ON THE ORIGIN OF THE 1999 LEONID STORM AS DEDUCED FROM PHOTOGRAPHIC OBSERVATIONS

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Abstract. Photographic multi-station observations of 18 Leonid meteors obtained by the Spanish Photographic Meteor Network are presented. For each meteoroid the radiant position, trajectory data and orbital parameters are discussed and compared to theoretical radiant positions and orbital elements of particles ejected from 55P/Tempel–Tuttle in 1899. We discuss the role of mean velocity imprecision in the dispersion of some orbital parameters, specially the semimajor axis. Finally, by applying the dust trail theory we have adjusted the1999 Leonid storm orbits to a defined semimajor axis value to test the quality of photographic observations.

Keywords: 55P/Tempel–Tuttle, comets, Leonid meteors, meteorites, meteor storm

1. Introduction

The systematic observation of meteors using photographic, video and CCD techniques has become one of the rare fields in astronomy in which amateurs can work together with professionals and make important contributions to science. Meteor studies use the atmosphere as a giant detector to estimate the flux of extraterrestrial matter on Earth. In the range of millimetric or submillimetric debris comets are the most important contributors (Hughes, 1995). One important influx of matter comes from cometary dust trails (Kresak, 1993) on the rare occasions when Earth intercepts one of them and a meteor storm is produced (Jenniskens, 1995, 1996). The Leonids activity is caused by a dense cloud of meteoroids from a relatively recent ejecta from comet 55P/Tempel–Tuttle. During the years of return of this comet to perihelia, a young meteoroid cloud appears producing meteor outbursts (Yeomans et al., 1996). Until 1997 all studies of Leonid activity were obtained from visual observations even though photographs are also available from the 1966 Leonid storm (Milon, 1967). In previous works (Trigo-Rodríguez, 2000; Trigo-Rodríguez et al., 2001), we derived the spatial densities of the shower during this

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cometary return from photographs taken by the Spanish Photographic Meteor Network in the period 1997–1999. In this paper we analyse the orbital elements of the brightest meteors registered during the 1999 Leonid storm from five stations of our network. A detailed orbital analysis is of special interest because precise information on orbital elements of meteoroids producing a Leonid storm is scarce. In fact only 29 well-determined orbits were available in the period 1938–1985 (Lindblad et al., 1993; Wu and Williams, 1996). Then Betlem et al. (1997) and Shiba et al. (1998) obtained additional data for the 1995 and 1996 apparitions, respectively, and Betlem et al. (1999) calculated from double-station meteor work 75 very precise orbits of meteoroids producing the 1998 Leonid outburst. The 1999 Leonid storm was also observed from the south of Spain by the same team (Betlem et al., 2000) and detailed data was obtained on 47 Leonid storm meteoroids. Precise orbits and trajectories of meteors provide important clues in order to gain further insight into the orbital dynamics of meteoroids and the physical properties during atmosphere interaction. We present here precise observational data on 18 Leonid meteors photographed during the 1999 Leonid storm. The intrinsic value of our orbital data lies in the fact that it has been obtained using a different methodology. Therefore, we also present theoretical orbital data as a good test to compare the quality of double-station photographic observations analysed by different methods.

2. Observations and Data Reduction

The measurements were made by the Spanish Photographic Meteor Network, SPMN (Trigo et al., 2001), from five photographic stations located in the east of Spain, around the Castelló province. Table I provides the geographic situation and height of these stations. In each station several camera batteries with 50 mm to 35 mm optics equipped with rotating shutters were installed. Time exposures were made with an accuracy of a second by camera operators, while the time of occurrence of the bright meteors were taken by SPMN members from simultaneously visual observations.

A specific software application called *Photographic centres for multiple station meteor observations* was developed by the SPMN team in order to provide the centre for each station depending on the geometry of meteor apparitions and the position of the participating stations. The negatives were developed and scanned to 2700 points by inch using a Kodak SprintScan scanner. We used PhotoFinish 4 software to made the astrometric measures of the star trails and the meteors. The astrometric measurements were then introduced into our *Network* software which, from the different photographs, provided the equatorial coordinates of the meteors with an astrometric accuracy of 0.005°. Our software also allows the identification of the same meteor from various stations assuming the typical values of ablation height through an automated search on the database for meteors appeared during the same observing interval. It allowed a quick identification of the different met-

TABLE I
The five stations participating in the 1999 Leonid campaign

Station (province)	Longitude (°)	Latitude (°)	Height (m)
Desert de les Palmes (Castelló)	0°02′40″ E	40°04′55″	390
Pla d'Arguines (València)	0°24′05″ W	39°45′34″	260
El Remolcador (Castelló)	0°20′51″ W	40°06′12″	1010
Titaïgues (València)	1°04′59″ W	39°51′52″	832
Torre de Porta Coeli (València)	0°30′31″ W	39°38′42″	160

eors registered from the different stations and calculated directly the atmospheric trajectory and radiant for each meteor. The trajectory length and shutter breaks were used by our software to derive the velocity of the meteoroid. To determine orbital elements from our trajectory data we used the program *MORB* provided by Z. Ceplecha, P. Spurny and J. Borovicka of the Ondrejov Observatory (2000).

3. Trajectory Data and Radiants

Around 150 meteors were photographed from the different stations, although most of them were recorded only from single stations and, in consequence, it was not possible to derive trajectory and radiant data. 26 double station meteors were clearly identified by our software. Among the 26 precisely reduced meteors, 18 had convergence angles larger than 20 degrees. The convergence angle (Q) is the angle between the two planes delimited by the through observing sites and the meteor path in the triangulation. Taking into account that only meteors with $Q > 20°$ can provide accurate radiant and orbital data (Betlem et al., 2000), we have only performed a detailed study of these 18 meteors. The trajectory data of these accurately reduced meteors are given in Table II, where a code used for identification, apparent visual magnitude (M_v), the meteor trail beginning and end height on the Earth's surface (H_b and H_e in km), the geocentric radiant coordinates (α_g and δ_g to Eq. 2000.00) and the velocity in km/s (at the top of atmosphere, geocentric and heliocentric) are compiled. All meteors listed in Table II are Leonids except the last one (T1) that is a North Taurid meteoroid associated to comet 2P/Encke.

To test the quality of the trajectories obtained we have analysed the correlation between the ending height of meteors, H_e, and their visual magnitude, M_v, following a similar method to that employed by Brown and Arlt (2000). A clear correlation ($r = 0.86$) between the ending height (H_e) and the visual magnitude (M_v) of the Leonid meteors can be seen in Figure 1, showing that the deepening in the atmosphere depends on the Leonid magnitude following Equation (1):

$$H_e(M_v) = 108.9 + 4.3 \cdot M_v. \quad (1)$$

TABLE II
Trajectory and radiant data of accurate meteors observed during the 1999 Leonid SPMN Campaign

Code	M_v	H_b	H_e	α_g (°)	δ_g (°)	V_∞	V_g	V_h
L1	−5	110.9	88.7	153.61 ± 0.03	21.81 ± 0.03	71.8 ± 0.2	70.6	41.4
L2	−3	110.7	98.7	152.43 ± 0.02	22.31 ± 0.02	71.6 ± 0.2	70.6	41.3
L3	−2	112.3	99.0	153.91 ± 0.03	21.37 ± 0.02	71.7 ± 0.2	70.5	41.2
L4	−1	111.3	102.8	154.18 ± 0.02	21.73 ± 0.02	71.8 ± 0.2	70.6	41.4
L5	−1	116.3	102.7	154.83 ± 0.03	21.61 ± 0.02	71.6 ± 0.2	70.4	41.2
L6	−8	115.5	75.9	154.35 ± 0.02	21.46 ± 0.01	71.9 ± 0.2	70.7	41.4
L7	−4	98.8	87.7	155.14 ± 0.03	21.59 ± 0.03	67.6 ± 0.2	65.7	36.6
L8	−3	104.5	90.2	153.94 ± 0.03	21.83 ± 0.02	71.6 ± 0.3	70.4	41.2
L9	−2	123.6	105.3	153.3 ± 0.6	21.47 ± 0.03	71.8 ± 0.3	70.6	41.3
L10	−3	115.7	99.6	153.52 ± 0.03	21.93 ± 0.02	71.5 ± 0.2	70.3	41.1
L11	−1	119.8	105.2	153.43 ± 0.02	21.99 ± 0.02	71.8 ± 0.3	70.6	41.4
L12	−1	112.8	104.9	153.44 ± 0.02	21.56 ± 0.02	71.6 ± 0.3	70.4	41.3
L13	−3	106.2	90.7	153.26 ± 0.02	21.48 ± 0.02	71.5 ± 0.2	70.5	41.2
L14	−4	109.6	87.2	153.67 ± 0.03	21.69 ± 0.03	71.6 ± 0.2	70.4	41.1
L15	−2	108.3	97.3	152.90 ± 0.03	22.01 ± 0.02	71.5 ± 0.3	70.5	41.2
L16	−2	108.3	98.9	153.21 ± 0.01	20.88 ± 0.01	71.7 ± 0.2	70.5	41.1
L17	−2	111.7	101.6	153.42 ± 0.01	22.79 ± 0.02	71.5 ± 0.2	70.3	41.2
L18	−3	111.3	93.1	153.59 ± 0.01	21.82 ± 0.02	71.7 ± 0.2	70.5	41.2
T1	−4	90.2	75.4	62.61 ± 0.02	23.92 ± 0.02	31.40 ± 0.08	29.4	38.2

4. Orbital Data

Table III lists the corresponding orbital elements of the 18 Leonids and one North Taurid meteor. In order to analyse the meteoroids that produced the 1999 Leonid storm, two meteoroids of Table II were removed from the study for different reasons. One of them (L15) appeared the night prior to the storm and in consequence probably belonged to the annual shower, not to the dust trail that caused the storm. The trajectory of another meteoroid (L7) was very peculiar (see Table II) since both its measured speed and trajectory height were low with respect to the mean values. The orbital elements calculated for L7 (Table III) led to an orbit with a semimajor axis and eccentricity values less than those expected for Leonids. This type of orbits were observed previously by Betlem et al. (1999) and can only occur after a close encounter with the Earth. L7 meteoroid could be also ejected in a relatively recent cometary return to perihelia but a previous encounter with our planet significantly changed its velocity and, in consequence, its orbital elements.

After the removal of meteors L7 and L15 and taking into account the data given in Tables II and III for the 16 Leonid meteors photographed during the storm, we

TABLE III

Orbital elements of the analysed meteoroids. Equinox (2000.00)

Code	Q	a	e	i	ω	Ω
L1	0.98412 ± 0.00015	10.57 ± 2.5	0.906 ± 0.023	162.46 ± 0.07	172.10 ± 0.17	235.30648 ± 0.00001
L2	0.98796 ± 0.00003	9.7 ± 2.2	0.898 ± 0.023	162.27 ± 0.06	177.07 ± 0.09	235.31648 ± 0.00001
L3	0.98301 ± 0.00017	9.2 ± 2.0	0.894 ± 0.022	162.89 ± 0.06	171.15 ± 0.18	235.30568 ± 0.00001
L4	0.98258 ± 0.00015	10.8 ± 2.7	0.909 ± 0.023	162.18 ± 0.06	170.84 ± 0.16	235.29276 ± 0.00001
L5	0.97933 ± 0.00024	9.3 ± 2.0	0.895 ± 0.023	161.94 ± 0.07	168.58 ± 0.21	235.29683 ± 0.00001
L6	0.98126 ± 0.00011	11.5 ± 0.9	0.915 ± 0.006	162.51 ± 0.03	169.90 ± 0.09	235.26779 ± 0.00001
L7	0.9715 ± 0.0005	1.95 ± 0.05	0.503 ± 0.013	160.79 ± 0.07	161.5 ± 0.4	235.26780 ± 0.00001
L8	0.98364 ± 0.00018	9.0 ± 2.2	0.890 ± 0.028	162.13 ± 0.07	171.7 ± 0.2	235.29941 ± 0.00001
L9	0.9853 ± 0.0019	9.7 ± 3.7	0.90 ± 0.04	163.1 ± 0.4	173.2 ± 1.9	235.2705 ± 0.0012
L10	0.98518 ± 0.00010	8.9 ± 1.5	0.889 ± 0.018	162.23 ± 0.05	173.07 ± 0.13	235.30073 ± 0.00001
L11	0.98561 ± 00.0001	10.7 ± 3.1	0.91 ± 0.03	162.21 ± 0.06	173.56 ± 0.15	235.30560 ± 0.00001
L12	0.98491 ± 0.00012	10.1 ± 2.8	0.90 ± 0.03	162.88 ± 0.06	172.92 ± 0.17	235.30262 ± 0.00001
L13	0.98530 ± 0.00019	8.9 ± 3.0	0.89 ± 0.04	163.10 ± 0.05	174.35 ± 0.11	235.27051 ± 0.00001
L14	0.98437 ± 0.00013	8.7 ± 1.4	0.886 ± 0.018	162.51 ± 0.06	172.28 ± 0.15	235.29573 ± 0.00001
L15	0.98411 ± 0.00015	9.1 ± 2.3	0.89 ± 0.03	162.45 ± 0.06	171.89 ± 0.18	234.38780 ± 0.00001
L16	0.98471 ± 0.00009	8.4 ± 1.3	0.882± 0.018	164.08 ± 0.04	172.59 ± 0.12	235.28866 ± 0.00001
L17	0.98646 ± 0.00005	9.0 ± 1.5	0.890 ± 0.018	160.89 ± 0.04	174.53 ± 0.09	235.28875 ± 0.00001
L18	0.98480 ± 0.00010	9.5 ± 1.7	0.896 ± 0.018	162.37 ± 0.05	172.71 ± 0.12	235.28879 ± 0.00001
T1	0.358 ± 0.003	2.66 ± 0.12	0.865 ± 0.007	3.37 ± 0.06	292.02 ± 0.06	234.23413 ± 0.00002

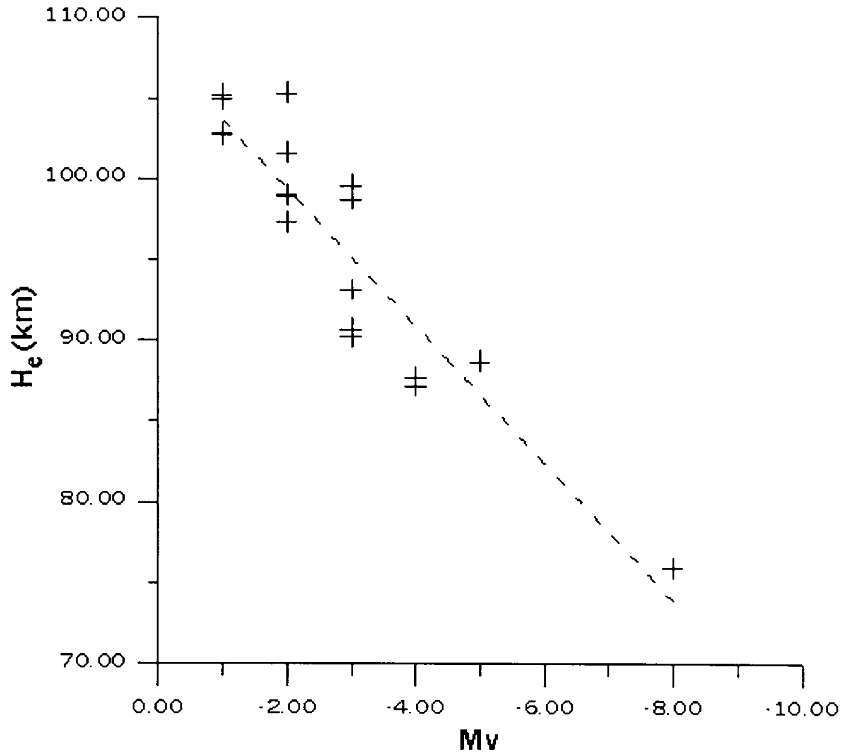

Figure 1.

may compare our results with those obtained by other authors. Table IV gives the averaged geocentric radiant and orbital elements obtained in this work compared to those previously reported for 1998 and 1999 Leonids (Betlem et al., 1999, 2000). The interest of this comparison lies in the extraordinary similarity obtained despite the fact that data were analysed in a different way. Betlem used the Astroscan software (Betlem et al., 1997) and we reduced our photographs using our *Network* program following the astrometric procedure developed by Steyaert (1990).

On comparing the data in Table IV it is deduced that the averaged values obtained for the two samples are identical, despite the fact that our radiant data has larger standard deviations probably due to the intrinsic error associated to time determination from visual observations (usually between one or two seconds) and less astrometric accuracy. In fact, Betlem et al. (2000) used an all-sky intensified video camera to record the time of occurrence of the bright meteors to improve the accuracy in time determination. Between the orbital data, the only difference is a lower mean semimajor axis probably associated to observational errors in velocity determinations. In fact the estimated uncertainties in the geocentric velocities allow Betlem et al. (1999) to conclude that the semimajor axis is an orbital parameter that

TABLE IV

Averaged geocentric radiant and orbital elements compared to those obtained for 1998 and 1999 Leonids by Betlem et al. (1999, 2000). The given errors are standard deviations

Reference	Radiant ($\lambda_0 = 235°$)		Main orbital elements (2000.00)			
	R.A.	Dec.	q	a	I	ω
This work	153.43 ± 0.61	+21.83 ± 0.40	0.9838 ± 0.0002	9.6 ± 2.1	162.4 ± 0.7	172.4 ± 1.9
Leonids 1999	153.39 ± 0.25	+21.80 ± 0.13	0.9844 ± 0.0009	10.1 ± 2.4	162.50 ± 0.22	172.4 ± 0.9
Leonids 1998	153.29 ± 0.53	+22.12 ± 0.33	0.9839 ± 0.0014	9.7 ± 2.8	162.05 ± 0.49	171.9 ± 1.5

can be not genuine. In the next section we discuss this point in order to determine the real capacity of double-station photography.

5. The Orbital Evolution Taking into Account the Influence of Radiation Pressure

In this section we compare the previously deduced orbital elements with the expected theoretical orbits to meteoroids ejected during 1899 return to perihelia of comet 55P/Tempel–Tuttle. According to Wyatt and Whipple (1950) the radial and perpendicular components of the equations of motion are:

$$r - r \cdot \theta^2 = -\frac{\mu}{r^2} - \frac{2\beta \cdot r}{r^2} \tag{2}$$

$$\frac{d}{dt}(r^2 \cdot \theta) = -\beta \frac{d\theta}{dt}, \tag{3}$$

where $\mu = GM - \beta c$ represents the solar gravitational constant decreased by the outward- directed radiation pressure. We also found the parameter β that takes into account the radiation pressure according to the following equation:

$$\beta = \frac{3E}{16\pi c^2 \cdot s \cdot \rho} = \frac{3.55 \times 10^{-8}}{s \cdot \rho} \left[\frac{\mathrm{AU}^2}{\mathrm{year}}\right]. \tag{4}$$

In Equation (4) E denotes the total energy emitted by the Sun per second and s and ρ denote the radius and the density of the particle in question, expressed in c.g.s. units, respectively. Using this equation we can estimate the typical β value for 1999 Leonid storm meteoroids considering Rietmeijer (2002) estimations for radius and density. We derived a value of $\beta = 0.001$ for a -2 mag. Leonid meteoroid with a typical radius of 1×10^{-3} m and a density of 2 g/cm^3, identical to the one proposed by Williams (1997) as typical for visual Leonids. In consequence we took this value as the reference to estimate the influence of the radiation pressure over Leonid photographic meteoroids in the magnitude range: $-8 < M_v < -1$. We also took $\beta = 0$ for comparison, which is equivalent to consider only gravitational perturbations over the meteoroids, without Poynting–Robertson drag.

Using both values for β, D. Asher (personal communication) used Everhart's (1985) 15th order Radau integrator software in a program by Chambers (1999) to calculate the theoretical orbital elements for meteoroids ejected during the 1899 return of comet 55P/Tempel–Tuttle to perihelion and reaching their descending node at the time of the 1999 Leonids. The results of these numerical integrations are given in the first two lines of Table V. We computed the orbital parameters of the dust trail centre without considering radiation pressure ($\beta = 0$) and taking into account the typical radiation pressure for meteoroids with masses producing visual meteors ($\beta = 0.001$). The expected differences for the orbital elements of Leonids that intersect the Earth are in the last decimal place given here (Asher, 1999; McNaught and Asher, 2001). Because radiation pressure is an inverse square law like solar gravity (see Equation (2)), the particle affected by radiation pressure moves in a slightly different Keplerian ellipse. For the sake of comparison the mean orbit of Leonids obtained by us and by Betlem et al. (2000) associated to the 1999 storm are also listed in Table V. The semimajor axis and inclination values are slightly different but they seem to be in good agreement within the uncertainty associated to the observational geocentric velocity error.

From Table V we can conclude that the orbital elements of SPMN 1999 Leonids are nearly identical (considering the data accuracy) to those obtained by Betlem et al. (2000). Major differences are in the semimajor axis (a), although this orbital element is highly influenced by geocentric velocity uncertainty in the measurements.

It is well known that a considerable uncertainty in determining the semimajor axis (a) from observations exists due to uncertainties in velocity measurements. A small error in velocity translates to a significant error in a, as explained by Betlem et al. (1999), introducing a false dispersion in this orbital elements. Meteoroids within a dust trail have orbits that are very similar to each other, and also similar to that of the parent comet. Hence differences between the orbital parameters, in particular the semimajor axes, are small. The semimajor axis is associated to the orbital period ($P \approx a^{3/2}$), which shows whether the meteoroids are in mean motion resonances with the planets. Since the semimajor axis is also inversely proportional to energy, this implies that the ejection velocity is small compared with the orbital velocity (Arter and Williams, 2002). Moreover, it is known that ejection velocity of meteors from a comet nucleus remains within a narrow interval, which in turn results in very similar semimajor axis values. In fact, the well-documented storms yield typical ejecta velocities averaging 5 m s^{-1} without large dispersion (Brown and Arlt, 2000), which is close to the values found by Kresak (1993) for meteoroids associated to IRAS dust trails. But the period can be slightly different for each trail and also along any single trail, because gravitational perturbations change the comet's semimajor axis by amounts in the order of 0.1 AU between successive returns (Asher, 1999). In any case, for meteoroids belonging to the same trail, the semimajor axis probably remains similar in a short timescale when few revolutions are involved. Brown (1999) deduced that dust trail average density decreases by 2–3 orders of magnitude one century after ejection due to dispersion induced by planetary perturbations, which supports the similarity of Leonid orbits in a short timescale.

However, the dust trail theory predicts the semimajor axis quite precisely if we assume a value of radiation pressure (D. Asher, personal communication). This fact can be used to derive the other orbital elements from observations, as suggested by V. Emel'yanenko (personal communication). We have obtained interesting evidence of the stability and similarity of this semimajor axis of meteoroids causing

TABLE V

Theoretical orbital parameters for particles ejected in the 1899 return to perihelia of 55P/Tempel–Tuttle compared with photographic 1999 Leonid results

Identification	a (AU)	e	I (°)	ω (°)	Ω (°)
$\beta = 0$	10.391	0.9052	162.58	172.53	235.29
$\beta = 0.001$	10.184	0.9033	162.57	172.52	235.29
This work	9.6 ± 2.1	0.897 ± 0.022	162.4 ± 0.7	172.4 ± 1.9	235.28 ± 0.02
This work fixing $a = 10.18$	10.18	0.9034 ± 0.0003	162.5 ± 0.5	172.2 ± 2.2	235.28 ± 0.02
Betlem et al. (2000)	10.1 ± 2.4	0.901 ± 0.025	162.50 ± 0.22	172.4 ± 0.9	235.28 ± 0.02

the 1999 Leonid storm. We use the fact that the "dust trail" theory predicts the semimajor axis quite precisely (assuming a value of β) to test the quality of our observations. Our procedure consists in changing the observed velocities until we reach an adjusted value that provides the expected semimajor axis value. We have adjusted mean velocities for all observed meteoroids in this way to obtain orbits with a semimajor axis identical to the theoretical value ($a = 10.18$). The results are given in Table V, which shows how by fixing a, the other orbital elements are automatically adjusted to a very similar value to that of the computed theoretical orbit taking into account radiation pressure ($\beta = 0.001$). In fact it is quite apparent that the large deviation observed in some parameters, probably due to the velocity uncertainty, is in this way clearly removed. It is specifically significant that eccentricity (e) and inclination (i) standard deviations are improved to a considerable extent. On the other hand, Table V shows that the theoretical orbit calculated without considering radiation pressure ($\beta = 0$) on meteoroids is clearly not realistic compared to observational data.

We can apply this result to study the velocity and semimajor axis accuracy from photographic measurements. As we explained above, observational imprecision associated to the determination of meteoroid velocities mainly affects the semimajor axis of the orbit. In the same way as was described by Betlem et al. (2000) we determine the meteor velocity obtaining a mean value through the observed trajectory. This averaged velocity is usually considered as a good estimate of the pre-atmospheric entry velocity, but what is its involved uncertainty? To solve this question we decided to compare our averaged velocities with the adjusted ones in order to obtain the semimajor axis predicted by the "dust trail" theory. Our averaged velocity for 1999 Leonids is 71.5 ± 0.1 km s^{-1}, while the adjusted velocity is only slightly larger: 71.6 ± 0.1 km s^{-1}.

Another interesting point is to compare each of the observed and adjusted velocities directly. The typical standard deviation between both values was: $\delta v = 0.15$ km s^{-1}, which represents the limit to obtain more accurate velocities that allow the determination of a more realistic value of a. In fact we note that to adjust the orbits exactly to $a = 10.18$ AU, we need a velocity resolution more than one order of magnitude lower, around 10 m s^{-1}. Nowadays it is not possible to obtain this uncertainty from photographic observations using 50 mm lenses – it is necessary to use larger focal distances and high resolution video observations to improve velocity measurements.

6. Conclusions

From photographic observations of the 1999 Leonid storm, we conclude the following:

(i) The 1999 storm was produced by meteoroids belonging to a narrow dust trail ejected in 1899 from comet 55P/Tempel–Tuttle. The radiant and orbital parameters of the analysed meteoroid sample are identical to those obtained independently by Betlem et al. (2000).

(ii) The 1999 Leonid storm meteoroids followed very similar orbits, intrinsically different to the annual Leonid meteoroids that form a background component.

(iii) The orbital elements obtained for 1999 Leonid meteoroids from photographic observations are the same (taking into account the observational accuracy) as the theoretical parameters obtained from numerical integration.

(iv) The standard deviation usually derived from photographic observations on several orbital parameters (a, e and i) is associated to velocity uncertainties and it is not real. In fact, by applying the "dust trail" theory it is possible to predict a semimajor axis value, which may allow us to derive the other orbital elements from observations as suggested by V. Emel'yanenko (personal communication). Correcting our orbits in this way we found full accordance with theoretical orbital elements. This method can be used to test the accuracy of photographic velocity estimations.

(v) A direct consequence of (iv) is that the Leonid 1999 storm was produced by a narrow dust trail where meteoroids followed close orbits such as is expected theoretically if they were ejected in 1899 from the 55P/Tempel–Tuttle (McNaught and Asher, 1999).

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