PRECISE TRAJECTORIES AND ORBITS OF METEOROIDS FROM THE 1999 LEONID METEOR STORM

HANS BETLEM
Dutch Meteor Society, Lederkarper 4, 2318 NB Leiden, The Netherlands
E-mail: betlem@strw.leidenuniv.nl

PETER JENNISKENS
SETI Institute, NASA ARC, Mail Stop 239-4, Moffett Field, CA 94035
E-mail: pjenniskens@mail.arc.nasa.gov

PAVEL SPURNÝ
Astronomical Institute, Ondrejov Observatory, 251 65 Ondrejov, Czech Republic

GUUS DOCTERS VAN LEEUWEN, KOEN MISKOTTE, AND CASPER R. TER KUILE
Dutch Meteor Society, Lederkarper 4, 2318 NB Leiden, The Netherlands

and

PETER ZARUBIN AND CHRIS ANGELOS
Fremont Peak Observatory Association, P.O. Box 1110, San Juan Bautista, CA 95045

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Abstract. Photographic multi-station observations of 47 Leonid meteors are presented that were obtained from two ground locations in Spain during the 1999 meteor storm. We find an unresolved compact cluster of radiants at $\alpha = 153.67 \pm 0.05$ and $\delta = 21.70 \pm 0.05$ for a mean solar longitude of 235.282 (J2000). The position is identical to that of the Nov. 17/18 outburst of 1998, which implies that both are due to comet 55P/Tempel-Tuttle's ejecta from 1899. We also find a halo which contains about 28% of all meteors. The spatial distribution of radiant positions appears to be Lorentzian, with a similar fraction of meteors in the profile wings as the meteor storm activity curve.

Keywords: Comet dust trial, dispersion, Leonids 1999, meteor, meteor orbit, meteor trajectory, orbital dynamics

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1. Introduction

Precise orbits and trajectories of meteors provide insight into the orbital dynamics of meteoroids and the physical properties of the meteoroids during interaction with the atmosphere. Many open questions regarding the density and fragmentation of large meteoroids and the physical processes that determine the dynamics of meteoroid streams are summarized in the reviews by Ceplecha *et al.* (1998) and Jenniskens (1998).

The Leonid showers offer an unusual opportunity to study the formation and early evolution of a meteoroid stream. The first Leonid outburst was observed in 1994, amongst others from locations in California and Spain (Jenniskens *et al.*, 1996).

The discovery of enhanced Leonid activity led to the mounting of a multi-station photographic campaign at these two sites during the Leonids of 1995. Measurements of 23 precisely reduced Leonid orbits in Nov. 1995 showed a compact radiant defined by 7 orbits that were the first orbital elements of outburst Leonids (Betlem *et al.*, 1997). Similar measurements of seven orbits during a campaign from California in 1997 provided the first evidence for a systematic displacement of that compact radiant (Jenniskens and Betlem, 2000), which was confirmed by measurements from two sites in China during the outburst of 1998 in the night of Nov. 16/17 (Betlem *et al.*, 1999). Although this radiant was much more compact than that of the annual Leonid shower, we measured significant spread in the radiant positions of this component (Jenniskens and Betlem, 2000). Together with the relatively large nodal dispersion of this outburst component, called the Leonid Filament, this pointed towards a relatively high age. Indeed, numerical modeling shows the Leonid Filament to be the result of accumulation of debris in orbital resonances over the past 1000 years (Asher *et al.*, 1999; Jenniskens and Betlem, 2000).

Meteor storms are the result of more recent ejecta. From the tables of McNaught and Asher (1999) we conclude that the second peak in the night of Nov. 17/18, 1998, may have been caused by ejecta from 1899 or from 1932. We measured a significant dispersion in declination which, together with an asymmetric activity profile (Jenniskens, 1999), is evidence for planetary perturbations of the 1899 ejecta found by McNaught and Asher (1999) from numerical modeling.

Hence, we were eager to measure the radiant distribution for an unperturbed meteor storm, expecting the radiant to be more compact and the orbits of the meteoroids to be more similar. This would be a good test for our error estimates and an invitation to push the capability of the technique to the limit. Observations of the storm were performed from Spain, while similar observations from California served for reference. Only part of the data have been reduced at this time. Here, we report on the first data measured in Spain during the 1999 Leonid meteor storm.

2. Methods

The measurements were made from two observing sites at Punto Alto (38° 22' 45".25 356° 58' 1".88; height 772m) and Casa Nueva (39° 07' 01".30 357° 16' 39".90; height 785m) in Spain. Time exposures were made by fixed cameras, while an all-sky intensified video camera recorded the time of occurrence of the bright meteors. We deployed the same clusters of small (35 mm format) cameras with 50 mm f/1.8 optics and crystal controlled rotating shutters as in Betlem *et al.* (1999). The negatives were developed, scanned on Kodak Photo CD, and analyzed using interactive Astroscan software in the normal manner (Betlem *et al.*, 1997; 1998). The typical astrometric accuracy is 0.003°.

3. Results

Around 1100 meteors were photographed from Punto Alto and about 700 were photographed from Casa Nueva on the night of Nov. 17/18, 1999. The first 65 precisely reduced orbits are presented in this paper.

Of the first 65 precisely reduced orbits, 47 turn out to have convergence angles larger than 20 degrees. These provide the most accurate results and are listed in Tables I and II. The convergence angle is the angle between the two planes defined by each observing site and the meteor trajectory. Table I gives the trajectories of 47 Leonids that are part of the 1999 Leonid meteor storm. The columns list apparent visual magnitude (Mv), beginning and end height (km), heliocentric velocity (Vh), geocentric velocity (Vg), geocentric radiant coordinates (α, δ), and convergence angle (Q). The heights represent the lowest and highest point of the recorded trajectory, respectively, which does not take into account that some meteors may have entered the field of view, while others may have left, without their actual beginning or end point being recorded. Table II lists the corresponding orbital elements of these 47

Leonid storm meteors: perihelion distance (q), semi major axis (a), inclination (i), argument of perihelion (ω) and ascending Node (Ω).

TABLE I

Code	**Day UT**	**Mv**	**H beg**	**H end**	**V h**	**V g**	**± V**	**α Geo**	**± α**	**δ Geo**	**± δ**	**Q max**
1999008	18.01383	-5	118.72	92.19	41.39	70.69	0.16	153.62	0.06	21.67	0.03	20.71
1999010	18.03427	-1	117.28	107.67	41.25	70.54	0.06	153.61	0.04	21.74	0.04	29.81
1999011	18.03427	-1	117.26	108.31	41.33	70.63	0.15	153.61	0.16	21.65	0.04	27.45
1999013	18.04760	0	120.78	106.42	41.03	70.31	0.18	153.69	0.19	21.78	0.17	27.37
1999014	18.05128	-1	114.46	103.04	41.91	71.15	0.11	153.83	0.08	22.00	0.08	27.19
1999015	18.05166	-1	114.65	103.26	41.56	70.86	0.06	153.64	0.24	21.71	0.22	24.63
1999016	18.05387	0	113.75	104.70	41.69	71.00	0.12	153.80	0.12	21.56	0.11	31.83
1999017	18.05821	-3	114.18	94.85	41.49	70.78	0.03	153.63	0.00	21.73	0.00	38.30
1999018	18.05838	0	113.08	103.53	40.91	70.20	0.14	153.52	0.09	21.74	0.08	28.18
1999026	18.06705	-1	113.24	102.57	41.26	70.57	0.12	153.66	0.14	21.66	0.13	31.44
1999028	18.06954	0	111.74	100.69	41.54	70.82	0.14	153.67	0.07	21.79	0.06	33.26
1999029	18.06977	0	112.99	104.40	41.27	70.56	0.23	153.71	0.14	21.69	0.13	27.77
1999030	18.07054	0	113.34	101.66	41.61	70.90	0.08	153.75	0.06	21.70	0.06	27.89
1999031	18.07112	0	111.05	104.22	41.05	70.29	0.48	153.24	0.14	22.31	0.13	31.22
1999032	18.07148	-1	113.08	100.93	41.53	70.84	0.05	153.60	0.02	21.68	0.01	33.44
1999033	18.01383	-1	118.72	92.19	41.39	70.69	0.24	153.62	0.06	21.67	0.03	20.62
1999036	18.07451	-1	113.11	100.21	41.23	70.53	0.07	153.60	0.07	21.71	0.03	36.11
1999037	18.07529	0	115.05	102.11	40.94	70.22	0.25	153.76	0.07	21.71	0.07	77.71
1999041	18.07688	0	113.76	103.09	41.39	70.71	0.23	153.70	0.13	21.49	0.12	27.06
1999043	18.07907	-1	112.65	98.94	41.15	70.44	0.08	153.54	0.00	21.74	0.00	20.51
1999044	18.07940	-4	119.16	94.99	41.28	70.57	0.06	153.64	0.03	21.72	0.03	28.25
1999045	18.07948	-1	112.18	101.39	41.38	70.66	0.12	154.03	0.13	21.59	0.12	23.77
1999046	18.07979	0	114.00	105.73	41.31	70.65	0.27	153.33	0.22	21.55	0.21	25.74
1999047	18.08043	-1	113.17	101.67	41.25	70.60	0.07	152.57	0.12	21.85	0.11	27.82
1999050	18.08253	-1	112.65	100.59	41.50	70.79	0.10	153.70	0.01	21.73	0.00	32.01
1999057	18.08580	0	112.87	103.57	41.55	70.85	0.32	153.63	0.03	21.67	0.02	32.37
1999058	18.08630	0	114.87	103.03	41.55	70.82	0.12	153.68	0.00	21.82	0.00	33.11
1999059	18.09192	-1	114.47	99.26	41.30	70.60	0.11	153.65	0.04	21.69	0.04	70.05
1999061	18.08779	-1	118.14	97.71	41.45	70.76	0.14	153.50	0.08	21.70	0.07	76.81
1999064	18.08905	-1	113.69	96.81	41.36	70.60	0.05	154.39	0.01	21.71	0.00	35.47
1999065	18.08919	0	113.49	99.30	41.33	70.63	0.19	153.68	0.13	21.67	0.07	28.67
1999066	18.08936	0	112.92	104.85	40.60	69.88	0.18	153.31	0.11	21.96	0.04	26.54
1999067	18.08968	-1	110.83	94.94	41.06	70.33	0.08	153.84	0.11	21.78	0.10	21.83
1999071	18.09102	0	112.94	105.33	40.75	70.02	0.17	153.92	0.08	21.68	0.04	27.15
1999074	18.09296	0	114.02	99.25	41.04	70.33	0.15	153.66	0.05	21.72	0.04	77.33
1999079	18.10307	-1	113.12	100.91	41.10	70.38	0.11	153.92	0.17	21.62	0.16	19.85
1999081	18.09657	0	114.20	104.24	41.42	70.72	0.16	153.57	0.22	21.70	0.20	25.73
1999085	18.09917	-1	114.39	99.19	41.24	70.52	0.10	153.73	0.01	21.70	0.01	34.88
1999087	18.09788	0	112.99	101.69	41.61	70.89	0.26	153.73	0.09	21.78	0.08	47.05
1999088	18.10159	-4	115.76	89.90	41.53	70.83	0.02	153.71	0.02	21.64	0.02	30.23
1999105	18.11101	0	112.21	103.51	41.71	70.99	0.24	153.40	0.50	21.95	0.47	25.17
1999106	18.11076	-3	120.58	96.32	41.13	70.42	0.07	153.69	0.04	21.68	0.02	35.35
1999112	18.10750	1	111.15	99.28	41.47	70.73	0.31	154.14	0.12	21.71	0.06	25.70
1999114	18.11946	0	111.98	98.45	41.07	70.35	0.13	153.84	0.22	21.70	0.13	22.62
1999115	18.12153	-1	117.54	98.66	41.00	70.30	0.08	153.67	0.13	21.59	0.07	30.34
1999117	18.12295	-1	111.27	95.97	41.49	70.79	0.06	153.49	0.03	21.70	0.01	24.18
1999129	18.14267	-3	117.09	87.29	41.35	70.65	0.05	153.71	0.05	21.65	0.03	40.67
Mean			114.35	100.40	41.31	70.60	0.14	153.66	0.10	21.72	0.08	
Stand. Dev.			2.49	4.52	0.26	0.26		0.25		0.13		

TABLE II

Code	**q**	**± q**	**1/a**	**± 1/a**	**i**	**± i**	**ω**	**± ω**	**Ω**	**± Ω**
1999008	0.9843	0.0002	0.092	0.022	162.62	0.07	172.24	0.23	235.21500	0.00000
1999010	0.9844	0.0002	0.105	0.001	162.49	0.07	172.35	0.16	235.23561	0.00000
1999011	0.9843	0.0005	0.098	0.014	162.65	0.11	172.28	0.50	235.23561	0.00000
1999013	0.9842	0.0007	0.125	0.017	162.34	0.30	172.09	0.65	235.24906	0.00000
1999014	0.9843	0.0003	0.043	0.010	162.06	0.13	172.38	0.27	235.25277	0.00000
1999015	0.9844	0.0009	0.076	0.006	162.58	0.38	172.41	0.80	235.25314	0.00000
1999016	0.9837	0.0005	0.064	0.012	162.74	0.18	171.83	0.39	235.25536	0.00000
1999017	0.9845	0.0000	0.082	0.003	162.53	0.01	172.47	0.02	235.25974	0.00000
1999018	0.9847	0.0003	0.137	0.013	162.47	0.15	172.56	0.32	235.25992	0.00000
1999026	0.9850	0.0005	0.105	0.012	162.73	0.23	172.93	0.49	235.26866	0.00000
1999028	0.9845	0.0003	0.078	0.013	162.42	0.11	172.51	0.23	235.27117	0.00000
1999029	0.9842	0.0005	0.103	0.021	162.51	0.22	172.11	0.49	235.27140	0.00000
1999030	0.9841	0.0002	0.071	0.008	162.53	0.11	172.16	0.20	235.27218	0.00000
1999031	0.9863	0.0004	0.123	0.045	161.76	0.24	174.22	0.52	235.27277	0.00000
1999032	0.9846	0.0046	0.078	0.005	162.64	0.02	172.56	0.07	235.27313	0.00000
1999033	0.9843	0.0002	0.092	0.022	162.62	0.07	172.24	0.23	235.21500	0.00000
1999036	0.9846	0.0002	0.107	0.006	162.54	0.06	172.49	0.21	235.27618	0.00000
1999037	0.9839	0.0003	0.134	0.023	162.39	0.12	171.85	0.28	235.27697	0.00000
1999041	0.9839	0.0005	0.092	0.022	162.86	0.21	171.95	0.45	235.27856	0.00000
1999043	0.9848	0.0000	0.115	0.117	162.51	0.01	172.69	0.04	235.28078	0.00000
1999044	0.9845	0.0001	0.102	0.005	162.51	0.05	172.40	0.11	235.28111	0.00000
1999045	0.9829	0.0005	0.093	0.011	162.50	0.20	171.08	0.43	235.28119	0.00000
1999046	0.9852	0.0007	0.100	0.026	162.97	0.36	173.16	0.77	235.28150	0.00000
1999047	0.9874	0.0002	0.105	0.007	162.93	0.19	175.93	0.40	235.28214	0.00000
1999050	0.9844	0.0000	0.082	0.010	162.49	0.02	172.34	0.06	235.28427	0.00000
1999057	0.9845	0.0002	0.077	0.030	162.65	0.07	172.52	0.18	235.28756	0.00000
1999058	0.9846	0.0000	0.078	0.011	162.38	0.02	172.56	0.06	235.28807	0.00000
1999059	0.9845	0.0002	0.100	0.010	162.56	0.06	172.40	0.14	235.29373	0.00000
1999061	0.9850	0.0003	0.086	0.013	162.66	0.13	172.91	0.27	235.28957	0.00000
1999064	0.9817	0.0000	0.095	0.004	162.08	0.01	170.16	0.04	235.29085	0.00000
1999065	0.9843	0.0003	0.097	0.018	162.58	0.13	172.27	0.29	235.58202	0.00000
1999066	0.9857	0.0003	0.165	0.017	162.20	0.10	173.53	0.37	235.29116	0.00000
1999067	0.9838	0.0004	0.122	0.008	162.25	0.17	171.78	0.37	235.29149	0.00000
1999071	0.9833	0.0003	0.151	0.016	162.31	0.09	171.22	0.29	235.29283	0.00000
1999074	0.9844	0.0002	0.124	0.014	162.46	0.08	172.27	0.17	235.29479	0.00000
1999079	0.9833	0.0007	0.119	0.011	162.47	0.27	171.36	0.58	235.29797	0.00000
1999081	0.9848	0.0008	0.089	0.015	162.61	0.35	172.74	0.74	235.29842	0.00000
1999085	0.9842	0.0001	0.106	0.009	162.47	0.02	172.15	0.07	235.30104	0.00000
1999087	0.9844	0.0003	0.072	0.025	162.42	0.15	172.41	0.32	235.29975	0.00000
1999088	0.9843	0.0001	0.079	0.002	162.65	0.03	172.26	0.06	235.30348	0.00000
1999105	0.9857	0.0015	0.062	0.023	162.37	0.79	173.75	1.65	235.31298	0.00001
1999106	0.9843	0.0001	0.116	0.006	162.52	0.04	172.22	0.13	235.31273	0.00000
1999112	0.9828	0.0005	0.084	0.029	162.26	0.13	171.06	0.41	235.30944	0.00000
1999114	0.9838	0.0008	0.122	0.012	162.37	0.16	171.80	0.69	235.32150	0.00000
1999115	0.9843	0.0003	0.129	0.007	162.65	0.13	172.14	0.27	235.32358	0.00000
1999117	0.9851	0.0001	0.083	0.006	162.67	0.03	173.10	0.11	235.32502	0.00000
1999129	0.9844	0.0002	0.095	0.004	162.59	0.06	172.36	0.17	235.34490	0.00000
Mean	0.9844	0.0004	0.099	0.016	162.50	0.14	172.39	0.33		
Stand. Dev.	0.0009		0.024		0.22		0.86			

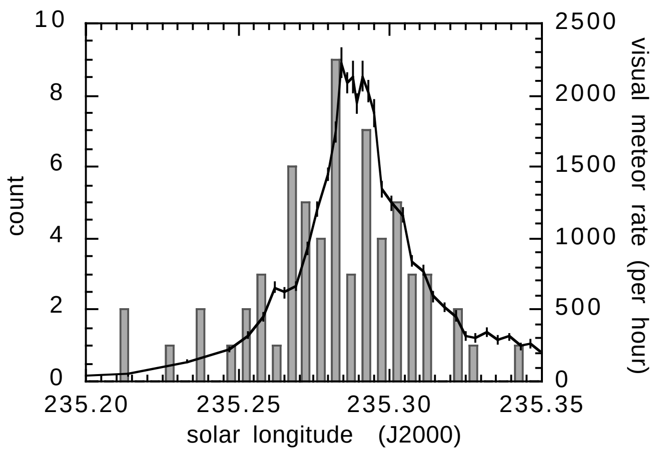

Figure 1. Rate of reduced multi-station photographed meteors in relation to the apparent flux of meteors seen by visual observers of the Dutch Meteor Society in southeastern Spain.

The sample of reduced meteor orbits covers most of the 1999 Leonid storm activity profile, which is shown by a solid line with error bars in Figure 1. This profile represents mean counts from two groups of visual observers of the Dutch Meteor Society at observing sites in southeastern Spain. In the same figure, the Leonids presented in Table I and II are counted in black columns.

The geocentric radiant positions of the meteors are plotted in Figure 2. We find that most meteors are in a very compact cluster, but there is also a significant halo around that cluster. The central position is at α = 153.67 ± 0.05 and δ = 21.70 ± 0.05 (J2000) for a mean solar longitude of 235.282. The dispersion in α *cos* (δ) and δ is equal within error: 0.046 ± 0.009 and 0.050 ± 0.009 degrees, respectively. The estimated error in the measurement has a median value of 0.06 and 0.04 degrees, respectively, which is in good agreement. Hence, we conclude that the central cluster has not been resolved. The halo, however, is significantly larger than our measurement error.

4. Discussion

In relation to past Leonid showers, we compared radiant positions by correcting for the daily changing direction of motion of Earth itself to that at arbitrary solar longitude 235.0, i.e., $\Delta\alpha$ = +0.99 degrees and $\Delta\delta$ =

-0.36 degrees per degree solar longitude. In this system, the 1999 Leonid storm radiant was at α = 153.39 ± 0.05 and δ = 21.80 ± 0.05 (J2000). Compare this to the radiant position of the 1998 outburst on Nov. 17/18, at α = 153.43 ± 0.09 and δ= 21.97±0.14 (Betlem *et al.*, 1999). We conclude that both are identical, which implies that the second outburst in 1998 was in fact caused by the same dust trailet responsible for the 1999 Leonid storm. Based on the models by McNaught and Asher (1999), both must be due to ejecta from 1899.

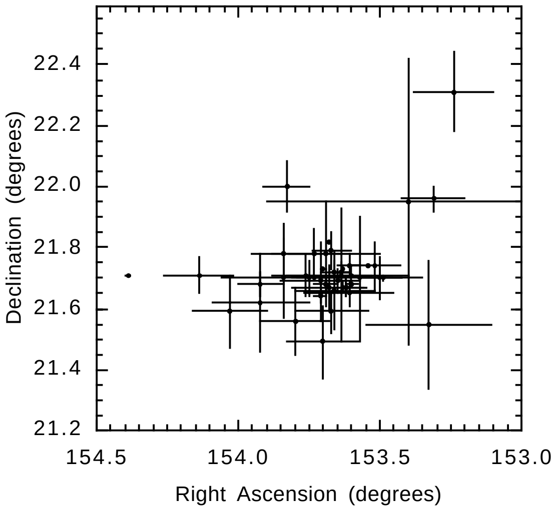

Figure 2. Geocentric radiant position of Leonids at the time of the 1999 Leonid storm.

With at least 13 out of 47 meteors (28 %) part of this halo, it is unlikely that the halo is due to the relatively weak annual Leonid shower or the (almost) absent Leonid Filament (Jenniskens and Betlem, 2000). The halo implies strong wings in the radiant dispersion of the storm, unlike a Gaussian distribution. Instead, the spatial radiant distribution appears similar to the Lorentzian shape of the nodal distribution (Jenniskens *et al.*, 2000). Indeed, the relative flux in the background profile versus the total flux curve of that Lorentzian curve is 28%, which is in agreement with the distribution of radiant positions.

The distribution of orbital elements may serve to improve meteor stream models. It is very significant that all observed orbits are well dated, being ejected during the return of comet 55P/Tempel-Tuttle in

1899. This is a very unusual situation. Further efforts at data reduction will expand the data set and thus improve the statistical accuracy.

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