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Precision meteor orbits obtained by the Dutch Meteor Society - Photographic Meteor Survey (1981-1993)

H. Betlem[1,⋆], **C.R. ter Kuile**[1], **M. de Lignie**[1], **J. van't Leven**[1], **K. Jobse**[1], **K. Miskotte**[1], **and P. Jenniskens**[2]

[1] Dutch Meteor Society, Lederkarper 4, 2318 NB Leiden, The Netherlands
[2] NASA/Ames Research Center, Mail Stop 239-4, Moffett Field, CA 94035-1000, U.S.A.

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Abstract. 359 precisely reduced meteor orbits are presented that are the result of the Dutch Meteor Society's Photographic Meteor Survey in the period 1981 until 1993. Orbits include those of major and minor showers, doubling the number of known precise orbits of some meteor streams. From the spread in solutions of all possible sets of two photographic stations, we derive the measurement uncertainties from which we are able to calculate the intrinsic scatter in the Perseid meteor stream. The new Geminid orbits are compared to those obtained in similar surveys in the 1950's. This first measurement of the rate of change of Geminid orbits over time agrees well with model predictions.

Key words: meteoroids

1. Introduction

The recent establishment of the IAU Meteor Data Center in Lund (Sweden) (Lindblad & Steel 1994), and an ongoing list of publications that make use of it, testify to the continued interest in meteor orbits. The advances in computer modeling has generated a new interest in meteor streams and their relationship to the parent comets (e.g. Fox et al. 1983; Jones 1985; Gustafson 1989; Williams & Wu 1993; Wu & Williams 1995). Key observations have been made in other fields, such as the discovery of IRAS dust trails in the orbit of short period comets (Sykes et al. 1986; Sykes & Walker 1992). Hence, new observations of meteor streams promise exciting discoveries and an increased understanding of meteor stream formation and evolution (Steel 1993; Jenniskens 1994).

Multi-station photography provides the very accurate orbital elements of meteoroids needed in theoretical studies. The accuracy of photographic orbits is typically an order of magnitude better than those of radar orbits. Unlike radar orbits, photographic data potentially allow resolving the intrinsic scatter in the distribution of orbital elements. The photographed meteors are typically in the size range of millimeter or centimeter size and larger, depending on entry velocity. These large grains contain most of the mass in comet ejecta and are least affected by radiation pressure.

The first meteor was photographed during the Andromedid storm of 1885 (Weinek 1886). An attempt at multi-station photography did not succeed at that time. Optical surveys of meteor orbits were started at Harvard where a small camera network was operated from 1936 to 1959 in a project led by F.L. Whipple (Whipple 1938). In total, some 1245 orbits were obtained (Lindblad & Steel 1994). Later, specially designed Baker Super-Schmidt cameras were used (Whipple 1947; Jacchia & Whipple 1956), from which almost 2529 orbits were measured (McCrosky & Posen 1961). Only 413 of these were calculated from a precise reductions of the data (Jacchia & Whipple 1961; Jacchia et al. 1967). At the same time, small camera surveys were performed in the former Soviet Union, in Dushanbe, Odessa and Kiev in the period 1940-1983, which resulted in 1111 precise orbits (e.g. Babadzanov & Kramer 1967). Small camera surveys have since been abandoned and are only used by amateur observers, with notable results by the Nippon Meteor Society (NMS) in Japan in the period 1974-1982 (325 orbits) (e.g. Koseki et al. 1990). These data, too, have not always been reduced precisely.

The Photographic Meteor Survey program of the Dutch Meteor Society started in 1982, when software developed at the University of Poznan (TURNER - Tadeusz 1983) and Ondřejov Observatory (REDCON, FIRBAL - Ceplecha et al. 1979) became available for astrometry and

Send offprint requests to: H. Betlem[1] or P. Jenniskens[2]
⋆ H. Betlem is guest observer at Leiden Observatory.

trajectory calculations. The programs were adapted for use on MS-DOS computers. Since that time, some of the older data in Betlem & de Kort (1976) have been reduced with the new techniques and the database now also contains some orbits from meteors dating back to 1972 (Betlem 1990). Preliminary results of 70 orbits were published in Betlem & de Lignie (1990).

In this publication we present all 359 meteor orbits of annual meteor streams and sporadic meteors obtained in the survey prior to August of 1993. Special attention is given to measurement uncertainty, which will allow addressing the intrinsic dispersion in meteor streams. An example will be given. In addition, the new data span a large gap in time between previous surveys in the mid 1950's and the present, which allows the first measurement of the rate of change of the orbital elements of the Geminid stream.

2. Experimental techniques

The meteors are photographed with batteries of 35 mm cameras equipped with F/2, $f = 50$ mm standard optics (e.g. Bone 1993). In front of the camera lens is a rotating shutter which interrupts the image 25 times per second. At least two camera batteries at locations 40−100 km apart are operated simultaneously. Every meteor photographed at more than one site allows triangulation of the path of the meteor by fitting planes through the meteor and the observing station. The position of the meteor is found with reference to the altitude-azimuth grid defined by the position of the stars at the beginning or end of the exposure and the exposure times. Once the trajectory has been determined, the instantaneous velocity follows from the number of the interruptions in the meteor path by the rotating shutter and the known shutter frequency. A fit to the changing velocity gives a measure of the amount of deceleration in the atmosphere, from which the pre-entry velocity (and its direction: the true terrestrial radiant) is calculated. This velocity vector, in combination with the time of the meteor, which is usually provided by a team of visual observers at each site, determines the orbit in space.

Table 1. The photographic observers that contributed to this project, the most frequent location of their station in the Netherlands and in France, and the number of multi-station components that were contributed

Name	Location Nl/Fr	N
C.R. ter Kuile	Buurse/Lardiers	208
H. Betlem	Varsseveld	183
M. de Lignie	Oostkapelle/Le Thouron	118
P. Jenniskens	Meterik/Quinson	107
K. Jobse	Oostkapelle/Lardiers	67
K. Miskotte	Harderwijk/Puimichel	47
F. Bettonvil	Heesch	29
C. Johannink	Denekamp	27
A. Scholten	Bussloo	23
M. Betlem	Elsloo	14
P.A. Koning	Loenen	14
R. Schievink	Buurse	14
M. Breukers	Hengelo	11
J. de Jong van Lier	Denekamp	10
J. van 't Leven	Bussloo	8
B.C. Apeldoorn	Winterswijk	4
E. van Ballegoy	Lheebroek/Puimichel	4
S.J. van Leverink	Bakkum	4
J. Nijland	Heiloo	4
J. Bruining	Appingendam	3
G.S. Cladder	Denekamp	2
G.A. Hafkenscheid	Heerhugowaard	2
P. van der Veen	Loosdrecht	2
L. Bruning	Epen	1
P. van Graafeiland	Heemstede	1
H. ten Haaf	Muiderberg	1
J. Hermans	Schaesberg	1
P. Koeyvoets	Roosendaal	1
M. Langbroek	Voorschoten	1
L. Muytjens	Breda	1
W. Nobel	Muiderberg	1
D. van den Oudenalder	Hilversum	1
U. Poerink	Vught	1
M. van Vliet	Oostkapelle	1

The photographic systems can detect meteors of visual magnitude +0 and brighter for fast meteors (angular speed $\sim 25°$/s) or magnitude +1 and brighter for slow meteors (angular speed $\sim 10°$/s). Exposure times are typically 15−30 minutes. The photographic film is usually either Kodak Tri-X, TMAX 400, or Ilford HP5, all nominally at 400 ASA but sometimes enhanced to about 1000 ASA by forced development. These emulsions are sensitive in the blue and near-UV, where fast meteors have a rich emission line spectrum, while at the same time they are relatively insensitive to diffuse background light.

The equipment was built, manned and operated by amateur meteor observers of the Dutch Meteor Society and some members of the Nederlandse Vereniging voor Weer en Sterrenkunde - Werkgroep Meteoren. The batteries are operated from various locations in the Netherlands ($\sim$ 06E, +52N) and, on occasion, in the Haute Provence ($\sim$ 06E, +44N), in the south of France. As a rule, observing campaigns are organised during moonless nights at the time of major stream activity. Hence, most of the data have been obtained in the second and third weeks of April (Lyrids), the month of July and the first two weeks of August (Delta-Aquarids and Perseids), the end of October and beginning of November (Orionids and Taurids) and the second week of December (Geminids). One major shower, the Quadrantids, eluded observations as a result of consistently bad weather during the first week of January.

Outside of these periodic campaigns involving small-camera networks, seven all-sky cameras were operated routinely during moonless clear nights. Only meteors brighter than about magnitude −3 are recorded. Often, the time of the meteor is obtained by automatic light detecting systems that utilize a photo-multiplier tube, which are designed for the purpose by H. Mostert (1982). This network of all-sky cameras participates in the European Network (Ceplecha 1982), aimed at recovering meteorites and measuring their orbit in space. Indeed, a few possible meteorite falls were photographed (e.g. Betlem 1989; Betlem 1993), but no fragements have been recovered. Only one meteorite is known to have fallen in the Netherlands during the 12 years of operation. That meteorite fell in the town of Glanerbrug on April 7, 1990, in evening twilight at a time when it was still too light for meteor photography. We were able to derive an approximate orbit only from 200 eye-withness accounts (Jenniskens et al. 1992; 1992a).

3. Reduction of the data

3.1. The path of the meteor in projection on the sky

The reduction of the negatives (e.g. Whipple 1938; Ceplecha et al. 1979; Ceplecha & Borovička 1992) was performed at the Sterrewacht Leiden of the Leiden University and at the Stichting Geavanceerde Metaalkunde of the Technical University of Twente. Each set of star trails and meteor trail were routinely measured in two directions to avoid hysteresis. The meteor is measured twice per shutter break at the head of the break to minimize the influence of wakes and trains. The measurement accuracy is limited by the quality of the meteor and star trail images, not by the measuring device, a Zeiss Astrorecord $X-Y$ measuring table, with a nominal accuracy of 0.001 mm. The image quality is determined by the quality of the camera optics, the focal length, the brightness of the meteor, the location on the negative, and by background fogging. The standard deviation of measured star positions and the calculated grid is about $30''-1'$ for the well focused F/2, $f = 50$ mm cameras with 35 mm film format and the 60 mm F/4, $f = 75$ mm cameras that were used in the small camera network. The all sky cameras, on the other hand, use 35 mm cameras with F/5.6, $f = 7.5$ mm or F/2.8, $f = 16$ mm fish-eye lenses, which results in a positional accuracy of about $3'-5'$. The meteor cameras are not guided but the instant of the beginning and ending of each exposure is known with an accuracy of better than ± 4 seconds and the time of the meteor is usually known to ± 5 seconds, which allows for a correction in RA of the stellar trails to the instant of the meteor to an accuracy of about ± 6 seconds ($1.5'$). Larger errors occur when the time of the meteor is incorrect due to a wrong identification from the visual observations. Large differences in time (more than a few minutes) do usually not result in a reasonable solution of the multistation calculation. However, extra effort is made to ensure that the correct identification is made.

The method of Turner (1907) is followed to calculate the stellar coordinates of the meteor path from the position of stars on the negative (Tadeusz 1983). The coordinates of the stars are taken from the Tirion Star Atlas 2000.0 (Sky Publishing), with $0.1''$ accuracy. The method uses some 20 stars spread over the negative with a triangle of stars around the approximate plate center and adopts a coordinate grid that accounts for projection distortions from the optical system. This distortion becomes too strong for the method in the case of fish-eye images. Hence, for fish-eye images we used the method of Ceplecha outlined in the REDCON software routine (Ceplecha et al. 1979). This method makes use of seven independent constants to link the measured rectangular coordinates with the horizontal coordinates but demands that the center of the plate is near the zenith. If the number of usable stars for determining the coordinate grid is insufficient, simpler procedures with less constants are applied but with, of course, less precision.

The trajectory of the meteor in the atmosphere is calculated, subsequently, by fitting planes through the station and meteor path. The location of the stations and their altitude is known within 30 meters or better. The best plane is calculated by a least squares fit through the measured positions of the meteor path. The combination of two planes then result in a (partial) meteor path. The mean trajectory is computed from all individual paths with weight factors:

$$W = W_1 \times W_2 \times \sin^2(Q) \tag{1}$$

with Q the convergence angle and $W_i = 1.0$ for most images and $W_i = 0.7$ for some less accurate fish eye components.

When a meteor is recorded by more than two stations, accuracy checks on trajectory and radiant data can be made by comparing two-station solutions. In most cases errors are caused by timing errors, either in the exposure times or in the time of the meteor. These errors are reflected in the scatter in the Right Ascension (RA) of the position of the radiant in the various solutions, but do also affect the Declination. Small convergence angles between the planes affect the radiant and the geographic data of the trajectory in a negative way. It is found that for convergence angles (Q) larger than 40 degree, the error in radiant position is about $\pm 0.1°$. For $Q = 20$ degree it is about $\pm 0.2°$ and for $Q = 10$ degree it is about $\pm 0.4°$. If the convergence angle is less than 10 degree, then the accuracy is not better than radio orbits of order $\pm 3°$ (Sekanina 1976). As much as 41 of the 359 precisely reduced meteor orbits in our study do not lead to precise results, because they have $Q < 10°$, but are still considered valuable in some cases due to the small number of known stream orbits, the large mass of the meteoroid, or a relatively high accuracy in a part of the orbital elements. Error estimates are given for each individual orbital element (Table 2).

The initial velocity is computed by making use of a fit through all computed positions of the meteor at the head of shutter breaks (Jacchia & Whipple 1961):

$$L = L(0) + B \times t + C \times \exp(K \times t)$$

$$H = H(0) + B \times t + C \times \exp(K \times t) \quad (2)$$

with L being the geographic position of the trail, H the height, while B, C and K are variables. It is found that this fit gives reliable results only for meteor trails with at least some 30 well measured breaks. In cases with less breaks ($N = 15{-}30$) a fit of the following equation is used instead (Ceplecha & Borovička 1992):

$$V(t)^2 = V_\infty^2 + K \times \rho(t) \quad (3)$$

where $\rho(t)$ is the air density at a given height (or time t of the meteor) computed from the CIRA 1961 reference atmosphere (Kallmann-Bijl et al. 1961). The final accuracy with which V_∞ is determined is about 1% in case a sufficient number of breaks can be measured. The correction from measured velocity at the beginning of the trajectory to the pre-entry velocity before deceleration in the atmosphere varies from 0.2 km/s for fast meteors up to 1.5 km/s for some slow meteors.

Given an accurate radiant position, the uncertainty in the orbit is mainly determined by the uncertainty in the velocity determination. That demands stable rotating shutters. Before 1986, all our rotating shutters relied on the stability of the mains frequency, which is thought to be constant and accurate at 50 Hz to within 0.5%. The chopping frequency of the shutters was measured to be accurate within 0.2%. However, the rotational period of the shutters can oscillate with a variable oscillation period and an amplitude up to 4%. Such oscillations occur when the rotating shutters are perturbed by strong winds or when there are system resonances. Such oscillations occur at random. Larger than 1% errors are seldomly found when information from more than one rotating shutter is available. To improve the quality of the computed orbits, the Dutch Meteor Society introduced crystal controlled rotating shutters in 1986 at some stations. Starting in 1992, all stations were equipped with new crystal controlled rotating shutters with twice the shutter frequency, increasing the shutter speed to 50 breaks per second with a stability of 0.1% or better.

The orbital elements (J2000) follow from the true radiant position, the computed initial apparent velocity and the position of the Earth at the time of the meteor (e.g. Katasev 1957). The calculations take into account such corrections as zenith attraction, the curvature of the Earth, and diurnal aberration, and give good results even at shallow entry angles and large distances between the stations (Ceplecha et al. 1979; Ceplecha & Borovička 1992). That was demonstrated again in one case DMS 85027, a sporadic fireball, which was photographed by four Dutch stations as well as by four distant German stations of the European Network (Betlem & de Lignie 1985). Independent reduction in Leiden and Ondřejov gave good agreement between the Dutch and German stations (Ceplecha, private communication).

Table 2. Orbital elements, encounter data and other relevant information of 359 photographic meteors. This table is published in electronic form only at the CDS. Columns give:

Code - DMS sequential numbering starting with the year
Month - month
Dec. Day - day and time (UT) in decimal days
N - number of multi-station components
Stream - meteor stream identification
M_v - absolute visual magnitude
q - perihelion distance (AU)
a - semi major axis (AU)
e - eccentricity
i - inclination (Eq. 2000)
omega - ω - argument of perihelion (Eq. 2000)
Node - Ω - ascending node (Eq. 2000)
pi - π - longitude of perihelion (Eq. 2000)
V_g - geocentric velocity (km/s)
V_h - heliocentric velocity (km/s)
V_{inf} - apparent pre-atmospheric velocity (km/s)
V - average velocity along trajectory
H_{beg} - beginning height (km)
H_{max} - height of brightest point on meteor track (km)
H_{end} - end height of meteor (km)
RA obs. - apparent right ascension of radiant (2000)
[+/−] - error due to uncertainty in time of meteor
DEC obs. - apparent declination of radiant (2000)
RA Geo - geocentric right ascension of radiant (2000)
Dec Geo - geocentric declination (2000)
CosZR - cosine of zenith angle of radiant at time of meteor
Q_{max} - maximum convergence angle between planes.

4. Results

The orbital elements, encounter data and other relevant information are listed in Table 2, which is available in electronic form at the CDS via anonymous ftp to “cdsarc.u-strasbg.fr” (130.79.128.5) or via “http://cdsweb.u-strasbg.fr/Abstract.html”. A printed version can be requested from the authors. Also, a subset of data (the orbital information) will be available at the IAU Meteor Data Center in Lund, Sweden.

The content of Table 2 is listed in the table caption above. Data are ordered according to solar longitude at the time of the meteor. Angular units are in Equinox 2000. Uncertainty limits are based on the assessment of measurement accuracy. For two-station meteors, a value of ± 0.2 degrees in RA and DEC was adopted for the uncertainty in the radiant position, unless Q was less than 10 degrees. The brightness of the meteors was not measured but obtained from the brightness estimates by the visual observers or merely guessed from the density of the images on the negatives. Photometric scans of a small number of meteors have been published in Radiant, the Journal of the Dutch Meteor Society (Betlem 1982; 1983; van Oudheusden & van Dijk 1991). The journal also gives many detailed descriptions of individual multi-station sets, including possible complications with the observational data. The best results are from long duration and not too bright meteors (-1 to -3 magnitude). Bright fireballs can result in blurred trails in which individual breaks are difficult to recognize. Weak meteors are usually also of short duration, with few measurable shutter breaks.

Indeed, the accuracy of the final orbital elements varies a lot. Apparently, his point is not recognized in previously published surveys of meteor orbits, which have never included error estimates.

4.1. Intrinsic dispersion in the Perseid meteor stream

Several major and minor meteor streams can be identified in our sample of meteor orbits. The Perseids and Geminids are especially well respresented. Stream membership was determined by comparing the orbital elements with mean values listed in Kresak & Porubcan (1970) and Cook (1973). We will now discuss two examples of how the observations can be used in the study of meteor stream evolution.

A significant number of orbits are of meteoroids of the Perseid meteor stream. From the spread in orbital elements and the estimated measurement uncertainties, we can calculate the intrinsic scatter in the orbital elements of this stream. Only those Perseids are considered that appeared between solar longitude 137.0 and 141.9 (J2000), which is the main peak of the Perseid shower (Jenniskens 1994). The median value for each orbital element, with an estimate of the accuracy of how well the median value could be determined, is listed in Table 3. The intrinsic dispersion was calculated as follows: Because the measurement uncertainty is only approximately known, we devided the sample in groups of about equal uncertainty in a given orbital element and plotted the square of the scatter in each group versus the mean of the calculated measurement error. The intercept for zero measurement uncertainty of a least squares fit to these data is the (square of the) intrinsic scatter. These values, with an uncertainty limit, are listed in Table 3.

These results are compared to the median values of Perseid orbits listed in the 1990 version of the IAU Meteor Data Center catalog for precisely reduced orbits (Lindblad 1991a, 1995; Lindblad & Steel 1994). We consider separately the recent dataset of the Nippon Meteor Society (NMS) and the other data (IAU). All were restricted to the interval 137.0−141.9 and the most obviously deviating cases were removed (7 in the IAU list). Subsequently, the mean values and observed dispersion were calculated.

We find good agreement between the mean orbits in our sample and the IAU data. On the other hand, the NMS data show significant deviations with both our data and the IAU data. The errors in the NMS data are partially caused by the fact that some orbits were computed using $R = 1$ for the Earth-Sun distance (Lindblad 1991). Both the NMS and IAU data have dispersions in orbital elements that are systematically larger than our new sample of orbits, and all datasets contain a significant amount of dispersion due to measurement error.

4.2. The evolution of the Geminid orbit

A dedicated observing campaign in France in 1990 resulted in about 100 precise orbits of the Geminid stream (Jenniskens et al. 1991; Betlem et al. 1994a,b). Together with some 30 orbits obtained in a similar campaign in the Netherlands in 1991, the sample doubles the number of precise Geminid orbits in the IAU archive.

Again, the orbits obtained by the Nippon Meteor Society (NMS) in the period 1970-1980 show significant differences compared to the older IAU data obtained mostly in the 1950's (Table 4). This might suggest a fast stream evolution. However, we do not confirm such fast stream evolution from our data and conclude that the difference is probably due to errors in (some of) the NMS orbits.

With the NMS data unavailable for analysis, this leaves a gap in coverage of the Geminid stream between the 1950's surveys and our recent work. Our data span a 35 year range that was not present in the older data and for the first time we can now measure the change in the orbital elements of the Geminid shower over time.

The IAU and DMS data were correlated with the node of the particle orbit in order to find the daily variation of the orbital elements. Examples of such correlation plots are shown in Williams & Wu (1993). The IAU dataset spans a wider range in node and, therefore, we have adopted the relationships found for this set to correct for the daily variation or all Geminid orbital elements (Table 5). All data were then corrected for this daily variation by normalisation to solar longitude 261.4 (at the peak of the shower) and plotted as a function of the year of the observation. The resulting mean value of the orbital elements for the year 2000 and the mean annual shift are given in Table 5.

We conclude that the perturbation of the particles is mainly at aphelion, because the perihelion distance does not significantly change. The change of the node is positive and two times the value for the annual Perseid shower. The inclination (i) and the longitude of perihelion (π) are

Table 3. Perseid median orbit (J2000), the observed dispersion of orbital elements (1σ), and the intrinsic dispersion after accounting for measurement error (1σ), for meteors in the solar longitude interval $\lambda_\odot = 137.0 - 141.9$

	N	year	q AU	$1/a$ AU^{-1}	e	i °)	ω °)	π °)
median:								
IAU	309	1940-1982	0.952±0.002	0.027±0.013	0.976±0.013	113.40±0.13	151.3±0.4	291.2±0.4
NMS	91	1964-1985	0.947±0.002	0.055±0.019	0.948±0.018	113.40±0.27	151.5 ± 0.5	290.7 ± 0.5
DMS	87	1981-1992	0.953±0.002	0.014±0.011	0.961±0.007	113.22±0.19	151.3±0.4	291.9±0.4
dispersion:								
IAU	309	1960	0.041±0.002	0.24±0.01	0.23±0.01	2.4±0.1	6.6±0.4	6.6±0.4
NMS	91	1978	0.019±0.002	0.19±0.02	0.18±0.02	2.6±0.3	4.9±0.5	4.7±0.5
DMS	87	1990	0.015±0.002	0.11±0.01	0.06±0.01	1.8±0.2	4.0±0.4	4.1±0.4
intrinsic:								
DMS	87	1990	0.009±0.001	0.04±0.01	0.035±0.005	1.5±0.2	2.3±0.3	3.3±0.8

Table 4. Geminid median orbit (J2000), for meteors in solar longitude interval $\lambda_\odot = 258.8 - 263.0$

	N	year	q AU	$1/a$ AU^{-1}	e	i °)	ω °)	π °)
IAU	93	1936-82 (1953)	0.1410±0.0007	0.726±0.004	0.8980±0.0009	23.60±0.19	324.28±0.17	226.20±0.19
NMS	99	1969-85 (1977)	0.1460±0.0029	0.806±0.011	0.882±0.0037	23.6±0.4	324.83±0.28	226.9±0.29
DMS	132	1990-91 (1990)	0.1410±0.0009	0.729±0.004	0.8980±0.0008	24.02±0.21	324.42±0.14	226.55±0.15
3200 Phaeton		1983	0.1395	0.786	0.8903	22.04	321.67	227.18

Table 5. Change in orbital elements of the Geminid stream between 1955 and 1990. The mean value at node $\Omega = 261.4$ is given for DMS and IAU data, and the change of orbital elements with node. [1] is a theoretical estimate by Kresak & Porubcan (1970) assuming $\Delta a/\Delta\Omega = 0$. After correction for the nodal dependence, the orbital elements of IAU and DMS data were correlated in time, which resulted in the mean value for the year 2000 and the annual variation $\Delta/\Delta t$ in Cols. 6 and 7. The latter value is compared to results derived for the shower members in the model of: [2] Williams & Wu (1993) and [3] Jones & Hawkes (1986)

element	mean DMS 261.4	mean IAU 261.4	$\Delta/\Delta\Omega$	$\Delta/\Delta\Omega$ [1]	mean IAU+DMS $t = 2000$	$\Delta/\Delta t$	$\Delta/\Delta t$ [2]	$\Delta/\Delta t$ [3]
q (AU)	0.1400	0.1399	+0.0010	+0.0023	0.1400	+1.97e-7	2.1e-6	
$1/a$ (AU^{-1})	0.730	0.721	−0.011	(0.00)	0.737	+0.00038	+0.00031	(+0.00016)
i°)	24.19	24.27	−0.13	−0.20	24.27	+0.0097	+0.0017	+0.0030
ω°)	324.45	324.28	−0.41	−0.33	324.63	+0.0078	+0.0048	+0.0027
Ω°)	261.40	261.40	+1.00	+1.00	261.433	+0.00068	−0.00508	−0.0025

increasing in time, while the semi major axis is decreasing with −0.00068 AU per year (the table lists $1/a$).

The measurements are in good agreement with the theoretical model of Jones & Hawkes (1986) and Williams & Wu (1993) for the case of ejection of particles at some distant point in time (1000 yrs ago). The only exception is the change of the ascending node with time. We do not find the strong negative precession of the mean orbit of the model Geminids with time. The nodal change is small and consistent with the observation that the peak of the shower has not significantly changed in the past century (Fox et al. 1982; Jenniskens 1994). Fox et al. (1983) pointed out that the intersection points of Geminids with the ecliptic plane are at an angle with the normal line to the Earth's orbit and, as a result, the gradual outward movement of the stream shifts the mean node forward for the subset of particles that intersect with the Earth's orbit. This compensates the negative movement due to precession from planetary perturbations on the prograde orbits. In the model of Jones & Hawkes (1986), the nodal change is $\Delta\Omega/\Delta t = -0.0025$ for the shower as opposed to −0.152 degree per year for the stream as a whole. Our measurements confirm this behavior and, perhaps, suggest the effect to be even slightly stronger than calculated, with $\Delta\Omega/\Delta t \sim +0.0007$ degree per year.

5. Conclusions

New orbital elements have been measured of 359 meteors, including a large sample of Perseid and Geminid meteors. These results have been used to measure the intrinsic dispersion in the annual Perseid shower at the core of the stream. Comparison of Geminid orbits with similar data obtained in the 1950's has allowed a determination of the present annual change in orbital elements of the Geminid shower. The result is in good agreement with theoretical models of Geminid meteor stream evolution. These are but two examples of how these new orbits can be used, which serve to demonstrate the quality of the orbital data.

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