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Very precise orbits of 1998 Leonid meteors

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Abstract. Ground stations in support of Leonid MAC were set up in China. Purpose was to measure the meteor flux in timezones +1 and +2 west from Okinawa, Japan, and to measure precise meteor trajectories and orbits using photography and video techniques, in an ongoing program to study the dynamics of meteor stream formation and evolution. Here we report on the photographic results of stereoscopic imaging of the Leonid meteors. We find that our solutions for trajectories and orbits are precise enough to recognize significant dispersion in the orbital elements. We find significant different orbits for meteors collected on Nov. 16/17, dominated by a broad component rich in bright meteors, and on Nov. 17/18, dominated by a more narrow secondary peak in the flux curve. The semi-major axis is confined to values close to that of the parent comet, while the distribution of inclination is in a narrow range on Nov. 16/17, but more dispersed on Nov. 17/18. This may provide the first evidence for the importance of orbital resonances in the dynamical evolution of the broad component.

INTRODUCTION

The rare event of a potential Leonid meteor storm in 1998 invited a dedicated observing campaign in our ongoing effort to monitor the activity of the Leonid shower by visual, photographic and video techniques (Jenniskens 1996, Jenniskens et al. 1997, 1998; Betlem et al. 1997, 1998). Of particular interest was the opportunity to measure the orbits and debris distribution of relatively recent cometary ejecta at unprecedented precision and abundance at a unique position behind the parent comet at a unique moment in time (for a review see: Ceplecha et al. 1998, Jenniskens 1998).

Fig. 1. The observers of the Dutch Meteor Society during a preparatory meeting in April of 1998. Back row from left to right: Robert Haas, Annemarie Zoete, Klaas Jobse Jos Nijland, Romke Schievink, Marc de Lignie, Carl Johannink, Koen Miskotte, Peter bus, and Jaap van 't Leven. Front row: Casper ter Kuile, Olga van Mil, Marco Langbroek, Hans Betlem, and Michelle van Rossum. Not in the picture are participants Alex Scholten, Arnold Tukkers, Reinder Bouma, and Rita Verhoef.

The 1998 Sino-Dutch Leonid Expedition consisted of two observational networks in the People's Republic of China. Of all potential observing sites, China offered the best prospects for good weather conditions in the middle of November, while being favourably located for viewing a storm at the expected time of the event. In an effort lead by researchers at Purple Mountain Observatory, a cooperative agreement between the Royal Dutch Academy of Sciences (KNAW) and the Chinese Academy of Sciences (CAS) made it possible for 19 members of the Dutch Meteor Society (Fig. 1) to deploy some 1050 kg of equipment at two remote observing sites. The effort was strengthened by the participation of Chinese, U.S., and Czech (amateur) astronomers and covered six nights around the peak of the shower.

Two double station networks for stereoscopic measurements were established at locations +1 and +2 time zones west from Okinawa, Japan. The stations would be able to measure Leonid meteor flux for up to two hours after the time when twilight would interfere with observations in Okinawa. The large separation enhanced chances that at least one of the sites would have clear weather at the time of the storm.

The first network was operated from the province of Hebei, about 150 km north-east of Beijing, where the main station was located at the Xing Long Observatory ($40^{o}24'$ N; $117^{o}35'$E). Local organization was in hands of the Beijing Astronomical Observatory (BAO). At Xing Long, seven observers settled with platforms of 35 mm cameras equipped with crystal controlled rotating shutters and operating with 50 mm optics. Low light television cameras were used to monitor bright meteors for accurate timings. A second station of 35 mm cameras was established in the village of Lin Ting Kou, at a distance of 85 km to the south, a favourable direction for triangulation with respect to the Leonid radiant, which was rising rather steeply in the East.

The second network was established in the Province of Qinghai. Main station was the Delingha radio observatory (37°23’ N ; 97°44’E). Local organization was in hands of Purple Mountain Observatory (PMO). At this site, an improved array of six 35 mm cameras equipped with 85 mm optics and high shutter speed was operated. Double station images were obtained from a second site equipped with fourteen 50 mm and six 85 mm cameras near the village of Ulan, about 65 km SSE of the Delingha Observatory. Visual observations provided the meteor timing at these locations.

RESULTS

Although a meteor storm did not occur, large numbers of bright Leonids provided a bounty of data. The Hebei and Qinghai networks together measured 136 double station photographic meteors, 78 of which provided accurate orbits. The results are summarized in Tables 1-3. In addition, we report here on multi-station results from a network of small cameras of the BAA Meteor Section in the U.K. 5 Leonids were captured in the night of Nov. 16/17. These results were analysed in the same way as all others.

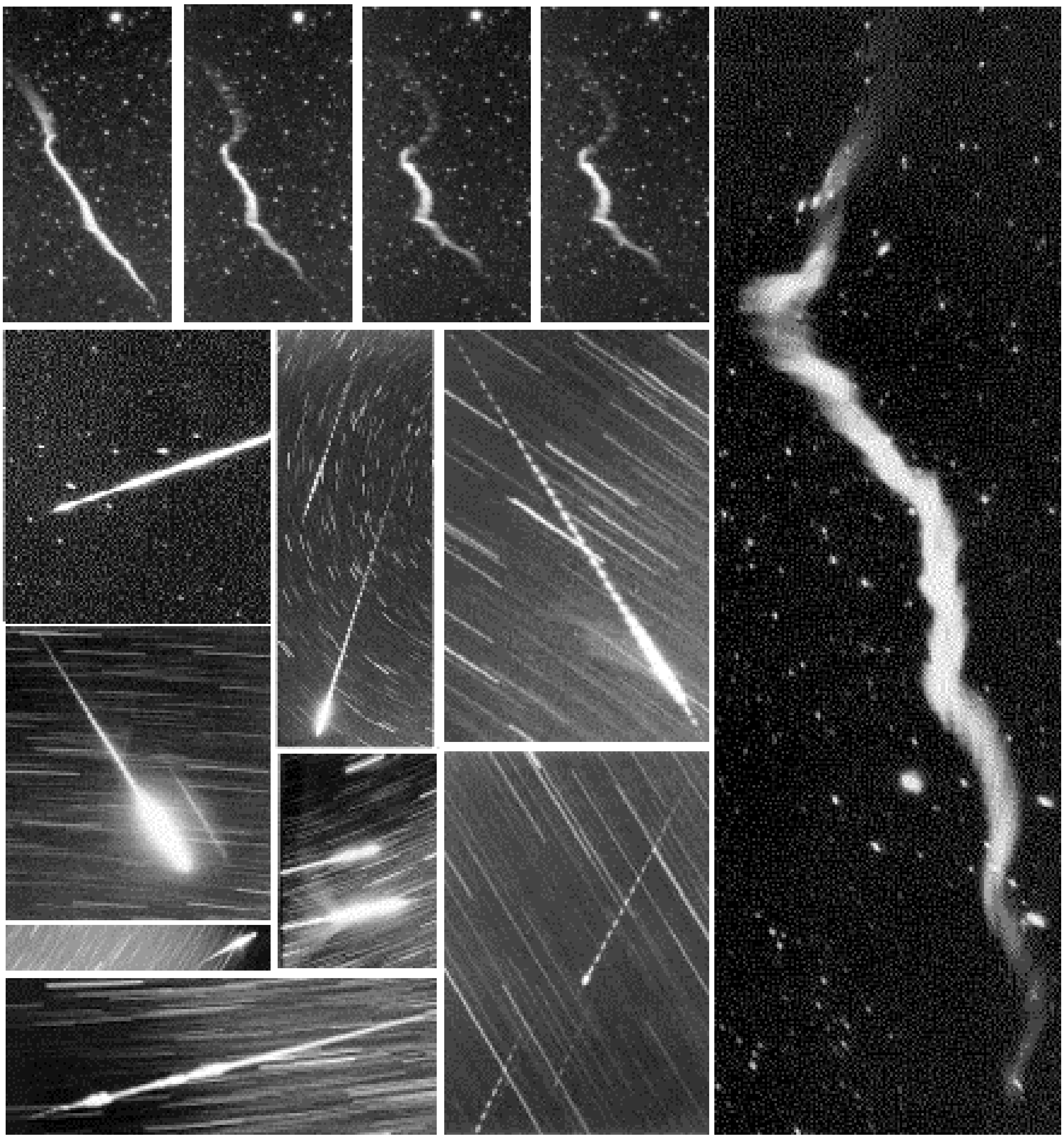

Fig. 2. These examples show the irregular light curves of bright Leonids as well as the evolution of Leonid persistent trains in our photographic records.

At both locations in China, double station video and photographic projects were run during the nights November 16/17, 17/18 and 18/19. Between 100 and 140 meteors were captured on film on every station, all but a few were Leonids (Fig. 2).

Each set of photographs was reduced in the normal manner in an interactive way by using Astrorecord measuring software (version 3.02), developed by Marc de Lignie of the Dutch Meteor Society. Some images were also measured at the Ondrejov Astrorecord X-Y measuring table, which demonstrated the claimed accuracy (Table 4) and enabled photometry. A typical positional accuracy for the 35mm cameras is 0°.003. In total 384 photographic images were measured. The trajectories and orbits were calculated with FIRBAL (version 7.0), developed by Zdenek Ceplecha, Pavel Spurny and Jiri Borovicka of Ondrejov Observatory.

Code	q	[+/-]	q	[+/-]	1/a	[+/-]	1/a	[+/-]
1998002	0.9830	0.0003	0.9834	0.0001	0.096	0.044	0.093	0.003
1998003	0.9830	0.0004	0.9828	0.0002	0.122	0.040	0.154	0.002
1998008	0.9831	0.0002	0.9833	0.0002	0.133	0.038	0.101	0.030
1998011	0.9819	0.0001	0.9819	0.0001	0.054	0.015	0.053	0.015
1998012	0.9832	0.0003	0.9831	0.0002	0.079	0.030	0.089	0.030
1998015	0.9830	0.0001	0.9830	0.0001	0.082	0.020	0.084	0.020
1998020	0.9813	0.0002	0.9814	0.0002	0.221	0.028	0.209	0.028
1998023	0.9839	0.0002	0.9837	0.0001	0.115	0.011	0.106	0.013
1998041	0.9838	0.0001	0.9839	0.0001	0.042	0.034	0.075	0.028
1998043	0.9832	0.0002	0.9832	0.0003	0.135	0.033	0.119	0.052
1998044	0.9831	0.0001	0.9835	0.0002	0.104	0.022	0.102	0.041
average:	0.9830	0.0002	0.9830	0.0002	0.107	0.029	0.108	0.024

Table 4. Comparison of measurements with the interactive Astrorecordsoftware program (left) and the Ondrejov Observatory Astrorecord X-Y measuring table (right) for 11 bright Leonids. The latter include all-sky images of the meteors from Xing Long.

All data are from two stations only. Hence, errors in the trajectory and orbit calculations were estimated by rigorous progression of measurement errors. For meteors that have known times of appearance, the uncertainty in the result is determined mainly by the observed lengths of the meteor trails on both images, the angular distances to the radiant, and the angle between the meteor trails. Best results were obtained from long trails, which were numerous in our data sample. Hence, we obtained many very precise results. To increase the accuracy of deceleration measurements, we used a relatively high shutter speed of 50 breaks/second at the Hebei network, and up to 75 breaks/second for the 50 mm cameras and 100 breaks/second for the 85 mm cameras at the Qinghai network. We also improved earlier observing efforts of the Leonids by using 85 mm cameras at the Quinhai stations. When time of meteors is unknown or the identification is uncertain, we did calculate the trajectories and velocities, but realize that the radiation right ascension (RA) is uncertain by up to ± 1°.25 and the orbital elements are similarly affected. Tables 1-3 include 12 such solutions. Here, we will discuss only the most precise values, with known times and convergence angle > 11 degrees.

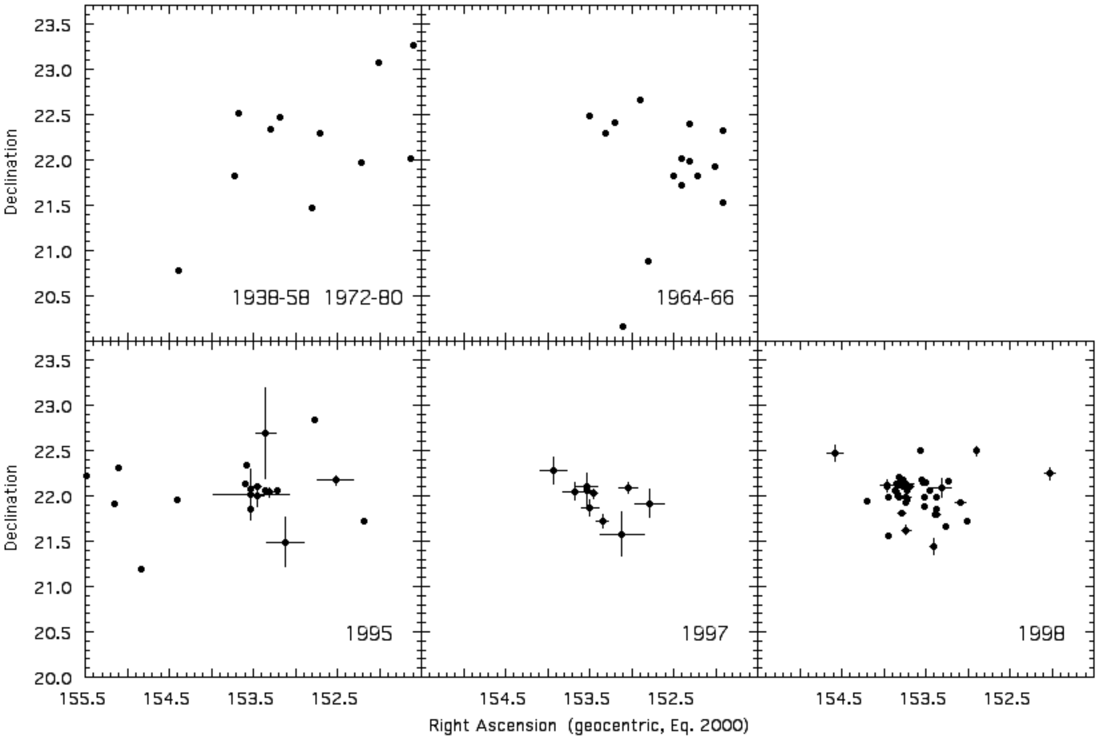

Figure 3. Radiant dispersion at different times.

TRAJECTORIES AND RADIANTS

The radiant is the direction of the meteor velocity vector before it is affected by Earth's gravity and deceleration. The radiant dispersion of Leonids photographed in years of normal annual activity is shown in Fig. 3 (top left) , and is compared to the radiant distribution in years of enhanced activity due to recent ejecta. The early data were taken from the IAU database, while recent data are from our observing efforts (Betlem et al. 1998). Note that the radiant has significantly shifted compared to that of meteors from the same dust component measured in 1964-1966 (Fig. 3, top right).

All positions have been corrected for a changing Earth's velocity vector to that at the solar longitude 235.0 (J2000), using a daily radiant drift of ΔRA = +0.99 per degree solar longitude and ΔDEC = -0.36 per degree. This daily drift accounts for the changing vector of Earth's velocity and assumes that the vector of the meteoroids stays the same over the period of three days. In that case, we find significant differences in the radiant position for data obtained on Nov. 16/17 as compared to those of Nov. 17/18 (Fig. 4). This separation of radiants is present also in uncorrected data. The radiants of Nov. 16/17 appear to form a small circle, while those of Nov. 17/18 are more dispersed in declination. We also find that from 1995 to 1998 the center of mass of the radiant points shifted slightly to larger right ascension (Fig. 3). We suspect that these differences reflect different dust components in the stream that dominated the Leonid shower activity in each night (see below).

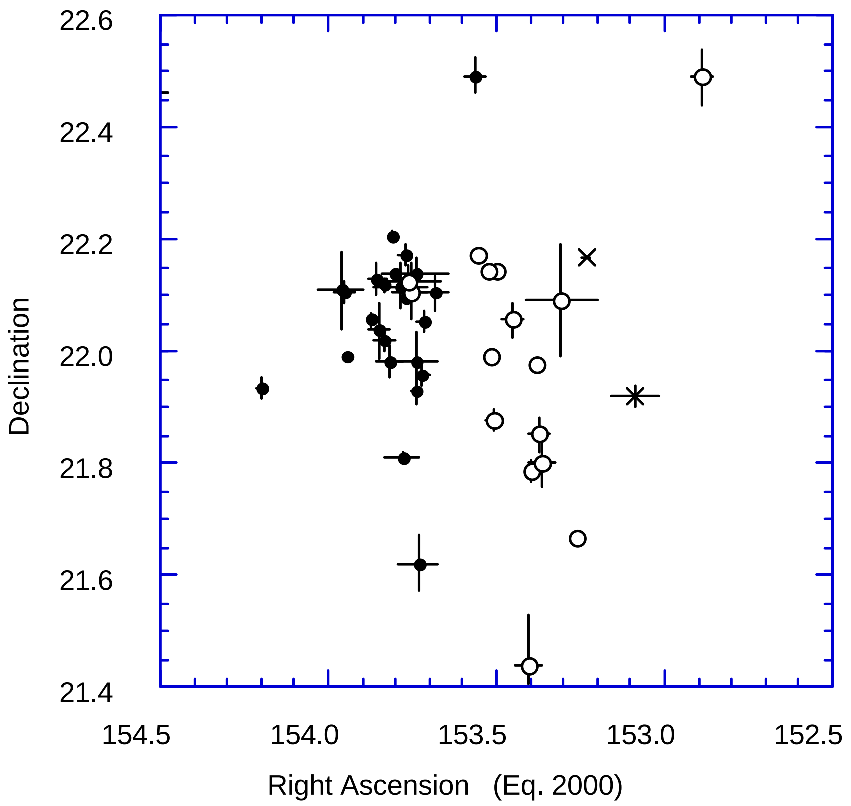

Fig. 4. Enlargement of Fig. 3 bottom right panel. Symbols are for Night 16/17 (•), 17/18 (o) and 18/19 (x).

On the other hand, it is possible to adopt an artifical radiant displacement that corrects well for the observed displacement in the three nights. The 1998 observations suggests an effective radiant drift of ΔRA = 0.68±0.04 degrees per degree solar longitude. The drift in declination is much as expected. Although such a value is ad-hoc, we note that all three nights are now providing nearly the same radiant position and some previous conclusions will not be valid anymore. For example, we find no significant drift over the past few years, with the median radiant position at 153.48±0.08 degrees in 1995, 153.55±0.11 degrees in 1997 and 153.55±0.05 degrees in 1998 (at λo = 235.0), and the declination at +22.07±0.03.

The radiant drift correction also affects the observed dispersion of radiants. The circular structure apparent in Fig. 4 is not maintained . Some other features do stand out. We find that the dispersion measured during enhanced Leonid activity is much smaller than that of the annual (off-season) Leonid shower (Fig. 3, top left panel). The dispersion in 1998 is not less than measured during the Leonid outbursts in 1995 and 1997. At no times is the radiant dispersion centrally condensed.

The accuracy is good enough to recognize the intrinsic dispersion in the radiants of the outburst component. Fig. 4 shows our best results with an accuracy of ±0.1 degree or better in radiant position. The radiant positions of different nights are marked with different symbols. The dispersion is larger than the measurement error, and equal to 0.095±0.020 degrees for the data from Nov. 16/17 and 0.14±0.04 degrees for the data of Nov. 17/18 (1 σ). If the remainder is due to ejection velocities only, then these should be or order 100 m/s (Jenniskens 1998), which is much larger than typically assumed (of order 1-10 m/s for the relevant mass range). This suggests that at least some of the dispersion is due to planetary perturbations.

The radiant right ascension does not change with magnitude (+0 to -4). There may be a mass-dependence in the distribution of declinations (Fig. 5), but this conclusion is hampered by the low number of bright meteors observed.

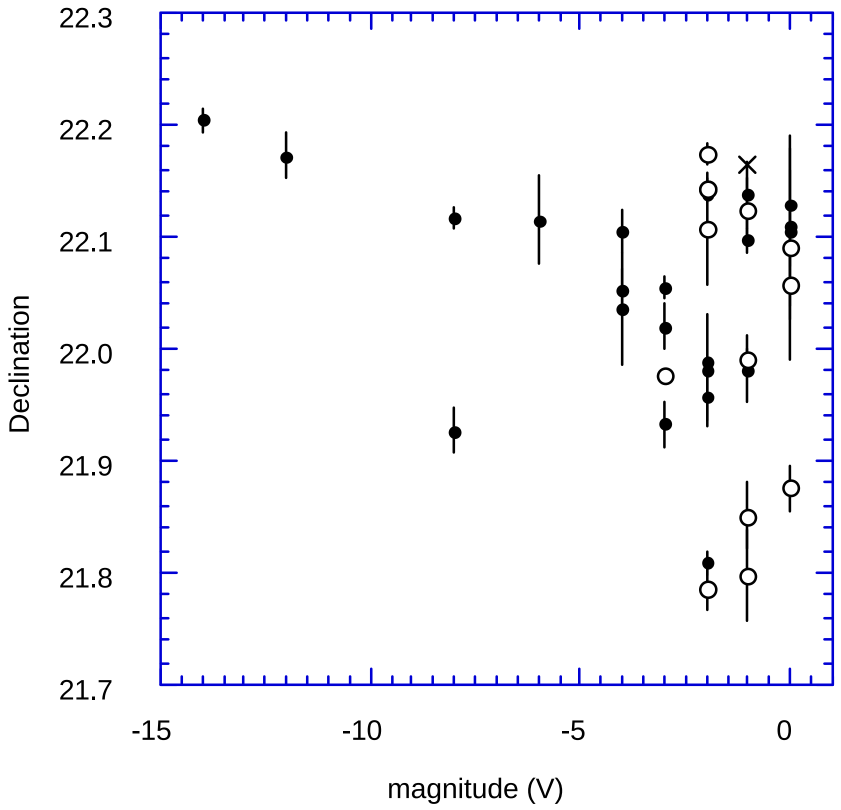

Fig. 5. Declination of the radiant as a function of meteor peak brightness. Symbols as in Fig. 4.

ORBITS

The calculated orbits reflect the correction for Earth's velocity vector alone, not for one or the other systematic variation in the velocity vector of the stream. Hence, the differences apparent in Fig. 4 are also manifested in the orbits calculated from radiant and speed (Table 2). The perihelion distance (and angle of perihelion) is systematically smaller for the meteors photographed on Nov. 16/17. The inclination of these meteors is also slightly smaller. Again, we do not find a dependence of orbital elements on the meteor magnitude, for as large a range as from +0 to -14 magnitude (a factor of 600 in particle mass).

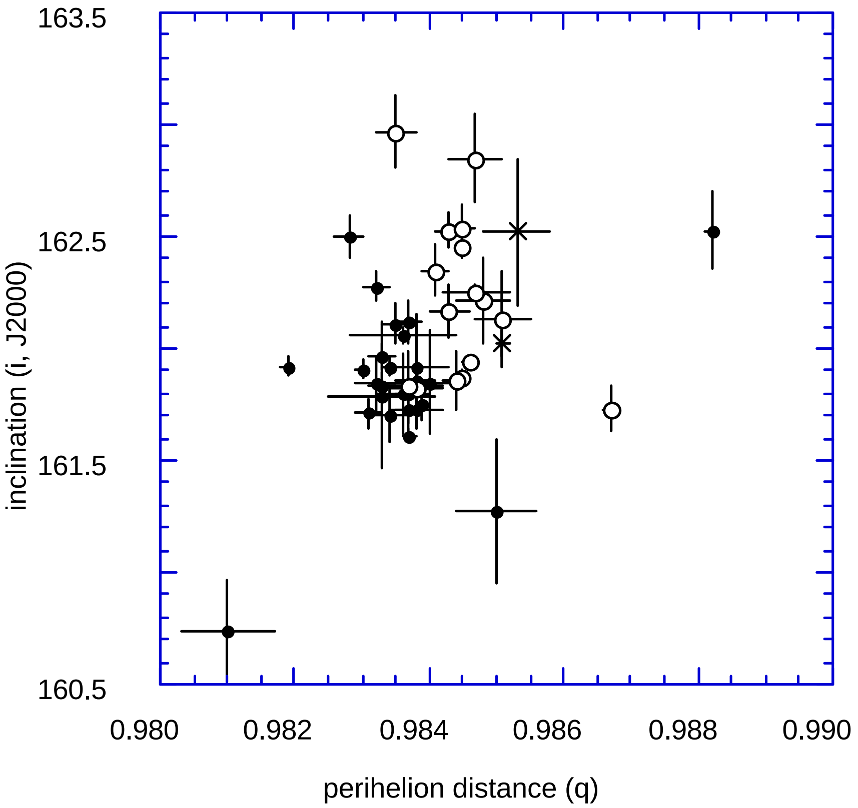

Fig. 6. Distribution of perihelion distance and inclination for all data. Symbols as in Fig. 5.

Of particular interest is the distribution of perihelion distance and inclination (Fig. 6). Both are mainly determined by measurements of the radiant position. We find that the data for Nov. 16/17 cluster in a small region of parameter space, much as expected for a random distribution with a small dispersion. The data for Nov. 17/18, however, show a significant dispersion in inclination and are systematically displaced.

While the radiant is a signature of perihelion distance and the angle of perihelion, the speed affects the semi-major axis. The semi-major axis (a) is a measure of the orbital period ($P \sim a^{3/2}$) and a measure of the furthest point from the sun (~ a(1+e)). Typically, the error in speed is significantly larger than that in the radiant vector and the semi-major axis is ill defined for long period and Halley type comets such as 55P/Tempel-Tuttle.

We find that our most accurate solutions cluster in a narrow range of semi-major axis. We obtain a mean value close to that of the parent comet if we accept the mean velocity of the observed trajectory as a good estimate of the pre-atmospheric entry velocity (Fig. 7). If we fit an equation that weights to points later in the trajectory for a derivation of deceleration, then we tend to find a value of the semi-major axis that is about 50% larger. We don't think our observations warrant such a high <a>.

For one meteor, 1998003, we were able to calculate a complete single-body solution from the fish-eye picture (Spurny 1999, this publication). This solution supports the use of average velocities for Leonids, because the exact solution gave Vinf = 71.207 km/s, and average solution for the same record and interval of breaks gave practically the same value Vinf = 71.199 km/s.

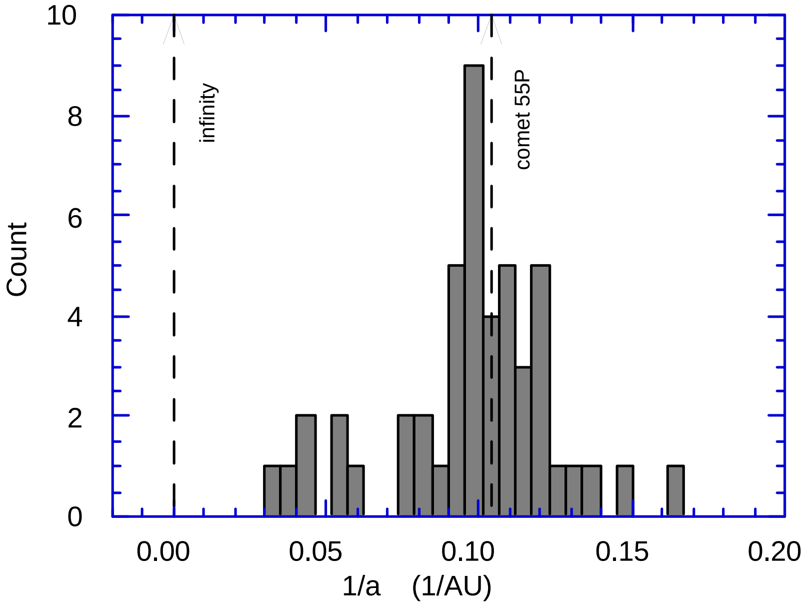

Fig. 7. Histogram of 1/a for the orbits with the most accurately measured velocities.

Three orbits are outlayers. All were detected on November 16/17.
They have a significantly deviating semi-major axis and a larger dispersion in radiant position. While the radiant of the shower is that of the Leonids, the semi-major axis is much less than that of the comet. This type of orbit can only occur after a close encounter with Earth and we conclude that three out of 98 Leonid meteoroids had a previous encounter with Earth. For a significant number of such meteoroids to be detected, Earth would have had to cross the stream numerous times before.

DISCUSSION

From the meteor activity curve, at least three dust components were detected during the November 1998 return of the Leonids (Arlt 1998, Jenniskens 1999 in this issue). A one-day wide component rich in bright fireballs was responsible for most, if not all, of the Leonids detected on November 16/17. On top of that, a narrow peak was observed between 16 and 21.5 UT on November 17/18.

We conclude that these dust components are also manifested in the measured orbital elements. The systematic displacements of the Nov. 16/17 and Nov. 17/18 data suggests an origin at different epochs or a different orbital evolution since ejection.

In recent models of the Leonids shower, narrow components are typically ascribed to ejecta that are only 2-4 revolutions old (e.g. Asher 1998). We do not confirm the expected narrow radiant distribution. Of course, Earth did not pass close to the debris trails ejected in recent returns and the observed peak on Nov. 17/18 must signify relatively dispersed matter in the plane of the comet orbit.

The broad component rich in bright meteors was recently ascribed to matter trapped in orbital resonances, specifically ejecta from the return of 1333 (Asher et al. 1999). The relatively narrow range in semi-major axis observed for our best meteors is consistent with such origin, but does not exclude other mechanisms. Clearly, the matter is older ejecta because it is significantly dispersed, not only in node but also in all other orbital elements. The radiant dispersion is resolved. Particles in orbital resonance are not necessary in exactly the same orbit, rather they have an orbital period close to a simple fraction with that of the major planets. It is not unlikely that the particles librate around this resonance and orbital elements vary slightly with time. The only characteristic being that particles stay in similar orbits for longer periods of time than that they would do otherwise.

If Asher's hypothesis is correct, we would expect a relatively narrow dispersion in q and I on Nov. 16/17, as observed. This confinement of values is remarkable. Perhaps, the larger dispersion for matter detected on Nov. 17/18 testifies to this matter being in non-resonant orbits. This may be the first direct evidence that the broad component of large grains is indeed in orbital resonance.

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Editorial handling:

REFERENCES

Arlt R. (1998) Bulletin 13 of the International Leonid Watch: The 1998 Leonid Meteor Shower. WGN, the Journal of the IMO 26, 239-248.

Asher D.J., Bailey M.E., Emel'yanenko V.V. (1999) Resonant meteoroids from Comet Tempel-Tuttle in 1333: the cause of the unexpected Leonid outburst in 1998. Mon. Not. R. Astron. Soc. XXX, XXX-XXX.

Asher D.J. (1998) The Leonid meteor storms of 1833 and 1966. Mon. Not. R. Astron. Soc. XXX, XXX-XXX

Betlem H., ter Kuile C., van 't Leven J., de Lignie M., Ramon Bellot L., Koop M., Angelos C., Wilson M., Jenniskens P. (1997) Precisely reduced meteoroid trajectories and orbits from the 1995 Leonid meteor outburst. *Planet. Space Sci*. **45**, 853-856.

Betlem H., ter Kuile C.R., de Lignie M., van 't Leven J., Jobse K., Miskotte K., Jenniskens P. (1998) Precision meteor orbits obtained by the Dutch Meteor Society - Photographic Meteor Survey (1981-1993). Astron. Astrophys. Suppl. Ser. 128, 179-185.

Betlem H, Van Mil O. (1999) *Radiant* **21** (1999) pp. 65 ev.

Brown P., Simek M., Jones J., Arlt R., Hocking W.K., Beech M., (1998) Observations of the 1996 Leonid meteor shower by radar, visual and video techniques. *Mon. Not. R. Astron. Soc.* **300**, 244-250.

Ceplecha Z., Borovicka J., Elford W.G., Revelle D.O. Hawkes R.L., Porubcan V., Simek M. (1998) Meteor phenomena and bodies. Space Science Reviews 84, 327-471.

Jenniskens P. (1996) Meteor stream activity III. Measurement of the first in a new series of Leonid outburst. *Meteoritics & Planetary Science* **31**, 177-184.

Jenniskens P. (1998) On the dynamics of meteoroid streams. *Earth Planets Space* **50**, 555-567.

Jenniskens P., Betlem H., de Lignie M. Langbroek M., van Vliet M. (1997) Meteor stream activity VI: The Quadrantids, a very young stream. Astron. Astrophys. 327, 1242-1252.

Jenniskens P., Betlem H., de Lignie M., Langbroek M. (1997) The detection of a dust trail in the orbit of an earth-threatening long-period comet. *Astrophys. J.* **479**, 441-447.

Jenniskens P., Betlem H., de Lignie M., ter Kuile C., van Vliet M.C.A., van 't Leven J., Koop M., Morales E., Rice T. (1998) On the unusual activity of the Perseid meteor shower (1989-96) and the dust trail of comet 109P/Swift-Tuttle. *Mont. Not. R. Astron. Soc.* **301**, 941-954.

Jenniskens P., de Lignie M., Betlem H., Borovicka J., Laux C.O., Packan D., Kruger C.H. (1999) Preparing for the 1998/99 Leonid Storms, in*: Laboratory Astrophysics and Space Research*, P. Ehrenfreund et al. (eds.), Kluwer Academic Publishers, p. 425-455.

Jenniskens P., de Lignie M., Betlem H., Borovicka J., Laux C.O., Packan D., Kruger C.H. (1999) Preparing for the 1998/99 Leonid Storms, in*: Laboratory Astrophysics and Space Research*, P. Ehrenfreund et al. (eds.), Kluwer Academic Publishers, p. 425-455.

Langbroek M. (1999) Leonid outburst activity 1996: A broad structure and a first occurrence of a narrow peak of fainter meteors. *Meteoritics & Plan. Sci.* **34**, 137-145.