedures that influence the simulations’ results. Several experimental integrations of the Geminids parent asteroid, which we performed from the present to the past and then back to the year 2015, showed that a complete reproduction, including also the mean anomaly, is only possible for a time span of about 2700 years.

Keywords: meteors, meteoroid orbits, meteoroid streams, meteor showers, video databases

1. Introduction

The recent rapid development of video techniques is reflected in the massive increase in detected meteors. This is of high significance for minor meteor showers radiants determinations, derivations of meteoroid flux densities and other purposes. However, the production of a large number of meteor orbits often comes at the expense of their quality. This is then reflected in the meteor’s characteristics and influences further analyses, models of the meteoroid streams and searches for the parent bodies. The biggest problem is the measurement and determination of velocity, as the value of the semi-major axis is very sensitive to the value of the heliocentric velocity. When studying the structure of meteoroid streams through shower meteors, the fact that the original orbital dispersion can be smeared by larger observational and measurement errors has also to be considered. The initial dispersion of meteoroids in a stream is influenced by a number of processes, which appear during different stages of the stream evolution. An overview of the underlying principles of meteor stream formation and evolution has been given by Kresák (1992), Williams (2003), and others. The effect of these processes on the structure of meteoroid streams naturally depends on the type of stream (Williams & Ryabova, 2011). However, Kresák (1992), analyzing widely dispersed annual meteor showers from the photographic catalogues of the IAU MDC, showed that the measurement errors can be two or three orders of magnitude larger than the dispersion produced by planetary perturbations integrated over several revolutions. The most significant source of uncertainty in semi-major axis determination is inaccuracy in the heliocentric velocity $v_H$. Errors in $v_H$ of 1 km/s correspond to about 0.08 to 0.09 AU$^{-1}$ in 1/a. For short-period meteoroid streams, differences in velocity are less representative and the dispersion in the semi-major axes is
smaller. Thus, discovering errors is more difficult because they do not produce a spurious hyperbolicity as clear evidence of their presence, as is the case with long-period streams (Hajduková, 2011, 2013).

The Geminids is one of the largest showers in the meteor databases, which was observed using different techniques and studied by a large number of researchers over a large time scale. A comprehensive review of observational and theoretical studies of the Geminid stream was published by Nersisyan (2015). The Geminid meteor shower, observed by video technique, was reported by Ueda & Fujiwara (1993); de Lignie et al. (1993); Elliott et al. (1993); Andreic & Segon (2003); Jenniskens et al. (2010, 2011, 2016a); Trigo-Rodríguez et al. (2010); Tóth et al. (2011, 2012); Rudawska et al. (2013); Madiedo et al. (2013); Molau et al. (2015, 2016), and others.

In this study, we concentrate on the influence of both the accuracy of various measurements and the precision of orbit determination on the distribution of meteor orbits within the stream of Geminids and on the dispersion of their radiant points. The dispersions are studied, comparing several catalogues (introduced in section 2), which enables the specific features of the Geminids, as well as the diversities of the catalogues, to be shown. In section 3, we describe the dispersion of the Geminids’ radiant points, and in section 4, the dispersion of their orbits. We also discuss the dynamics of the Geminid stream in terms of the uncertainties of the numerical integration procedures, which reflect the reliability of the results obtained (section 5).

2. Video orbits and their precision

The necessity of high quality orbits of video meteors and precision in their velocity measurements has been discussed by Atreya et al. (2012) and Egal et al. (2014), who, to make improvements, introduced the CABERNET (Camera for Better Resolution Network) system. The importance of an error analysis was reported by Drolshagen et al. (2014) and Albin et al. (2015) in their analysis of the meteor velocity distribution from the CILBO (Canary Island Long-Baseline Observatory) double station video camera data. The accuracy of video meteor orbits was discussed by Skocic et al. (2016), who analysed several major showers obtained by several video networks including the Croatian Meteor Network.

In this study, we analyze Geminids from six different video catalogues. The individual samples of the Geminids were obtained using the Welch procedure (Welch (2001), described in more detail in section 5). All of them fulfill
the Southworth-Hawkins D-criterion for orbital similarity (Southworth & Hawkins, 1963), with the condition $D_{SH} < 0.2$. The data used are summarized in Table 1. The observed orbital and radiant dispersions of video Geminids, including the measurement errors, obtained separately for each catalogue, are compared with those obtained from the photographic and radio Geminids selected from the IAU Meteor Data Center (Lindblad et al., 2003; Neslušan et al., 2014; Lindblad, 2003).

We used data from our own video observations, carried out in the Slovak and Czech Republics, that are collected in the Slovak Video Meteor Network’s database (Tóth et al., 2015) and in the Czech Catalogue of Video Meteor Orbits (Koten et al., 2003). We also selected orbits of the Geminids from several video catalogues that were available: the Cameras for Allsky Meteor Surveillance (CAMS) Meteoroid Orbit Database (Jenniskens et al., 2011), Dutch Meteor Society Video Database (de Lignie, 1996), the SonotaCo Shower Catalogue (SonotaCo, 2009), and the European Video Meteor Network Database - EDMOND (Kornoš et al., 2014). The data used are based on various meteor-detection software packages and various meteor orbital element softwares. In this section, therefore, we introduce briefly all the databases of the video networks used, their instrumentation and data reduction.

### 2.1. Slovak Video Meteor Network’s (SVMN) Database

The Slovak Video Meteor Network, governed by Comenius University in Bratislava, consists of four video stations situated in various locations in Slovakia, which monitor meteor activity above Central Europe. The SVMN uses the semi-automatic all sky video cameras (All-sky Meteor Orbit System, AMOS), which record meteors of +4 magnitude and brighter (Tóth et al., 2015). For meteor detection and astrometric data reduction, UFOCapture software and UFOAnalyzer (SonotaCo, 2009) are used. For meteor orbit computation, the new Meteor Trajectory software, based on the Ceplecha (1987) paper, was developed (Kornoš et al., 2015). The program computes orbital and geophysical parameters, together with their uncertainties, based on the Monte Carlo simulation. The velocity determination, giving uncertainties about 0.1 km/s, is still being worked on. So far, the achieved precision is $< 3$ deg in radiant position and $< 10\%$ in velocity. Data from SVMN are continuously published (Tóth et al., 2015) and contribute to the EDMOND database (see section 2.5). However, the Slovak data from the SVMN observations are also analysed differently. For the EDMOND, velocity and radiant
are calculated as average values from the stations (according to the Sono-taco), while in the SVMN, trajectory and velocity are calculated by our own software [Kornoš et al., 2015] based on Ceplecha (1987) and by fitting the observed meteor velocity.

2.2. Czech Catalogue of Video Meteor Orbits (Ondřejov data)

The Czech database of the video meteors [Koten et al., 2003] contains data obtained within the double station observational campaigns carried out in the Czech Republic. These campaigns were dedicated to several selected meteor showers. The video cameras, connected with image intensifiers, were aimed at one particular meteor shower during each campaign, so the geometry of observation was optimized for this shower. The limiting magnitude is +6. The observed data are recorded in time resolution 0.04 second. Records are searched using automatic detection software MetRec [Molau, 1999]. Found meteor images are digitalized with a PC frame grabber, transformed into 768 x 576 pixel, 8-bit monochrome images, and stored as sequences in a non-compressed AVI format. All the recorded meteors are carefully reviewed and only records of good quality are taken into account. Raw data are measured manually and atmospheric trajectories and heliocentric orbits calculated. No automatic reduction or calculation software is applied. Only well proven methods are used for image measurement (Koten, 2002), and trajectory and orbit calculations (Borovička, 1990). The errors of the measurement are propagated through the calculation to the errors of the parameters. The achieved precision is usually a few tenths of a degree in the radiant position and up to 0.5 km/s in the velocity. The database contains only reliable data, at the expense of the total number of trajectories and orbits, which is rather small.

2.3. Dutch Meteor Society Video (DMS) Database

The double-station video observations in the Netherlands are among the first video observations of meteors, which started about 30 years ago. Their cameras recorded meteors with the limiting magnitude +7, in a 25 degrees field of view (de Lignic, 1996, 1999). The data reduction was done with the AstroRecord measuring program and with the Ceplecha (1987) software for calculating trajectories and orbital elements (de Ligne & Betlem, 1999). The double-station meteors are measured with an astrometric accuracy of 45 arc seconds. The results from video observation campaigns by the Dutch
Meteor Society have been published on a regular basis and are available at their website: http://dmsweb.home.xs4all.nl/video/video.html.

2.4. Cameras for Allsky Meteor Surveillance (CAMS) Database

The Cameras for Allsky Meteor Surveillance system operates 60 identical narrow-angle field-of-view cameras at three locations in California (Jenniskens et al., 2011), detecting mostly $+4$ to $-2$ magnitude meteors. The data are automatically processed using the detection algorithms and modules from the MeteorScan software package (Gural, 1995, 1997) and a newly developed software for calibration and multistation coincidence processing which produces atmospheric trajectories and orbital elements (Jenniskens et al., 2016a,b). The achieved precision is $<2$ deg in radiant direction and $<10\%$ in velocity (mean values are 0.24 deg and 2\%, respectively). The project was designed to validate the unconfirmed showers in the IAU working list of meteor showers. The meteors assigned to the various showers are identified in the CAMS Meteoroid Orbit Database 2.0 (which can be accessed at http://cams.seti.org) and are submitted to the IAU Meteor Data Center.

2.5. European Video Meteor Network Database (EDMOND)

The multi-national network EDMOND (Kornoš et al., 2014) was created thanks to the broad international cooperation of video meteor observers from several European countries. The national networks involved are: BOAM (Base des Observateurs Amateurs de Metores, France); BosNet (Bosnia); CEMeNt (Central European Meteor Network, cross-border network of Czech and Slovak amateur observers); CMN (Croatian Meteor Network or Hrvatska Meteorska Mreza, Croatia); FMA (Fachgruppe Meteorastronomie, Switzerland); HMN (Hungarian Meteor Network or Magyar Hullcsillagok Egyesulet, Hungary); MeteorsUA (Ukraine); IMTN (Italian amateur observers in Italian Meteor and TLE Network, Italy); NEMETODE (Network for Meteor Triangulation and Orbit Determination, United Kingdom); PFN (Polish Fireball Network or Pracownia Komet i Meteorów, PkiM, Poland); Stjerneskud (Danish all-sky fireball cameras network, Denmark); SVMN (Slovak Video Meteor Network, Slovakia); UKMON (UK Meteor Observation Network, United Kingdom), BRAMON (BRAzilian MeteOr Network), and the International Meteor Organization Video Meteor Network (IMO VMN). Meteors (registered with the limiting magnitude $+4$) are obtained and reduced using two different tools, the MetRec (Molau, 1999) and UFO softwares (SonotaCo.
The computation of meteor orbits is performed by using the UFOOrbit software; therefore, data obtained by the MetRec software are converted into the UFO format using the SonotaCo program INF2MCSV. Multiple filters and selective criteria involving the quality parameters (as defined in the SonotaCo format) are applied (Kornoš et al., 2013) to eliminate meteors with the largest errors in their velocity determination. For our analysis, we applied additional criteria to separate orbits of the highest quality from the EDMOND data. These included: the meteor trail had to be longer than 1 degree, the duration of the trail had to be over 0.3 s, and the entire meteor trail had to be inside the field of view of at least two video meteor stations.

2.6. SonotaCo Meteor Shower Catalogue

Video observations have been carried on for more than a decade by the SonotaCo consortium (SonotaCo, 2009), using more than 100 wide-angle video cameras at 25 stations in Japan. The network registers meteors mostly up to +2 magnitude. Data are reduced using the UFO software package developed by SonotaCo (2009), which makes the catalogue homogenous in spite of the large number of individual observers. On account of their larger fields of view, the precision of the radiant positions measured is approximately a factor of two less precise than the CAMS network (Rudawska & Jenniskens, 2014), which corresponds to an average spread in radiant of about 5 deg.

A detailed analysis of the SonotaCo meteor orbits concerning the qualitative aspects was made in the paper by Vereš & Tóth (2010). The SonotaCo network simultaneously-observed meteor data sets are freely accessible at http://sonotaco.jp/doc/SNM/. For our analysis, in the case of the SonotaCo data, we applied additional selective criteria, as we did with the EDMOND database (Hajduková et al., 2014), and used the obtained subset of higher quality orbits.

Except for the above mentioned video networks, there are some others we would like to mention to complete this overview. Another automated system to observe video meteors is the Canadian Automated Meteor Observatory (CAMO). Their wide-field camera system, appropriate for measurements of meteoroid fluxes, has average radiant errors of 0.3 deg and speed uncertainties of 3% (Weryk et al., 2013; Musci et al., 2012).

The Spanish Meteor Network (SPMN) (Trigo-Rodriguez et al., 2007, 2008; Madiedo et al., 2008), which uses high-sensitivity CCD video devices and
Table 1: The Geminids analysed in this work. All the orbits from the video catalogues used were selected under the condition $D_{\text{SH}} < 0.2$ of the Southworth-Hawkins $D$-criterion for orbital similarity.

| Database                                           | No of Geminids |
|----------------------------------------------------|----------------|
| The Slovak Video Meteor Network (SVMN)             | 143            |
| The Czech Catalogue of Video Meteor Orbits (ONDŘEJOV) | 74             |
| The Cameras for Allsky Meteor Surveillance (CAMS)   | 4827           |
| The SonotaCo Shower Catalogue (SONOTACO)           | 8264           |
| The European Video Meteor Network Database (EDMOND) | 2401           |
| The Dutch Meteor Society Video Database (DMS)      | 104            |

CCD all-sky cameras, provides high accuracy orbits of meteors, especially fireballs.

3. Geminid shower. Radiant and speed

Measurement errors are, in general, smaller for long-lasting meteors. Their distributions for Geminid meteors obtained by Slovak and Czech video observations, and compared with CAMS data, are shown in figure 1. The plot is based on figure 10 from Jenniskens et al. (2011), who compared their mean measurement errors to those reported for several other surveys, using various observational techniques. The apparent radiants in the CAMS data are measured with a median uncertainty of $\pm 0.31$ deg having a standard deviation of $0.42$ deg. Their uncertainty in apparent entry velocity is $\pm 0.53$ km/s, with a standard deviation of $0.91$ km/s (Jenniskens et al., 2011). For CAMS Geminids, the median error in the entry velocity has a value of $\pm 0.35$ km/s, and in the declination $\pm 0.21$ deg. The median uncertainties of Ondřejov Geminids are $\pm 0.21$ km/s in entry speed and $\pm 0.155$ deg in declination. As it is seen from figure 1, no Geminids with an error larger than 0.09 deg in declination and 2% in speed are in the Czech video catalogue, in comparison with the values of 2 deg and 10% for CAMS data.

The error in declination for the Geminids observed by the Slovak Video Meteor Network reaches up to 2.9 deg, and the velocity error is kept under 10%. AMOS cameras have a large field of view and high sensitivity at the same time, which leads to the detection of faint and short meteors on one side, and bright and long meteors, up to fireballs, on the other side. As a result,
Figure 1: Error in apparent entry velocity and in declination of the Geminids from Czech and Slovak video meteor data compared with those from CAMS. The vertical and horizontal lines represent the limits for errors in speed and declination for Czech (red dotted lines), Slovak (green dash-dotted lines) and CAMS (black dashed lines) data.

both meteors of lower precision (due to the limitation of a small number of observed points on the atmospheric trajectory) and meteors of higher precision (with sufficient data points for the velocity fit and precise trajectory determination) are obtained. This is why two groups partly overlapping each other on the uncertainty velocity distribution graph (figure 1) appear; the first group with a good velocity fit with small uncertainty (under 2% in the velocity error) and the second group with velocity determined solely by the arithmetic mean from the first third of the atmospheric trajectory (with the velocity error above 2%).

3.1. The mean radiant and its motion

The influence of measurement errors can also be seen from the distributions of the radiant points. Kresák & Porubčan (1970), analysing several photographically observed major meteor showers showed that the radiant dispersion undoubtedly increases with the velocity dispersion, and vice versa. For most of the showers analysed, the positional errors were negligible in comparison with the actual deviations from the mean value. However, the authors concluded that errors in the radiant positions may play some role
in the relatively small radiant area of the Geminid shower. The deviations of shower meteors with respect to their position and velocity were analysed also by Molau (2008), who demonstrated that, for short-lasting meteors, even small measurement errors can result in large errors of their direction.

The compactness of the Geminid stream is reflected in the relatively small radiant area of the shower (Kresák & Porubčan, 1970; Porubčan et al., 2004). The distributions of the geocentric radiants of the Geminids from various data sets are shown in figure 2a. The figure shows a good agreement in the radiants among all the data, whereby large data sets show larger dispersions, reaching the dispersion of the radio observed Geminids (fig. 2b). Radiant points of the SVMN and the Ondřejov Geminids show the highest concentrations. However, one would expect a wider spread in the SVMN data, taking into
Table 2: The radiant ephemeris for the video Geminids determined from Slovak, Czech and CAMS databases

| Database | right ascension (2000.0) | declination (2000.0) |
|----------|-------------------------|----------------------|
| SVMN     | 113.2 + 0.91(L_S - 261.8) | 32.3 - 0.02(L_S - 261.8) |
| ONDREJOV | 113.3 + 1.11(L_S - 262.1) | 32.3 - 0.11(L_S - 262.1) |
| CAMS     | 112.5 + 1.02(L_S - 261.1) | 32.4 - 0.14(L_S - 261.1) |

account their given uncertainties (seen in the figure 1). This suggests that the formal uncertainties in the SVMN data could be overestimated.

Figure 2c shows the radiant positions corrected for the radiant motion for Slovak, Czech and CAMS Geminids. The daily motion in right ascension and declination was found by the least-squares solution. The corresponding determined equatorial coordinates of the mean geocentric radiants are listed in Table 2. The L_S is the solar longitude of the time of observation for equinox 2000.0. The solar longitude used for the radiant corrections was the mean value determined from each catalogue separately. The vast majority of SVMN Geminids are within a very small interval of solar longitude; therefore, the daily motion of the radiant declination was not possible to determine confidently for this data.

The radiant area of Geminids (figure 2c) is approximately 15 x 10 deg obtained from the large CAMS catalogue and about 10 x 5 deg obtained from the Ondřejov data. The found spread includes the dispersion caused by measurement errors. The calculated median uncertainties of Czech/Ondřejov (Slovak/SVMN) Geminids are 0.23 deg (0.55 deg) in right ascension and 0.16 deg (0.42 deg) in declination. The corresponding values for CAMS data are 0.44 deg and 0.69 deg. Kresák & Porubčan (1970) found the median real dispersion of the photographic Geminids to be 0.49 deg, which suggests how strong is the influence of measurement errors in the video data.

3.2. Radiant dispersion as a function of semi-major axis

To analyse the radiant area in connection with the distribution of meteoroids with different semi-major axes, we divided the data into three samples. The number of meteors in each sample was kept near 1/3 of the total number. The results for four catalogues are shown in Figure 3 a, b, c, d. The
plots demonstrate that the diffused marginal regions of the Geminid radiant are affected mostly by meteoroids with extreme values (small or large) of the semi-major axes. The radiant points of the meteoroids with semi-major axes from the middle interval (which mostly define the stream) are more concentrated and create a central area of about 5 x 5 deg obtained from the larger catalogues.

In all four data sets, meteoroids of shorter semi-major axes occupy the eastern side of the radiant area, whereas those of longer semi-major axes concentrate at the western part. A similar displacement of radiant points, depending on the semi-major axes, due to a vectorial composition of velocities, was found by Kresák & Porubčan (1970). Furthermore, the dispersion in the right ascension seems to be slightly greater for lower values of a, that in the declination, for higher values of a (seen especially in the Ondřejov data).

3.3. Velocity distribution - a shift in the video data

Normalized distributions of the reciprocal semi-major axes and geocentric velocities of the video Geminids from all of the catalogues used, and their comparison with the photographic and radio Geminids from the IAU MDC are shown in Figure 4 a and b. The distribution of both the semi-major axes of meteor orbits and the geocentric velocities in all the video data sets except the Ondřejov data seem to be systematically biased in comparison with the photographic and radar meteors. The observed distributions in $1/a$ are shifted towards higher values of $1/a$. The determined velocities seem to be underestimated, probably as a consequence of the methods used for the measurement of the meteor positions and velocities (due to measuring of the center of the meteor image, and absent or insufficient correlations for atmospheric deceleration). The largest shift is observed in the EDMOND and SonotaCo data, both determining the speed value as an arithmetic mean. In the SVMN database, it is possible to determine their entry velocity with a higher precision, though only for the meteor data which allow us to determine the deceleration using the exponential fit. The velocities in the Czech data are computed from the manual measurements of the individual meteor points. For each frame the meteor position is measured not as the position of the head edge of the meteor but the effect of blooming is taken into account. Therefore, the position is measured "inside" the meteor image. The distance from the edge is the same as the half-width of the meteor image. The measurement of the image edge can lead to overvaluing of the velocity,
Figure 3: Radiant dispersion as a function of semi-major axis for video Geminids from CAMS (a), EDMOND (b), SonotaCo (c), and Ondřejov (d) data.
Figure 4: Normalised distributions of the reciprocal semi-major axes and geocentric velocities of the video Geminids from the different catalogues used, and their comparison with the photographic and radio Geminids from the IAU MDC. The observed shift in semi-major axes medians (and in the median values of the geocentric velocity) from the video data is visible in almost all the catalogues except for the Ondřejov data.

whereas the measurement of the image center causes undervaluing.

To demonstrate the shift in the video data more clearly, we plotted magnitudes of Geminid meteors as a function of their geocentric velocity (figure 5). Each video data set (black squares) is separately compared with the photographic Geminids from the IAU MDC (grey triangles). The shift is demonstrated by the gap between the vertical lines, showing the mean and median values of the geocentric velocities from the video and photographic catalogues. The smallest gaps are seen in the data sets from Ondřejov and CAMS, both registering fainter meteors - of about 2 magnitudes more than SonotaCo or EDMOND observations, the limiting magnitude of which is comparable with the photographic data set. This fact shows that the shift is not caused by the different masses of the data sets, but owing to the errors. This is also supported by the comparison with the radar observations registering even fainter meteors, distribution of which does not show any shift in the semi-major axes in comparison with the photographic data (see also fig. 4 and/or Table 3).
Figure 5: Magnitude as a function of geocentric velocity of the Geminids from different video data sets (black squares), compared with the photographic Geminids from the IAU MDC (grey triangles). The vertical lines represent the mean (dotted line) and median (solid line) values of the velocity determined from the video (black) and photographic (grey) data.
Table 3: The Geminids mean orbits determined from various video data and compared with those of the photographic and radio Geminids. For video data, the mean values of the orbital elements and geocentric parameters were determined by weighted arithmetic mean, using the Welch method.

| Catalogue       | a [AU]   | e       | q [deg] | i [deg] | ω [deg] | Ω [deg] |
|-----------------|----------|---------|---------|---------|---------|---------|
| ONDŘEJOV        | 34.06±1.25 | 1.35    | 0.15±0.01 | 0.89±0.02 | 22.98±2.31 | 323.7±1.7 | 262.1±0.4 |
| SVMN            | 33.55±1.37 | 1.29    | 0.15±0.01 | 0.89±0.02 | 22.42±1.92 | 324.1±1.7 | 261.9±1.3 |
| CAMS            | 34.23±1.45 | 1.34    | 0.14±0.01 | 0.89±0.02 | 23.34±2.10 | 324.4±1.5 | 261.2±1.7 |
| SONOTACO       | 33.81±0.01 | 1.30    | 0.15±0.01 | 0.89±0.01 | 22.85±1.71 | 324.2±1.3 | 261.5±1.6 |
| EDMOND          | 33.49±1.21 | 1.28    | 0.15±0.01 | 0.88±0.02 | 22.49±2.01 | 324.3±1.5 | 261.2±1.6 |
| DMS             | 33.80±0.88 | 1.31    | 0.14±0.01 | 0.89±0.01 | 22.35±2.09 | 324.1±1.0 | 262.3±0.1 |
| PHOTOIAU        | 34.32    | 1.36    | 0.14    | 0.89    | 23.70    | 324.4    | 261.8    |
| RADIOIAU        | 34.33    | 1.40    | 0.14    | 0.89    | 23.56    | 324.7    | 259.7    |

4. Geminid stream. Orbits

4.1. Mean orbital parameters

To compare all the various data, we selected, from all the data sets, the Geminids that fulfilled the Southworth-Hawkins D-criterion for orbital dissimilarity (Southworth & Hawkins, 1963) with the condition $D_{SH} < 0.2$ (Table 1). We searched for the core of the shower by comparing the density values of the groups of meteors created by the Welch procedure (Welch, 2001) around each orbit. The higher the density value, the more important the group in the shower is. Consequently, we determined the mean orbital elements and geocentric parameters of the densest group by weighted arithmetic mean, using the Welch method. The weight of the meteor was determined by $(1 - D_i^2/D_c^2)$ (Welch, 2001). The resulted weighted mean parameters and their standard deviations for each examined catalogue are listed in the the Table 3. For a comparison, we listed also mean (not weighted) parameters obtained from the radio and photographic catalogues of the IAU MDC.

4.2. Orbital dispersion

The orbits of the Geminids with aphelia far inside the orbit of Jupiter indicate that the stream structure is dominated by their initial spread and the non-gravitational effects (Williams & Ryabova, 2011). However, the gravitational forces of Jupiter and inner planets also influence the stream structure (Ryabova, 2014), while the other outer planets influence is negligible. The differences in the velocities are less representative, and the dispersion in the semi-major axes smaller in comparison with long-period streams.
In analyzing the error function, we proceeded according to the analysis of the accuracy of the semi-major axes of meteoroid orbits made by Kresáková (1974). To describe the dispersion of the semi-major axis within the meteor stream, we used the median absolute deviation $\Delta_M$ in terms of $1/a$ ($\Delta_M(1/a) = |(1/a)_{1/2} - (1/a)_M|$), where $(1/a)_{1/2}$ are limiting values of the interval, which includes 50 percent of all orbits in the stream). The probable range of uncertainty was determined by $\pm n^{-1/2} \Delta_M(1/a)$, where $n$ is the number of the meteor orbits used for the median determination $(1/a)_M$. For the sake of comparison, we also derived the deviations of the median $(1/a)_M$ from the parent body $\Delta(1/a)_C = |(1/a)_M - (1/a)_C|$, where the $(1/a)_C$ is the reciprocal semimajor axis of asteroid (3200) Phaethon. The numerical results describing the observed orbital dispersion within the video Geminids are listed in Table 4. Their comparison with the Geminids’ dispersion from the photographic and radar data is shown in figure 6. The median absolute deviations $\Delta_M$ in terms of $1/a$ range from 0.028 to 0.049 AU$^{-1}$ for the different videocatalogues. The figure shows the dispersion of video Geminids to be comparable with the dispersion of photographic Geminids (0.040 AU$^{-1}$), and to be significantly smaller than the dispersion

![Figure 6: Observed orbital dispersion for Geminids described by absolute median deviation in terms of $1/a$: Thin line - interval between two limiting values of $(1/a)_{1/2}$, which includes 50 percent of all orbits. Bold line - interval between two limiting values of the uncertainty $(1/a)_L$ of the resulting values of median $(1/a)_M$. Dashed vertical lines - parent body. Good agreement in the medians of $1/a$ is seen in the IAU MDC photographic, radio, and in the Ondřejov video data. In all other video databases, it is shifted towards higher values.](image-url)
Table 4: Numerical data obtained for the orbital dispersion of the video Geminids. \( n \) - number of meteors; \((1/a)_M\) - the median \(1/a\); \(1/a\) - the mean value of \(1/a\); \(\Delta_M\) - the median absolute deviation; \(\Delta_L\) - the range of uncertainty; \(\Delta_C\) - deviation of the median \(1/a\) from the parent body; \(1/a\) of the parent comets (eq. 2000.0).

| Database   | No of orbits | \(v_G\) | \((1/a)_M\) | mean \(1/a\) | \(\Delta_M\) \((1/a)\) | \(\Delta_L\) \((1/a)\) | \(\Delta_C\) \((1/a)\) |
|------------|--------------|---------|-------------|-------------|----------------|----------------|----------------|
| SVMN       | 143          | 33.68   | 0.766       | 0.773       | 0.049          | 0.004          | - 0.021        |
| Ondrejov   | 74           | 34.29   | 0.734       | 0.775       | 0.044          | 0.005          | - 0.050        |
| CAMS       | 4829         | 33.97   | 0.758       | 0.739       | 0.046          | 0.001          | - 0.029        |
| SonotaCo   | 8264         | 33.82   | 0.766       | 0.764       | 0.036          | 0.001          | - 0.021        |
| EDMOND     | 2401         | 33.50   | 0.781       | 0.780       | 0.038          | 0.001          | - 0.006        |
| DMS        | 104          | 33.80   | 0.762       | 0.761       | 0.028          | 0.003          | - 0.025        |

of radio Geminids \((0.077 \text{ AU}^{-1})\). This is partly a consequence of different dispersions in the orbital elements for particles belonging to different mass ranges. The limiting magnitude of the SVMN, SonotaCo or EDMOND observations is comparable with that of the photographic data set, while that of the Ondřejov, CAMS and DMS data, is about 2 magnitudes more; and the radio observations register even fainter meteors. It also has to be considered that the video data were observed mostly during the last few years, whereas the photographic data cover more than 30 years of observations; thus, we are dealing with particles from a different cross section of the stream traversed by the Earth.

The deviation of the median reciprocal semi-major axis from the parent body, asteroid (3200) Phaethon, obtained from the photographic and radar orbits of the IAU MDC, and from the Czech Video Orbits Catalogue, is significantly larger than in the other video data sets. However, this is only a consequence of their above-mentioned shift. The actual reason for the deviation from their parent asteroid might be found when investigating the dynamical evolution of the Geminid meteoroids and the 3200 Phaethon.

5. The Geminid-stream dynamics and the uncertainties

The main purpose of this paper is to emphasize the problem of measurement/determination errors, which have to be considered when interpreting
results. Since similar problem also applies to analyzes based on numerical integration, we include a short section about the dynamics of the stream. We would like to briefly point out the problem of errors in the integration procedures which are used for stream modeling. The uncertainties influence the outputs of the simulations and give us important information about the reliability of the results obtained.

5.1. Models versus observations

The initial dispersion of meteoroids in a stream is influenced by a number of processes (planetary perturbations, collisions, solar radiation, solar wind and other non-gravitational forces), which appear during different stages of the stream evolution. Williams & Ryabova (2011) have discussed their influence on the structure of meteoroid streams, and demonstrated that the dominant process depends on the stream and thus, for the stream models, it is important to consider both the initial processes of formation and the subsequent gravitational perturbations. There have not been any close encounters significantly affecting the Geminids’ orbits during at least the last ten thousand years (Ryabova, 2007), so the initial structure caused by the ejection process should still be traceable in the stream. The deviations which may have accumulated since the formation of the stream can hardly exceed a few thousandths in 1/a (Kresáková, 1974). Nevertheless, the non-gravitational forces have an influence on both the orbits of the meteoroids (e.g. P-R drag) and the orbit of the asteroid (e.g. rocket effect/yet force) (Galushina et al., 2015; Ryabova, 2016).

Over time, various Geminid stream models have been developed (Fox et al., 1982, 1983, 1984; Williams & Wu, 1993; Babadzhanov & Obrubov, 1983, 1986, 1987; Ryabova, 2001, 2007, 2008, 2016; Kaňuchová & Švoren, 2006). A compilation of them can be found in Neshšan (2015) and their detailed individual significance explained in Ryabova (2014). In spite of the large number of Geminid stream studies, there are still discrepancies between the models and observations, e.g. the width of the stream, the location of the stream and the maximum of the shower activity (Ryabova, 2016). The Geminid shower width does not increase, even if encounters with the inner planets are included into consideration in models (Ryabova, 2016). The most probable reason for the discrepancies is the transformation of the parent body orbit by the jet force (Ryabova, 2014, 2016) according to the Lebedinets (1983) hypothesis of a rapid release of the volatiles in the process of the stream single initial formation.
In general, if the orbit of a parent body was, in the past, significantly influenced by non-gravitational effects, the currently observed stream could have been formed when the parent body moved in a slightly different orbit than it moved at its last return to the perihelion (Neslušan et al., 2015). However, the Phaethons’ semi-major axis is stable, and the changes in the asteroid’s other orbital elements are smooth (Ryabova, 2008; Jakubík & Neslušan, 2015).

Jones et al. (2016) argued that most attempts to model the Geminid meteor stream had been based on Whipple’s model for the ejection of meteoroids from comets (assuming ejection speeds about a factor of at least 3 too low), which predicts much smaller dispersions in terms of the orbital elements than are found in the observed behaviour of the Geminids. However, Jakubík & Neslušan (2015) showed in their simulations that no matter if they assumed the unique speed and random directional distribution of the test particles or a more realistic ejection, the appropriate orbital phase space was fullfilled with test particles after a certain period (which is, using their model, about 30 orbital revolutions of the parent). This means, in the case of the asteroid 3200, it is less than a century. And most of the simulations exceed this time.

The authors (Jakubík & Neslušan, 2015) also examined the acceleration due to the P-R drag on the Geminid test particles which should, in general, cause an enlargement of the dispersion of orbits. This, however, may not be reflected in the corresponding meteor shower observed in the Earth’s atmosphere, since some stream particles can be completely deflected from a collisional course with the Earth. According to their model, the physical properties of the prevailing part of the Geminids correspond to the values from 0.005 to 0.018 of the $\beta$ parameter, which determines the strength of the P-R drag. The beta parameter stands for the ratio of the radiation pressure to the gravity, and characterizes the properties of the particle; thus, only the Geminids with the corresponding properties can be observed.

5.2. The simulations reliability

We studied the evolution of the orbit of the asteroid (3200) Phaethon by means of numerical integration using Everhart’s integrator RA15, from the package Mercury 6 (Chambers, 1999). The model of the Solar System used in the integration tests included 8 planets, the Moon as a separate body, and the most influential asteroids: Ceres, Pallas, Vesta, and Hygiea (Galad, 2001).
Table 5: The actual orbit of Phaethon and its orbits after the integration to the past for 10,000, 20,000 and 50,000 years and then back to the present. Differences in particular orbital elements can reach the following values: $\Delta a < 0.01 \, \text{AU}$, $\Delta e \sim 0.003$, $\Delta i \sim 1.5^\circ$, $\Delta \omega \sim 3.0^\circ$, $\Delta \Omega \sim 3.5^\circ$ and $\Delta q \sim 0.004 \, \text{AU}$.

|          | a [AU] | e      | i [deg] | peri [deg] | node [deg] | q [deg] |
|----------|--------|--------|---------|------------|------------|---------|
| present  | 1.2711 | 0.8898 | 22.24   | 322.14     | 265.27     | 0.1400  |
| after 10000 yr | 1.2740 | 0.8897 | 22.19   | 322.05     | 265.29     | 0.1404  |
| 20000 yr | 1.2780 | 0.8882 | 22.94   | 323.67     | 263.04     | 0.1428  |
| 50000 yr | 1.2772 | 0.8870 | 23.46   | 325.01     | 261.80     | 0.1443  |

Several experimental integrations of the asteroid, performed from the present to the past and then back to the year 2015, showed that it is not possible to reproduce the initial asteroid’s orbit. A complete reproduction, also including the mean anomaly, is only possible for a time span of about 2700 years; the mean anomaly differs only $3 \times 10^{-6}$ deg. After 3800 years, the difference is $\sim 0.03$ deg and after 4700 years, it is not possible to reproduce the mean anomaly. However, the chaos indicators behavior has to be taken into account. E.g. MEGNO (Mean Exponential Growth of Nearby Orbits) shows that the chaos along the Geminid’s orbit begins after already 400 years of integration [Galushina & Letner, 2016], and Lyapunov indicator shows that it begins after 1500 years approximately [Avdyushev, 2016].

In addition, the results of the integration depend not only on the chosen integrator, but also, within a particular integrator, on a specific perihelion passage, on the selected accuracy parameter, and on predetermined intervals of the outputs, which forces the integrator to modify its own integration steps to match the output moments.

6. Summary and Conclusions

We examined the influence of the uncertainties of the velocity measurements and orbit determination on the dispersion of radiants and meteoroid orbits within the stream of Geminids. The dispersion was studied, comparing several databases, based on various meteor-detection software packages and various meteor orbital element softwares. For the analysis, data from our own video observations, carried out in the Slovak and Czech republics, as well as data from several available video databases were used:
the Slovak Video Meteor Network’s database (Tóth et al., 2015), the Czech Catalogue of Video Meteor Orbits (Koten et al., 2003), the CAMS Meteoroid Orbit Database (Jenniskens et al., 2011), the Dutch Meteor Society Video Database (de Lignie, 1996), the SonotaCo Shower Catalogue (SonotaCo, 2009), and the EDMOND Database (Kornoš et al., 2014). The comparison of the errors distribution was based on the velocity and radiant uncertainties declared by the authors of the databases. To avoid the distortion by extreme deviations caused by gross errors, we chose the medians rather than arithmetic means as the basic dispersion parameter. For the mean orbit determination, we used the weighted values of the orbital elements.

The Geminids’ radiant dispersion obtained from the large video catalogues reaches the dispersion of the radio observed Geminids, whereby the diffused marginal regions are affected mostly by meteoroids with extreme values (small or large) of the semi-major axes. Meteoroids of shorter semi-major axes occupy the eastern side of the radiant area and those of longer semi-major axes the western part.

The observed orbital dispersions in the Geminid stream described by the median absolute deviation range from 0.028 to 0.049 AU for the different video catalogues. It does not differ significantly between the different video databases. It differs slightly between the data sets obtained by different observational techniques, which may be partly a consequence of different dispersions in the orbital elements for particles belonging to different mass ranges.

The distribution of the semi-major axes of video meteors in all the video data sets, except for the Ondřejov data, seem to be systematically biased in comparison with the photographic and radar meteors. The reciprocal semi-major axes are shifted towards higher values; the determined velocities are underestimated. This is a consequence of the methods used for the measurement of the meteor positions and the velocity. The measurement of the image edge can lead to overvaluing of the velocity, whereas the measurement of the image center causes undervaluing. The largest shift is observed in the EDMOND and SonotaCo data. The velocities in the Czech data, which did not show any shift, are computed from the manual measurements of the individual meteor points. For each frame, the position is measured "inside" the meteor image. This approach comes at the expense of the total number of trajectories and orbits; however, the database contains only reliable data.

To avoid entering poor quality data into the databases, an improvement in the measurement of the meteor positions and meteor velocities is essen-
Moreover, stronger filters for the selection of orbits should be used, which will come at the expense of the quantity of the data. However, for some purposes, only high accuracy data are applicable, failing which, each analysis using the velocity data will be seriously affected by measuring errors.

Aside from those measurement errors which have an effect on the analyses, we have also indicated the difficulties associated with the uncertainties of the numerical integration procedures that influence the results of the simulations. We performed several experimental integrations of the Geminids’ parent asteroid, from the present to the past and then back to the year 2015, and demonstrated that a complete reproduction is only possible for a time span of about 2700 years. This finding impacts analyses based on numerical integrations and/or their interpretations.

Acknowledgements. We gratefully thanks Galina Ryabova for helpful discussions and comments that have improved the article. The work was supported, by the Slovak Grant Agency for Science VEGA, grant no. 1/0225/14, by the Slovak Research and Development Agency under the contracts no. APVV-0517-12, and by the Grant Agency of Czech Republic, grant no. 14-25251S.

References

Albin, T.; Koschny, D.; Drolshagen, G.; Soja, R.; Poppe, B.; Srama, R., 2015, Proceedings of the International Meteor Conference, Eds.: Rault, J.-L.; Roggemans, P., 214

Andreic, Z., Segon, D., 2008, WGN, 36, 99

Atreya, P.; Vaubaillon, J.; Colas, F.; Bouley, S.; Gaillard, B., 2012, Mon. Not. R. Astron. Soc., 423, Issue 3, 2840

Avdyushev, V. A., 2016, Nov., private communication

Babadzhanov, P.B., Obrubov, Yu.V., 1983, Proceedings (A84-28901 12-90). Dordrecht, D. Reidel Publishing Co., 1983, 411
Babadzhanov, P.B., Obrubov, Iu.V., 1986, Akademiia Nauk SSSR, Doklady, vol. 290, no. 1, 54

Babadzhanov, P. B.; Obrubov, Yu. V., 1987, Doklady Akademiia Nauk TadzhSSR, Tom 30, no. 8, 486

Borovička, J., 1990, Astronomical Institutes of Czechoslovakia, Bulletin, 41, 391

Chambers, J. E., 1999, Mon. Not. R. Astron. Soc., 304, 793

Ceplecha, Z., 1987, Astronomical Institutes of Czechoslovakia, Bulletin, 38, 222

De Lignie, M.; Jobse, K.; Schievink, R., 1993, Proceedings of the International Meteor Conference, Editors: Ocenas, D.; Zinnikoval, P., 59

De Lignie, M., 1996, Proceedings of the International Meteor Conference, 8

De Lignie, M., 1999, Proceedings of the International Meteor Conference, Eds.: Arlt, R., Knfel, A., 5

De Lignie, M.; Betlem, H., 1999, WGN, 27, Nos. 3 - 4, 195

Drolshagen, E.; Ott, T.; Koschny, D.; Drolshagen, G.; Poppe, B., 2014, Proceedings of the International Meteor Conference, Eds.: Rault, J.-L.; Roggemans, P., 16

Egal, A.; Vaubaillon, J.; Colas, F.; Atreya, P., 2014, Proceedings of the International Meteor Conference, Eds.: Rault, J.-L.; Roggemans, P., 49

Elliott, A.J., Bone, N.M., 1993, Journal of the British Astron. Assoc. 103, 181

Fox, K., Williams, I.P., Hughes, D.W., 1982, Mon. Not. R. Astron. Soc. 200, 313

Fox, K., Williams, I.P., Hughes, D.W., 1983, Mon. Not. R. Astron. Soc. 205, 1155

Fox, K., Williams, I.P., Hughes, D.W., 1984, Mon. Not. R. Astron. Soc. 208, 11P
Galad, A., 2001, Astron. Astrophys., 370, 311

Galushina, T. Yu.; Ryabova, G. O.; Skripnichenko, P. V., 2015, Planetary and Space Science, 118, 296

Galushina, T. Yu.; Letner, O. N., 2016, Izvestiya Vuzov. Fizika. Vol. 59, N 10/2 (In Russian), submitted

Gural, P. S., 1995, WGN, Journal of the International Meteor Organization, vol. 23, no. 6, 228

Gural, P. S., 1997, WGN, Journal of the International Meteor Organization, 136

Hajduková, M., jr., 2011, Contrib. Astron. Obs. Skalnate Pleso, 41, 15,

Hajdukova, M., jr., 2013, Publ. Astron. Soc. Japan, Vol 65, No 4

Hajdukova, M.; Kornoš, L.; Toth, J., 2014, Meteoritics and Planetary Science, 49, Issue 1, 63

Jakubik, M. & Neslušan, L., 2015, Mon. Not. R. Astron. Soc., 453, Issue 2, 1186

Jenniskens, P., Mameta, K., Nakano, S., Koop, M., Trigo-Rodriguez, J.M., Madiedo, J.M., Pujols, P., Millan, J.C., Azcarate, J.A., Zamorano, J., Ocana, F., 2010, Central Bureau Electronic Telegrams, ed. D. W. E. Green, no. 2593, 1

Jenniskens, P.; Gural, P. S.; Dynneson, L.; Grigsby, B. J.; Newman, K. E.; Borden, M.; Koop, M.; Holman, D., 2011, Icarus, 216, Issue 1, 40

Jenniskens, P.; Nnon, Q.; Albers, J.; Gural, P. S.; Haberman, B.; Holman, D.; Morales, R.; Grigsby, B. J.; Samuels, D.; Johannink, C., 2016a, Icarus, 266, 331

Jenniskens, P.; Nnon, Q.; Gural, P. S.; Albers, J.; Haberman, B.; Johnson, B.; Holman, D.; Morales, R.; Grigsby, B. J.; Samuels, D.; Johannink, C., 2016b, Icarus, 266, 355

Jones, J.; Poole, L. M. G.; Webster, A. R., 2016, Mon. Not. R. Astron. Soc., 455, Issue 4, 3424
Kaňuchová, Z., Svoreň, J., 2006, Contrib. Astron. Obs. Skalnate Pleso, 36, 181

Kornoš, L.; Koukal, J.; Piffl, R.; Tóth, J., 2013, Proceedings of the International Meteor Conference, Eds.: Gyssens, M.; Roggemans, P., 21

Kornoš, L., Koukal, J., Piffl, R., and Tóth, J., 2014, Proceedings of the International Meteor Conference, Edited by M. Gyssens, and P. Roggemans, 23

Kornoš, L.; Duriš, F.; Tóth, J., 2015, Proceedings of the International Meteor Conference, Eds.: Rault, J.-L.; Roggemans, P., 101

Koten, P., 2002, Proceedings of Asteroids, Comets, Meteors - ACM 2002. Ed. Barbara Warmbein. ESA SP-500. Noordwijk, Netherlands: ESA Publications Division, 197

Koten, P., Spurný, P., Borovička, J., and Štork, R., 2003, Publ. Astron. Inst. ASCR 91, 1

Kresášk, L., 1992, Contrib. Astron. Obs. Skalnate Pleso, 22, 123

Kresášk, L. & Porubčan, V., 1970, Bull. Astron. Inst. Czechosl., 21, 153

Kresáková, M., 1974, Bull. Astron. Inst. Czechosl. 25, No.4, 91

Lebedinets V. N., 1985, Sol. Syst. Res., 19, 101

Lindblad, B.A., Neslušan, L., Porubčan, V., and Svoreň, J., 2003, Earth, Moon, Planets, 93, 249

Lindblad, B. A., 2003, private communication

Madiedo J.M., Trigo-Rodriguez J.M., 2008, Earth Moon Planets, 102, 133

Madiedo, J. M.; Trigo-Rodriguez, J. M.; Castro-Tirado, A. J.; Ortiz, J.L.; Cabrera-Cano, J., 2013, Mon. Not. R. Astron. Soc., 436, Issue 3, 2818

Molau, S., 1999, Proceedings of the International Meteor Conference, Eds.: Arlt, R., Knofel, A., 9

Molau, S., 2008, Proceedings of the International Meteor Conference, Eds.: Kaniansky, S.; Zimmikoval, P., 76
Molau, S.; Kac, J.; Crivello, S.; Stomeo, E.; Barentsen, G.; Goncalves, R.; Saraiva, C.; Maciewski, M.; Maslov, M., 2015, WGN, 43, no. 2, 62

Molau, S.; Crivello, S.; Goncalves, R.; Saraiva, C.; Stomeo, E.; Kac, J., 2016, WGN, 44, no. 2, 51

Musci, R.; Weryk, R. J.; Brown, P.; Campbell-Brown, M. D.; Wiegert, P. A., 2012, The Astrophysical Journal, 745, Issue 2, article id. 161, 6

Neslušan, L., 2015, Contrib. Astron. Obs. Skalnate Pleso, 45, no. 1, 60

Neslušan, L.; Porubčan, V.; Svoreň, J., 2014, Earth, Moon, Planets, 111, Issue 3-4, 105

Neslušan, L.; Vaubaillon, J.; Hajduková, M., 2016, Astron. Astrophys., 589, id. A100, 10

Porubčan, V., Kornoš, L., Cevolani, G., Pupillo, G., 2004, Il Nuovo cimento, 27, No. 4, 395

Rudawska, R., Daassou, A., Ait Moulay Larbi, M., Benkhaldoun, Z., Vaubaillon, J., Colas, F., Baratoux, D., Bouley, S., 2013, WGN, 41, 121

Rudawska, R.; Jenniskens, P., Proceedings of the Astronomical Conference held at A.M. University, Eds.: T.J. Jopek, F.J.M. Rietmeijer, J. Watanabe, I.P. Williams, A.M. University Press, 2014, 217

Ryabova, G. O., 2001, Proc. Meteoroids 2001 Conf. ESA Pub. Div., Noordwijk, 77

Ryabova, G. O., 2007, Mon. Not. R. Astron. Soc 375, 1371

Ryabova, G. O., 2008, Earth, Moon, Planets, 102, Issue 1-4, 95

Ryabova, G. O., 2016, Mon. Not. R. Astron. Soc., 456, Issue 1, 78

Ryabova, G. O., 2014, The Meteoroids 2013, Proceedings of the Astronomical Conference held at A.M. University, Poznan, Poland, Aug. 26-30, 2013, Eds.: T.J. Jopek, F.J.M. Rietmeijer, J. Watanabe, I.P. Williams, A.M. University Press, 2014, p. 205

Skocic, I., Segon, D., Kurtovic, G., 2016, Proceedings of the IMC, eds., A. Roggemans, and P. Roggemnas, P., 280

27
SonotaCo, 2009, WGN, 37, 55

SonotaCo, 2016, WGN, 44, no. 2, 42

Southworth R.B., & Hawkins G.S., 1963, Smith. Cont. Aph. 7, 261

Tóth, J.; Vereš, P.; Kornoš, L.; Piffl, R.; Koukal, J.; Gajdoš, S.; Majchrovic, I.; Zigo, P.; Zima, M.; Világi, J.; Kalmančok, D., 2011, WGN, 39, no. 2, 34

Tóth, J.; Kornoš, L.; Piffl, R.; Koukal, J.; Gajdoš, S.; Popek, M.; Majchrovic, I.; Zima, M.; Világi, J.; Kalmanók, D.; Vereš, P.; Zigo, P., 2012, Proceedings of the International Meteor Conference, Eds.: Gyssens, M.; and Roggemans, P., 82

Tóth, J.; Kornoš, L.; Zigo, P.; Gajdoš, S.; Kalmančok, D.; Vilagi, J.; Simon, J.; Vereš, P.; Silha, J.; Buček, M.; Galad, A.; Rusnak, P.; Hrabek, P.; Duriš, F.; Rudawska, R., 2015, Planetary and Space Science, 118, 102

Trigo-Rodriguez, J.M., Madiedo, J.M., Pujols, P., Millan, J.C., Azcarate, J.A., Zamorano, J., Ocana, F., 2010, Central Bureau Electronic Telegrams, No. 2593, 2

Trigo-Rodriguez J.M., Madiedo Llorca J., Gural P., Pujols P., Tezel T., 2007, Mon. Not. R. Astron. Soc., 380, 126

Trigo-Rodriguez, J. M.; Madiedo, J. M.; Gural, P. S.; Castro-Tirado, A. J.; Llorca, J.; Fabregat, J.; Vtek, S.; Pujols, P., 2008, Earth, Moon, Planets, 102, Issue 1-4, 231

Ueda, M., Fujiwara, Y., 1993, WGN, 21, 215

Vereš, P., Tóth, J. 2010, WGN, 38, 54

Welch, P. G., 2001, Mon. Not. R. Astron. Soc. 328, 101

Weryk, R. J.; Campbell-Brown, M. D.; Wiegert, P. A.; Brown, P. G.; Krzeminski, Z.; Musci, R., 2013, Icarus, 225, Issue 1, 614

Williams I., Ryabova, G.O., 2011, Mon. Not. R. Astron. Soc., 415, 3914
Williams, I.P., 2003, in: Dust in the Solar System and Other Planetary Systems, ed. S.F. Green, I.P. Williams, J.A.M. McDonnell and N. McBride IAU Colloq. No. 104, 83

Williams, I.P., Wu, Z., 1993, Mon. Not. R. Astron. Soc. 262, 231