Meteoritics & Planetary Science 35, 243–249 (2000)

Atmospheric behavior and extreme beginning heights of the thirteen brightest photographic Leonid meteors from the ground-based expedition to China

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(Received 1999 June 16; accepted in revised form 1999 Oct 12)

Abstract–Precise atmospheric trajectories including dynamic and photometric data on thirteen of the brightest Leonid fireballs have been determined from the double-station photographic observations of Leonid meteors during the ground-based expedition to China in 1998 November. The expedition was organized as a collaboration between the Dutch and Chinese Academy of Sciences and was supported by the Leonid multi-instrument aircraft campaign (MAC) program (Jenniskens and Butow, 1999). All data presented here were taken at Xinglong Observatory and at a remote station, Lin Ting Kou near Beijing, on the night of 1998 November 16/17. At the Xinglong station, photographic cameras were accompanied by an all-sky television camera equipped with an image intensifier and 15 mm fish-eye objective in order to obtain precise timings for all observed meteors up to magnitude +2. Whereas beginning heights of photographed meteors are all lower than 130 km, those observed by the all-sky television system are at ~160 km, and for three brightest events, even >180 km. Such high beginnings for meteors have never before been observed. We also obtained a precise dynamic single-body solution for the Leonid meteor 98003, including the ablation coefficient, which is an important material and structural quantity (0.16 s^2 km^{-2}). From this and from known photometry, we derived a density of this meteoroid of 0.7 g/cm^3. Also, all *PE* coefficients indicate that these Leonid meteors belonged to the fireball group IIIB, which is typical for the most fragile and weak interplanetary bodies. From a photometric study of the meteor lightcurves, we found two typical shapes of light curves for these Leonid meteors.

INTRODUCTION

Between 1998 November 7 and 22, the Dutch Meteor Society, in collaboration with organizers of NASA's Leonid multi-instrument aircraft campaign (MAC) (Jenniskens and Butow, 1999), launched an expedition to the People's Republic of China to observe the 1998 Leonid return. Because a possible meteor storm peak was expected to occur over Asia, a choice between various countries had to be made. Based on astronomical and meteorological conditions and political situations in an unstable part of the world, it was decided to establish the campaign as a cooperative venture between the Dutch and the Chinese Academies of Sciences. Four photographic and video stations were operated from two locations near Xinglong Observatory (the Hebei network) and from two locations near the Qinghai Radio Observatory near Delingha (the Qinghai network). The main observational campaign was performed during the three nights of 1998 November 16/17, 17/18, and 18/19 by seventeen observers of the Dutch Meteor Society and one Czech observer in close cooperation with Chinese astronomers (Betlem *et al*., 1999).

INSTRUMENTS AND OBSERVATIONAL SITES

Two double-station networks were established shortly after arriving in China, but data presented in this paper were obtained only by the group that performed double-station photographic and video observations in the province of Hebei, ~150 km northeast of Beijing. The main station was located at the Xinglong Observatory, whereas the remote station was established at Lin Ting Kou, a small village ~85 km to the south of Xinglong Station. Geographical coordinates of both places were determined with a standard hand-held GPS device (Magellan 2000) as an average value from many measurements for a whole observing period. The following positions of observational sites were used in all computations: λ = 117° 34' 27.5" E, φ = 40° 23' 48.5" N, and h = 960 m for Xinglong; and λ = 117° 30' 17" E, φ = 39° 37' 47" N, and h = 56 m for Lin Ting Kou. The main station was equipped with two batteries of 35 mm cameras containing altogether fourteen cameras of type Canon T-70 with high-quality FD 1.8/50 mm optics. Similar batteries comprising the same kind of cameras (12 pieces) and optics were also operated at the remote station. These batteries have a fully automated film transport. The photographic film Kodak Tri-X 400 ASA was used with 15 min exposure intervals. Each of these small camera batteries was equipped with one four-bladed rotating shutter that was placed in front of the objectives. We used a relatively high shutter speed of 50 breaks/s. These batteries covered the sky down from ~60° from the zenith and detected meteors of visual magnitude +1 and brighter. At Xinglong station, these cameras were accompanied by an all-sky video system consisting of an 8 mm camcorder, a Mullard XX1332 image intensifier, and the Canon FD 2.8/15 mm fish-eye objective. The main purpose of this equipment was to determine a precise time for each photographed meteor. All these instruments were constructed and operated by amateur meteor observers of the Dutch Meteor Society, Hans Betlem at Xinglong and Jaap van't Leven at Lin Ting Kou. In addition to this equipment, one all-sky photographic camera was operated at each observing site in order to derive the distribution of bright meteors along the entire sky and to compute trajectories of fireballs at zenith distances that are not covered by the small camera batteries. These cameras were equipped with very precise Opton Distagon fish-eye objectives (3,5/30 mm), which enabled us to derive positions from one photograph of the whole sky hemisphere (diameter of image 80 mm) with a precision of one minute of arc or better anywhere on the picture. The limiting magnitude for recording meteors is about –3, but it depends on the angular velocity of meteor

TABLE 1. Geophysical data for very bright 1998 Leonid meteors.*

Meteor number	Time (UT)	N_i	V_{inf} (km/s)	M_{max}	m_{inf} (kg)	*PE*/ type	H_B (km)	H_E (km)	L_{PH} (km)	t_{PH} (s)	Slope (degrees)
98002	16.69212	3	71.80	–7.6	0.013	–6.40/IIIB	128.9	102.8	116.6	1.62	12.46
98003	16.69326	2	71.21	–8.5	0.051	–5.72/IIIB	126.9	88.1	152.2	2.14	14.19
98008	16.73461	4	71.7	–7.8	0.011	–6.26/IIIB	121.6	94.6	61.9	0.86	25.67
98011	16.75537	3	72.2	–7.5	0.01	–6.18/IIIB	122.2	95.3	54.5	0.76	29.41
98012	16.76153	5	71.8	–8.7	0.025	–5.80/IIIB	123.9	87.5	68.4	0.95	31.91
98015	16.77279	3	71.9	–7.1	0.005	–5.82/IIIB	118.8	90.5	48.5	0.68	35.50
98020	16.80541	3	70.5	–7.6	0.006	–5.78/IIIB	122.8	88.5	48.8	0.69	44.52
98023	16.81479	6	71.55	–12.5	0.3	–5.43/IIIA	124.7	73.2	70.9	0.99	46.39
98041	16.89353	4	71.8	–13.2	1.1	–5.79/IIIB	134.7	73.1	67.0	0.93	66.82
98043	16.90470	3	71.3	–6.8	0.003	–5.78/IIIB	119.8	87.6	34.7	0.49	67.84
98044	16.90594	3	71.5	–14.4	1.0	–6.08/IIIB	126.5	77.6	52.8	0.74	67.65
98045	16.90609	4	71.7	–5.7	0.001	–5.87/IIIB	116.4	92.0	22.1	0.31	69.25

*Photographed in the Hebei network on 1998 November 16.

on the emulsion of film. With cameras of this kind, we used black-and-white sheet film Ilford FP4 125 ASA 9 × 12 cm. These cameras were constructed by the Astronomical Institute of the Academy of Sciences of the Czech Republic at Ondrejov Observatory and operated by Pavel Spurný at Xinglong Observatory and Jaap van't Leven at Lin Ting Kou. Unfortunately, this camera was not operated on the first night of observations, the so-called "fireball night," and therefore we do not have simultaneous data from this all-sky experiment.

RESULTS

Thanks to excellent observing conditions and clear weather for the whole planned observational period and a large number of bright meteors, we obtained plenty of data. About 120 meteors were captured on film at the stations of the Hebei network during three nights of observation, 68 of which were double-station. The all-sky photographic camera at Xinglong recorded 167 meteors during the exposure interval of 5 h 39 m on the "fireball" night of 1998 November 16/17, but most of these were so low on the horizon that we have only one-station data. The exceptionally high activity is clearly visible from the comparison with the numbers of fireballs from the following nights. In the second "regular maximum" night of 1998 November 17/18, we recorded only 12 fireballs; and on the following two nights, no fireballs were recorded. All these meteors were Leonids except one case from the first night, which was a Northern Taurid. In this paper we present data from only 13 cases, which were photographed with all our techniques and from which we have complete results including geophysical, dynamic, orbital, and photometric data. Because all orbital data are published in the earlier paper of Betlem *et al*. (1999), we are presenting only some important and interesting results concerning the atmospheric behavior of these Leonid meteors.

Basic Atmospheric Data

Basic atmospheric data are collected in Table 1. All fireballs mentioned here were recorded during the first double-station observing night of 1998 November 16/17. The first column contains the code of the meteor (the same as in the paper of Betlem *et al*., 1999), the second column contains the time of the fireball, and the third column N_i contains the number of images used for final computation from both stations. Columns with initial velocity V_{inf}, maximum absolute magnitude M_{max} (at 100 km distance) and initial photometric mass m_{inf} follow. For the determination of these photometric masses, the luminous efficiency for fast meteors derived in Ceplecha and McCrosky (1976) was used. The next columns contain the *PE* coefficient and fireball type (Ceplecha and McCrosky, 1976; Wetherill and ReVelle, 1981), followed by two columns with beginning heights H_B and terminal heights H_E obtained from photographic records. The next columns contain the length of the trajectory L_{PH} and corresponding duration t_{PH} of these fireballs, also taken from photographic records. The last column contains the slope of the atmospheric trajectory at the end point. Methods and procedures that were used for the computation of all data presented in Table 1 and in the following parts of this paper are described in detail in Ceplecha (1987), Pecina and Ceplecha (1983), and Ceplecha *et al*. (1993).

Photograhic and Television Beginning Heights

Columns H_B and H_E in Table 1 show the heights of the observed Leonid fireballs derived from photographic records. As was mentioned previously, the classical photographic cameras at the Xinglong observing site were accompanied by an all-sky video system built by Hans Betlem. This system was used mainly for the determination of the precise time of appearance of the meteor. It can detect stars up to magnitude +4 and meteors up to magnitude +2 for the visible hemisphere above 20° elevation. The limiting magnitude depends on the zenith distance of the observed meteor. Even at first sight, we recognized that the meteors detected by this system start sooner than the photographic records. Calculations of the trajectories indicate greater heights for the first detection. On the other hand, terminal heights are practically the same. Because we determine high-precision atmospheric trajectories from photographic cameras, and because we can approximate an atmospheric trajectory for such relatively short and fast meteors with a straight line, we can extrapolate a photographic trajectory to the point at which we first detect the meteor on the television record. We used this method for all the Leonid meteors listed above and found very interesting results that are shown in Table 2 and plotted in Figs. 1–3. The first three columns, which are repeated from Table 1, are followed by three columns describing observed photographic beginning heights $H_{B(PH)}$, beginning heights from television system $H_{B(TV)}$, and terminal heights H_E, which are nearly the same for both methods. The last two columns contain the length of the television atmospheric trajectory L_{TV} and the distance of the television beginning point from the Xinglong observing site R_{TV}. In six cases (98002, 98003, 98023, 98041, 98043, and 98044), the photographic

TABLE 2. Height scales for the brightest 1998 Leonids.*

Meteor number	M_{max}	m_{inf} (kg)	$H_{B(PH)}$ (km)	$H_{B(TV)}$ (km)	H_E (km)	L_{TV} (km)	$R_{B(TV)}$ (km)
98002	–7.6	0.013	125.1	161	102.8	236	161
98003	–8.5	0.051	122.6	168	88.1	301	321
98008	–7.8	0.011	121.6	159	94.6	145	252
98011	–7.5	0.01	122.2	164	95.3	138	165
98012	–8.7	0.025	123.9	161	87.5	138	213
98015	–7.1	0.005	118.8	158	90.5	114	180
98020	–7.6	0.006	122.8	160	88.5	101	198
98023	–12.5	0.3	123.2	183	73.2	151	183
98041	–13.2	1.1	126.1	191	73.1	128	241
98043	–6.8	0.003	117.6	156	87.6	73	156
98044	–14.4	1.0	122.6	199	77.6	131	200
98045	–5.7	0.001	116.4	146	92.0	58	178

*Determined from the photographic and television observations; observed in the Hebei network during the night of 1998 November 16.

beginning and end heights in Table 2 are a little different from the data presented in Table 1. This difference is caused by the fact that these six fireballs were measured with two different techniques, and the results presented in these tables differ according to the measuring technique used. All Dutch images were measured using Astrorecord measuring software (version 3.02) developed by Marc de Lignie of the Dutch Meteor Society. All images taken by the Czech fish-eye camera were measured at the Ondrejov Ascorecord X–Y measuring table. Moreover, the Dutch images of the above mentioned six cases were also measured at the Ondrejov Ascorecord. The Dutch measuring system uses a digitized picture of 2048 × 3072 pixels that is measured on a computer screen; whereas at the Ascorecord measuring device, the original image is measured directly by positioning the measuring table cross hairs by eye. The comparison of these two methods is presented in Betlem *et al.* (1999, Table 4).

The main conclusion is that both methods give practically the same results, but the Ondrejov Ascorecord results are slightly more precise, especially on overexposed images, which are frequent for fireballs. This is also the reason for the difference in beginning heights in Tables 1 and 2. The six fireballs listed above are only from Ondrejov Ascorecord measurements, and the remaining cases are from combined Astrorecord–Ascorecord measurements. In Table 2, all photographic beginning heights are determined from these combined measurements because of the consistency of the data in Figs. 1–3. It is evident from these two tables that the method that uses original images is more sensitive and gives higher beginning altitudes than the method that uses digitized images. In Fig. 1, beginning and terminal heights are plotted based on the initial mass or maximum absolute magnitude for each individual Leonid meteor. These data extend to significantly higher magnitudes than the earlier results on Leonid meteors in Betlem *et al.* (1997). Both graphs are very similar; the beginning heights are not very sensitive to the initial mass of the entering body. The values grow very slowly with increasing mass and all are within a range of 10 km over a range of three orders of initial mass. On the other hand, we can see a relatively strong dependence on end heights. The brightest Leonid meteors penetrate >20 km deeper than the faintest ones. Leonid meteors start their ablation very high; the average value is at ~122 km from photographic records, the highest value found for all known meteor showers. Similarly, the deepest penetrating Leonid of initial mass of 1 kg reached the lowest altitude of only 72 km, which is also very high in comparison with meteoroids of similar mass belonging to the other known meteor streams. This shift in the height scale towards higher values is caused only partly by the high initial velocity (the highest initial velocity among known meteor streams) but must be caused at least partly by the meteoroid structure. Leonid meteors appear to be very fragile and made of easily ablated material. This agrees well with values of the *PE* coefficient, which describes the penetration ability of the entering body. The *PE* values (see Table 1) are typical for the fireballs of type IIIB (Wetherill and ReVelle, 1981). The IIIB fireballs are the weakest of all and are presumed to be of cometary origin. Indeed, the parent body of the Leonid meteors is a comet, 55P/Tempel–Tuttle.

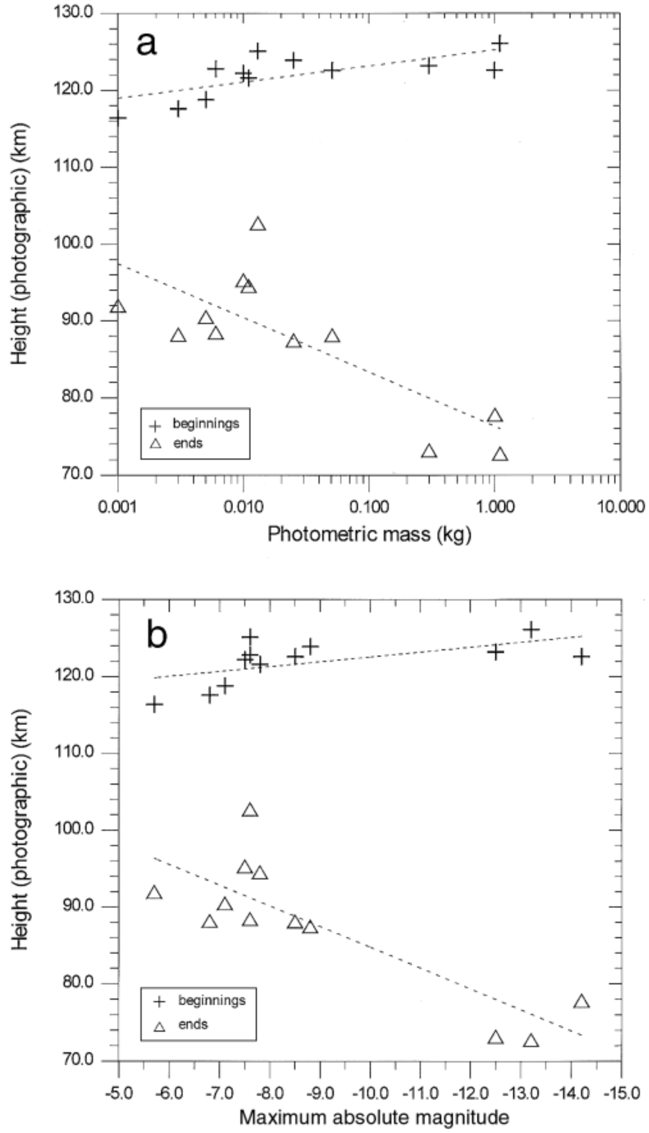

FIG. 1. Photographic Leonid beginning and terminal heights as a function of initial photometric mass (a) and maximum absolute magnitude (b).

Although photographic beginning heights for Leonid meteors are very high on average, it was evident from all-sky television records that these Leonids started their light even substantially higher. The results surpassed all our expectations. The final values are presented in the fifth column of Table 2 and are also plotted in

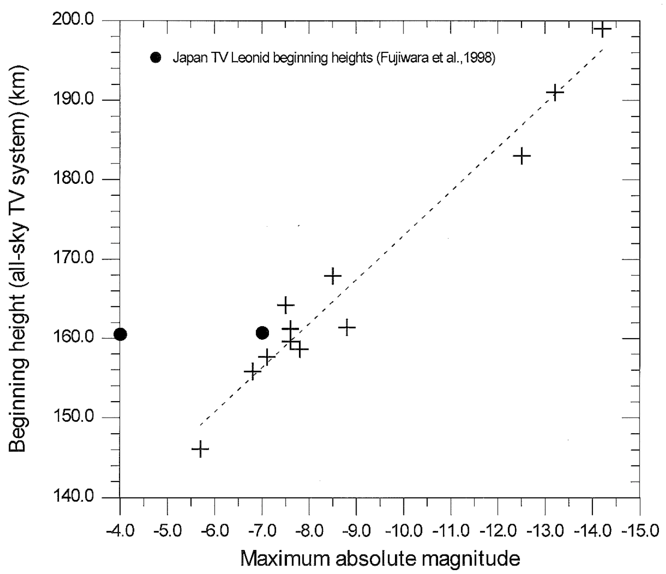

FIG. 2. Beginning heights determined from Hans Betlem's all-sky television system as a function of maximum absolute magnitude and comparison of our results with the Japanese television data.

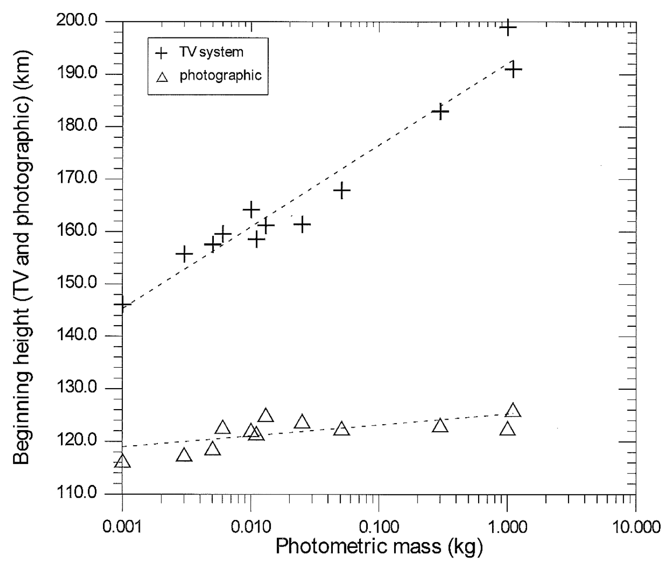

FIG. 3. A comparison of beginning television and photographic heights and their dependence on initial photometric masses.

Figs. 2 and 3. The previous record for the greatest height of a meteor was set by Fujiwara *et al*. (1998) from a Leonid fireball observed by a similar television–photographic experiment. They found for –4 and –7 magnitude Leonid fireballs television beginning altitudes of 160.7 and 160.5 km, respectively, whereas the photographic values corresponded well with the usually observed values for photographed Leonid meteors. Their results are compared with our values in Fig. 2 where the dependence of the television beginning heights on maximum absolute magnitude is plotted. Unfortunately, our values and the Japanese values are not completely comparable in magnitudes, because their magnitudes are not recomputed on a standard distance of 100 km (absolute magnitude) and are not obtained from exact photometry. They publish these magnitudes as visual magnitudes and it can not be excluded that the fainter (–4 magnitude) Leonid was underestimated. When we take into account these facts, our results for similarly bright Leonid meteors are in good agreement with Japanese data. Not surprisingly, our even brighter Leonid meteors have even higher television beginning heights. We find a narrow correlation and a very strong dependence of the television beginning heights on the absolute brightness (Fig. 2) or on the initial mass. This is in contrast to the same dependence for photographic beginnings (Fig. 3). For the three brightest Leonid meteors, we found television beginning heights >180 km, with the highest meteor ever observed beginning at almost 200 km!

There are two main differences between the photographic and television techniques. The first is in the sensitivity of these observing systems. However, the difference in limiting magnitudes for these two systems does not exceed three magnitudes, and that is not enough to explain such a big difference if we assume a standard exponential increase in brightness with altitude. It is possible that the luminous efficiency of meteors at high altitudes is different because the emission mechanism is different. The high television beginning altitudes suggest a higher luminous efficiency above 120 km than expected for metal atomic line ablation. The second difference is the different spectral sensitivity of both methods. It was first mentioned by Fujiwara *et al*. (1998). Whereas photographic emulsions are not sensitive above 670 nm, the television system is sensitive to longer wavelengths up to ~900 nm. This suggests that meteors initially produce the light mainly in the near infrared spectral region. This process is typical for heights from about 200 to 130 km for meteors as fast as Leonids. This might be the result of the excitation of atmospheric molecules, especially the OI line at 7772 Å, or the first positive bands of N_2 could be very intense. In that case, the luminous efficiency could change with the onset of metal atomic ablation (Na, Mg, Fe) ~120 km. Alternatively, the ablation of a volatile fraction of organic matter could produce luminosity at high altitude (C_2, CN emission?), which is not detected at lower altitudes. It is not easy to find a suitable explanation for these observational results and, therefore, we will extend our future observations of very fast meteors at higher altitudes with different observational techniques, especially with systems able to record meteors in the near infrared region, in order to find a better understanding of the luminosity mechanism of meteors at these very high altitudes.

Precise Dynamic Solution for the 98003 Leonid Meteor

Leonid meteors with initial velocities >70 km/s experience very little deceleration. Moreover, they ablate quickly, usually in less than a second. Such short trajectories allow us to measure the velocity of the entering body, but we are not able to apply more sophisticated analytical techniques to measure deceleration. Such models need very precisely measured values of heights and lengths for as many points as possible along the trajectory and a deceleration within the precision of these data. We found that these conditions were reached only for one of our Leonid meteors—case 98003. This meteor appeared only ~1 h after the rising of the Leonid radiant, which means that the slope of the atmospheric trajectory was very shallow—only 14°. Moreover, it had sufficient initial mass and, therefore, its atmospheric trajectory was adequately long. Thus, we were able to apply the gross-fragmentation model of Ceplecha *et al*. (1993) on previously determined atmospheric data, and we found a solution for the atmospheric motion of this meteoroid that implied it did not fragment on a large scale. This agrees well with visual observations of this fireball, because no fragmentation was directly visible. The difference between observed lengths and those computed from the above model for each measured point on the luminous trajectory is shown in Fig. 4. There is no systematic trend for the four parameter single-body solution. This means that this solution describes well the motion of this Leonid meteor with the following constants: initial velocity, V_{inf} = 71.207 ± 0.017 km/s and ablation coefficient, σ = 0.16 ± 0.01 s^2 km^{-2}. An additional product of this single-body solution is the knowledge of the value

$$Km_{\infty}^{-1/3} = 0.36 \pm 0.07$$

in c.g.s., where K is the shape–density coefficient, defined as

$$K = \Gamma A \rho_d^{-2/3}$$

where Γ is the drag coefficient, A is the shape factor, and ρ_d is the bulk density of a meteoroid. If we will assume standard value of ΓA = 1.1 (c.g.s.) (Ceplecha, 1996), a good agreement between dynamic and photometric masses, and substitute the computed photometric mass into the equations, we can compute the density of the meteoroid. The resulting value is 0.7 g/cm^3 (Table 3). We should point out here that this value is only a rough estimate, which depends on several assumptions of which the equality of the initial dynamic and photometric masses is the most critical. The determination of the photometric mass depends very strongly on the luminous efficiency τ, which is very difficult to derive for such fast meteors as Leonids. A value for log τ of –11.85 was used (Ceplecha and McCrosky, 1976). ReVelle *et al.* (1999) derived an initial mass for one very bright Leonid meteor from combined infrasonic and video detection. Even though they used a completely different method based on the determination of a total kinetic energy of the entering body, they found a very similar value for a comparable bright meteor as we determined from the photometry. This fact substantially increases reliability of the meteoroid density that we found. Moreover, this low density corresponds well with the determined ablation coefficient. This very important quantity describes the material properties of the meteoroid. Its very high value of 0.16 s^2 km^{-2} is typical for the weakest interplanetary bodies of group IIIB (Ceplecha, 1994) and is in very good agreement not

TABLE 3. Physical parameters of Leonid fireball 98003.

Meteor number	$Km_{\infty}^{-1/3}$ (c.g.s.)	V_{inf} (km/s)	σ (s^2 km^{-2})	m_{∞}(ph) (kg)	ρ (g/cm^3)
98003	0.36 ±0.07	71.207 ±0.017	0.16 ±0.01	0.051	0.7

only with the computed density of 0.7 g/cm^3, but also with the *PE* coefficient. All these results support the fact that Leonid meteors belong to the most fragile group of interplanetary bodies.

Typical Features of Leonid Lightcurves

The photometry for all Leonid meteors presented in Table 1 was determined by a standard method described in Ceplecha (1987) developed for all-sky pictures taken by the Czech fish-eye camera. With enough comparison stars (about 10 to 15) in an as wide as possible range of their magnitudes, a photometric precision of ±0.2 stellar magnitudes can be achieved in the entire field from the zenith down to a zenith distance of 70°. The last 20° above the horizon are progressively worse up to a factor of 3. However, all fireballs presented in this paper are recorded on the all-sky images below zenith distances of 60°. Likewise, observational conditions were excellent and, thus, the photometry for all fireballs is determined with good precision. This precision is somewhat worse for the brightest cases because these fireballs are also the brightest objects on the whole photographic record and, thus, the extrapolation of the characteristic density curve yields results with standard deviations that can exceed 0.5 magnitude. Basic photometric data such as the initial masses and maximum absolute magnitudes are included in both Tables 1 and 2. In addition to these data, we obtained detailed lightcurves for each fireball. We find two typical shapes for Leonid lightcurves. The first type, which is demonstrated in Fig. 5, has a quite symmetric shape with a relatively steep beginning, followed by a long plateau with frequent small variations in brightness (usually not exceeding one magnitude), after which the brightness fades steeply. Fireballs 98002, 98003 (Fig.5), 98008, and 98011 are typical members of this group. The second type is demonstrated in Fig. 6, and its highly assymmetric shape is a common feature for

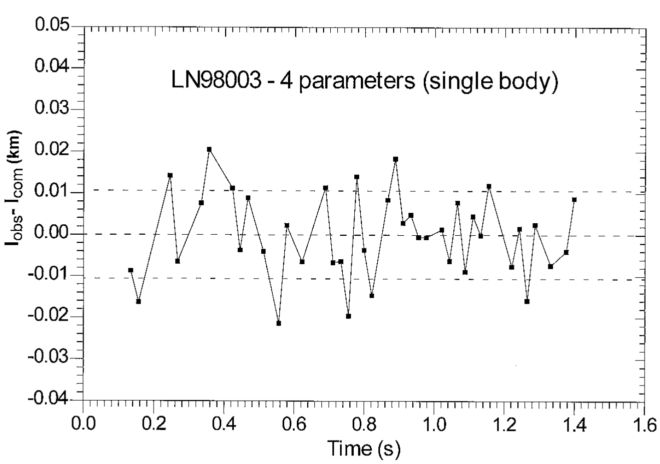

FIG. 4. Time dependence of length residuals from the single-body solution. l_{obs} = measured distances along the trajectory; l_{com} = computed distances from the single-body model.

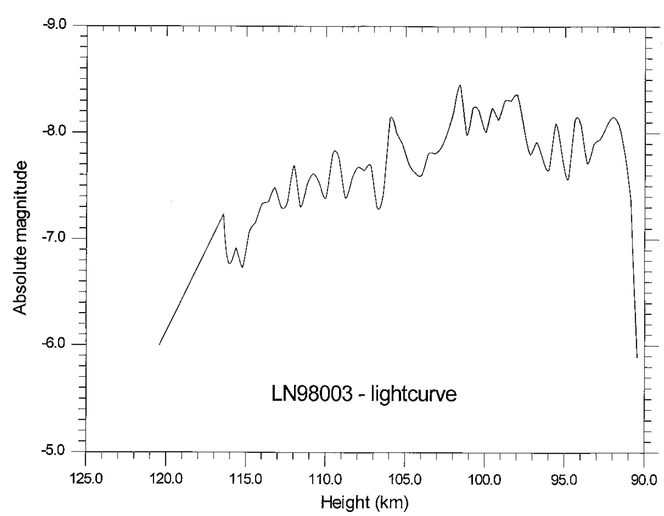

FIG. 5. The lightcurve of the Leonid fireball 98003.

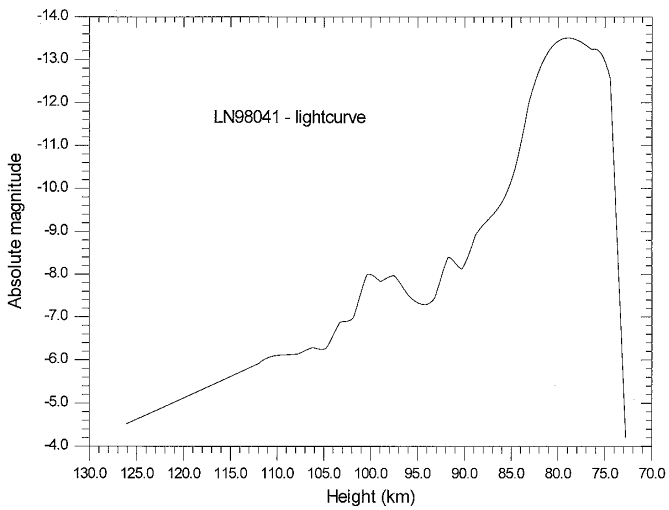

FIG. 6. The lightcurve of the Leonid fireball 98041.

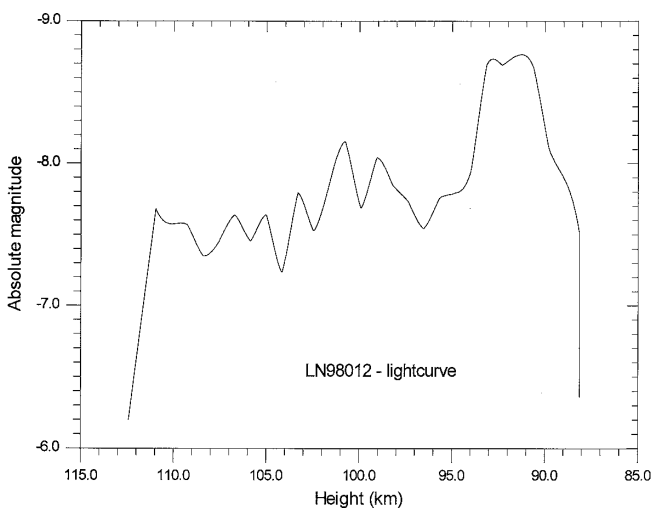

FIG. 7. The lightcurve of the Leonid fireball 98012.

these fireballs. The brightness reaches –5 magnitude relatively quickly, after which the fireball becomes steadily brighter with small fluctuations in brightness, culminating in a very bright flare near the end of its visible trajectory. The final fading portion of the lightcurve is very steep. This sudden end of the luminous trajectory is typical for the brightest cases 98041 (see Fig. 6) and 98044. These fireballs terminate practically immediately after reaching the maximum brightness. Members of this group are also 98020 and 98023. The fireballs 98012 (see Fig. 7), 98015, 98043, and 98045 belong to an intermediate group because these fireballs exhibit typical features of both previous groups. A substantial part of their lightcurves are practically constant, with small fluctuations in brightness followed by a moderate terminal flare, usually only slightly exceeding one magnitude.

If we compare lightcurves for individual fireballs with slopes of their atmospheric trajectories (last column in Table 1), we find a very interesting correlation. The first type of lightcurve is typical for fireballs with low slopes up to 30°; the intermediate group is typical for slopes between 30 to 45°. Finally, the second type of lightcurve, with a very bright terminal flare, is typical for slopes >45°. Only fireballs 98043 and 98045 do not exactly follow this rule, but these two cases are the faintest of all the fireballs presented here and their trajectories are significantly shorter.

CONCLUSIONS

In this paper we presented the atmospheric behavior of the thirteen brightest Leonid meteors recorded simultaneously by photographic and television techniques during double-station observations in the Hebei network in China. We determined precise atmospheric trajectories for all fireballs and found several important results. From combined photographic and television observations, we found extremely high television beginning altitudes and a strong dependence on the initial masses of entering bodies for all these Leonid meteors. The highest observed Leonid meteor with initial mass of ~1 kg started radiating at an altitude of almost 200 km! This is the highest beginning height of any meteor ever observed. The origin of meteor radiation at such high altitudes is still not well understood and more detailed observations will be needed, including near-infrared spectroscopy. From the atmospheric behavior of all the fireballs presented, we found that practically all belonged to the most fragile and weak fireball group IIIB. This result is also strongly supported by the precise dynamic study of the 98003 case. For the first time, we determined a value of the total ablation coefficient for a Leonid meteor (0.16 s^2 km^{-2}) and we were able to estimate the density for a Leonid at 0.7 g/cm^3. All these results, along with the known cometary origin, mean that Leonid meteors belong to the most fragile and weak interplanetary bodies. From the photometry of all the Leonid meteors described, we determined their precise lightcurves and we distinguished two main shapes for these lightcurves. We found that the main features of the lightcurves significantly depend on the slope of the fireball atmospheric trajectory.

Acknowledgements–The authors are very grateful to all the people who participated in the perfect organization of the Sino–Dutch Leonid expedition in 1998. Our thanks include those to Dr. Zhu Jin, Dr. Tan, and Dr. Xu Pin Xin from Beijing Astronomical Observatory and Purple Mountain Observatory. California Meteor Society member Ming Li helped us with translation and organization. We are also very much indebted to Mrs. J. Keclíková for her very precise and reliable work in the measurement of all the all-sky negatives and some of the Dutch small camera negatives.

The expedition was supported by the Dutch and Chinese Academies of Sciences, the Leiden University Kerkhoven Bosscha Fund, the Dutch Physics Foundation, and the NASA Planetary Astronomy Program. The work of the Czech member of the authors team has been partly supported by project No. K1-003-601 of the Czech Academy of Sciences and by grants No. 205-97-0700 and 205-99-0146.

Editorial handling: G. Wetherill

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