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New type of radiation of bright Leonid meteors above 130 km

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Abstract.

We report the discovery of new features and structures observed on Leonid meteors at altitudes above 130 km. Precise photographic orbital and trajectory data of the 1998 Leonid meteors observed during the ground-based expedition to China in 1998 were already presented in the previous papers (Spurny et al., 2000 and Betlem et al., 1999). We reported extremely high beginning altitudes for very bright Leonids up to height of 200 km. In this paper we study these high beginning parts of atmospheric trajectories for seven cases which were recorded by a sensitive TV systems equipped with image intensifiers able to register meteors up to apparent magnitude +6.5. For all of these seven cases we observed very quickly developing and changing diffuse, comet-like structures with dimensions in orders of kilometers. For the brightest event, the 98023 Leonid meteor (Figs.1-3) with a maximum absolute magnitude of -12.5, we observed an arc looking like a solar protuberance producing a jet detectable several kilometers away from the brightest parts of the meteor head. Similar jets are well detectable not only for this brightest case, but they are common features for almost all cases. All meteors were registered photographically from two 85 km distant stations so we know precise position, velocity and photometry for each observed point on the luminous trajectory. This diffuse structure is typically changing at altitudes of around 130 km when a meteor train begins to form and further downwards the standard ablation process starts and the diffuse structure disappears. This article deals with a description of the discovered phenomenon, which can not be explained with the standard ablation theory. Further studies for understanding this new type of radiation observed for bright Leonids above 130 km are thus required.

1. Introduction

All data presented in this paper have been taken during the Leonid meteor expedition to China organized by the Dutch Meteor Society in collaboration with organizers of NASA's Leonid multi-instrument aircraft campaign (MAC) (Jenniskens and Butow, 1999) in November 1998.

During the exceptional so-called "fireball night" of 1998 November 16/17 we recorded photographically more than 150 fireballs, but most of these were so low on the horizon that we have only single-station data. Most of the results based on photographic and all-sky video experiments were already published (Spurny et al., 2000 and Betlem et al., 1999).
In addition to the reported photographic efforts we also operated a double-station video experiment with a standard Super VHS and Hi8 camcorders equipped with image intensifiers (LLTV systems). We recorded about 300 double-station meteors of which data have not been published yet. Moreover, for seven bright events recorded photographically we found beginning parts of their atmospheric trajectories on video records. This paper deals with these video data.

2. Instruments and observational sites

Two photographic and video stations were operated from two locations in the province of Hebei, about 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 about 85 km to the south of Xinglong station.
Photographic experiments were covered by batteries of 35 mm cameras and all-sky cameras equipped with fish-eye lenses. Two batteries of 35 mm cameras of type Canon T-70 with high-quality FD 1.8/50 mm optics were placed at each observing site. This photographic system covered the sky down from ~60° from the zenith and detected meteors of visual magnitude +1 or brighter. In addition to this equipment, one all-sky photographic camera was operated at each station in order to record bright meteors (brighter then -3 magnitude) along the entire sky. These cameras were equipped with very precise F-Distagon 3,5/30 mm fish-eye objectives which enable 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. Such precision is comparable with the precision of 35 mm cameras equipped with 50 mm optics. The photographic cameras provide orbital and trajectory data for the brighter (larger) samples within the Leonid stream.
At Xinglong station, these photographic cameras were accompanied by an all-sky video system that was used to detect brighter meteor events and to supply the photographic experiments with the correct time of every fireball. It was the first use of an all-sky video system within the Dutch Meteor Society and it proved to be very successful. More than 90% of the photographed meteors from Xinglong station were recorded by this LLTV system providing the accurate time which is necessary to compute the right ascension of the photographic radiant. The all-sky video system consists of a standard Sony Hi-8 camcorder focussed on the focal plane of the image intensifier Mullard XX1332 equipped with a Canon FD 2.8/15 mm fish-eye lens. The system detects meteors of magnitude +2 and brighter, so all meteors within the photographic range of meteor cameras are recorded.
More detailed description of expedition setup is described in Spurný et al. (2000).

In addition to these photographic efforts, the results of which were already reported (Betlem et al. (1999) and Spurný et al. (2000)), the Leonid 1998 expedition operated LLTV cameras at both stations which were carefully pointed to a well defined area in the sky at about 105 km height in order to obtain double-station records of the fainter (magnitude +5 to +1) particles in the Leonid stream. The system used at Xinglong observatory consisted of a Panasonic NV-S88E commercial video camcorder and a second-generation Russian Dedal 41 image intensifier equipped with an Arsat photographic lens 1.4/50 mm providing a field of view of 25°. According to detailed study presented in Borovicka et al. (1999), this system is sensitive in the 330-880 nm range.

Similarly, the video system at the second station Lin Ting Kou was consisted from the commercial Hi8 video camcorder Sony and an image intensifier Mullard XX1332 equipped with a Canon FD 1.2/85 mm aspherical objective providing a field of view of 20°. We expect very similar spectral coverage as for system used at Xinglong observatory.
The video signal was recorded in S-VHS and Hi8 PAL system giving 25 full frames per second. A limiting sensitivity of +6.5 apparent stellar magnitude for meteors is estimated for both systems used.

3. Observational data

3.1 Height scales

When we compared photographed paths in the sky of the bright fireballs with the all-sky video images we noted, that the starting points of these fireballs were much higher in the atmosphere on the video records than on the photographic images although the limiting magnitude for both systems was practically the same. This effect was noted for 13 cases and the all-sky video data were included in the computations with a low weight in order to get an impression of the TV beginning heights. These values were reported in Spurný et al. (2000), where we published for the first time so extreme high beginning altitudes for meteors.

Table 1. Intervals of heights for photographic and video experiments

Meteor data		**Intervals of heights (km) for individual observing methods**				
Meteor No.	**Time (UT)**	**FE**	**SC-X**	**SC-L**	**TV-X**	**TV-L**
LN90002	16:36:39	119.3 - 103.3	128.9 -102.8	128.2 -114.3	148.8 - 141.6	-
LN98011	18:07:43	118.1 - 95.3	121.9 - 96.1	122.2 - 109.4	-	183.6 - 151.4
LN98013	18:25:31	113.3 - 95.7	115.4 - 94.8	-	-	154.9 - 113.4
LN98023	19:33:18	119.0 - 73.3	124.2 - 73.2	124.8 - 79.5	-	195.0 - 130.5
LN98035	20:56:10	-	115.3 - 92.1	102.9 - 92.2	-	156.7 - 112.3
LN98036	21:10:33	-	116.3 - 90.2	117.5 - 92.6	161.5 - 131.5	160.1 - 110.1
LN98043	21:42:46	115.1 - 88.2	115.8 - 88.7	119.8 - 87.6	-	178.2 - 140.3

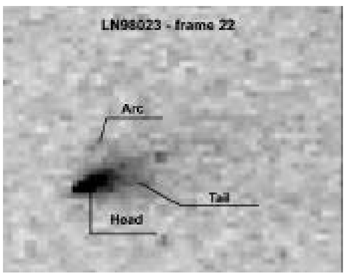
FE Fish-eye camera at Xinglong observatory. Limiting magnitude ~ –3.
SC-X Batteries of small photographic cameras (50 mm) at Xing Long observatory. Limiting magnitude ~ +1.
SC-L Batteries of small photographic cameras (50 mm) at Lin Ting Kou station. Limiting magnitude ~ +1.
TV-X Low light TV system at Xinglong observatory.
TV-L Low light TV system at Ling Ting Kou station.

As these values are much higher in the atmosphere than the standard aiming point for the LLTV double-station cameras we can hardly expect to find double-station video images of very-high-starting fireballs. However, the beginning of several double station photographed fireballs may be expected on one or the other LLTV video system.
A systematic search in the LLTV video database resulted in finding of seven cases with a recorded beginning of a bright fireball. Only the LN98002 fireball started out of the field of view. All seven fireballs were recorded during the night of 1998 November 16/17.
The video images were measured by the semi-automated measuring software developed by Pavel Koten and they were added to the photographic sets. An accuracy of these measurements is about 2 minutes of arc, a factor of 3 worse than a standard reduction of a photographic 50 mm lens. Tables 1 and 2 give the results of these recomputations. Table 1 lists height intervals recorded by different methods used for observations: Fish-eye camera's f/3.5/30 mm; 35 mm camera's f/1.8/50 mm and LLTV recordings.
The LLTV heights are amazingly high in the atmosphere. They confirm results found with the all-sky video system and presented earlier (Spurny et al., 2000). Because LLTV recordings are more sensitive then the all-sky video system, beginning altitudes presented now are for all three common cases even substantially higher. This difference is 20 km for the LN98011 fireball, 12 km for the LN98023 fireball and 22 km for the LN98043 fireball.

3.2 Structures in video images at very high altitudes

At very high altitudes the early beginning of bright fireballs show a remarkable structure. Recordings of our cases start around the limiting magnitude of the LLTV systems, magnitude +6. These images show a fuzzy, diffuse spot, rapidly widening and turning into a well defined V-shape, which remarkably looks like a well developed comet with head and tail. The head is surrounded by a kind of shock-wave at an angle changing around 40 degrees. When the meteors become brighter conspicuous structures become visible in this diffuse V-tail behind the meteoroid. In almost all cases several images show clearly visible jets and streamers. In the case of the LN98023 fireball an arc like a solar protuberance loop is well present on at least one of the images. It is demonstrated in Fig.1, but the reproduction might be less illustrative as the original record. It concerns also the set of frames in Fig. 3.

Fig.1. LN98023 fireball, frame 22 - detection of typical diffuse structures (negative projection)



As all investigated cases concern double-station meteors, heights and distances for each observed point on the meteor trajectory could be computed with an accuracy in order of tens of meters. This enables us to determine the minimum displacements of the most conspicuous details. The longest jet was observed for 98023 case up to 7 km of the brightest point of the meteor head at least. It seems to be formed out of the meteor head within one video frame (0.04 s) and it would indicate an ejection velocity greater then 100 km/s depending on the

position of its origin on the meteoroid body. Significant jets were detected also for the others meteors and their maximum lengths are 2.5 km for the LN98011 meteor, 6.5 km for the LN98036 meteor and 3.2 km for the LN98043 meteor.
Around a height of about 130 km the diffuse appearance of the image is gradually changing. We call this the "intermediate phase" (see Figs. 2-4). We directly observed the complete intermediate phase in 3 out of 7 cases. Beginning of this phase is visible also for the 98023 fireball. The intermediate phase is visible for 0.1 to 0.2 seconds only, and during this period the V-shape collapses fast and the classical drop-like ablation phase becomes visible. Another common feature for all these four cases is a formation of meteor train behind the meteor during this period. Atmospheric trajectory data for the 7 fireballs for which the diffuse phase is visible are collected in Table 2. The first column similarly like in Table 1 contains the code of the meteor. The following five columns describe the whole recorded trajectory. $\mathbf{H_B}$ and $\mathbf{H_E}$ are the beginning and terminal heights, **L** is the total length, **T** is duration of the record, **S** is the slope of the atmospheric trajectory at the end point, $\mathbf{R_B}$ and $\mathbf{R_E}$ are the distances of the beginning and terminal points from the observing site and $\mathbf{M_B}$ and $\mathbf{M_E}$ are the apparent magnitudes of the beginning and terminal points. The next three columns contain intervals of heights where the individual phases were observed. $\mathbf{H^d_B}$ and $\mathbf{H^d_E}$ describe the interval of heights where the diffuse phase was visible only, $\mathbf{H^i_B}$ and $\mathbf{H^i_E}$ describe the interval of heights of the intermediate phase and finally, $\mathbf{H^s_B}$ is the height from which the "sharp" ablation phase is visible only. The following column contains the maximum observed dimensions of the diffuse tail behind the meteor head. $\mathbf{L_{max}}$ is the length along the trajectory (the distance from the brightest point in the meteor head) and $\mathbf{W_{max}}$ means the width perpendicular to the direction of motion at the distance $\mathbf{L_{max}}$. The last column contains the value of $\mathbf{H_{max}}$, which is the corresponding height where this maximum structures were observed.

Table 2. Atmospheric data from LLTV video records

Meteor No.	$\mathbf{H_B}$ (km) $\mathbf{H_E}$ (km)	**L** (km)	**T** (s)	**S** (deg)	$\mathbf{R_B}$ (km) $\mathbf{R_E}$ (km)	$\mathbf{M_B}$ $\mathbf{M_E}$	$\mathbf{H^d_B}$ (km) $\mathbf{H^d_E}$ (km)	$\mathbf{H^i_B}$ (km) $\mathbf{H^i_E}$ (km)	$\mathbf{H^s_B}$ (km)	$\mathbf{L_{max}}$ (km) $\mathbf{W_{max}}$ (km)	$\mathbf{H_{max}}$ (km)
LN98002	148.8+ 141.6+	29.7	0.41	13.9	150.8 149.0	4.1 2.2	148.8+ 141.6+	-	-	4.2 1.2	142
LN98011	183.6 151.4+	63.5	0.88	30.3	203.5 176.0	6.1 3.3	183.6 151.4+	-	-	2.5 1.8	160
LN98013	154.9 113.4+	72.7	1.00	34.4	174.4 135.1	4.4 0.8	154.9 133	133 123	123	1.9 1.6	135
LN98023	195.0 130.5+	88.0	1.20	46.9	211.1 157.4	6.3 1.3	195.0 134	134 131+	-	5.5 3.8	148
LN98035	156.7 112.3+	50.5	0.68	61.2	170.0 138.2	5.2 1.1	156.7 135	135 125	125	2.8 1.9	138
LN98036L	160.1 110.1+	55.6	0.76	63.9	164.2 124.0	5.1 0.5	160.1 134	134 128	128	2.0 1.1	136
LN98036X	161.5 131.5+	33.4	0.48	64.0	169.2 139.8	5.6 3.0	161.5 131.5+	-	-	1.7 1.0	137
LN98043	178.2 140.3+	40.9	0.56	68.0	199.3 173.4	6.6 2.9	178.2 140.3+	-	-	1.2 1.6	145

\+ not real end or beginning (edge of field of view)

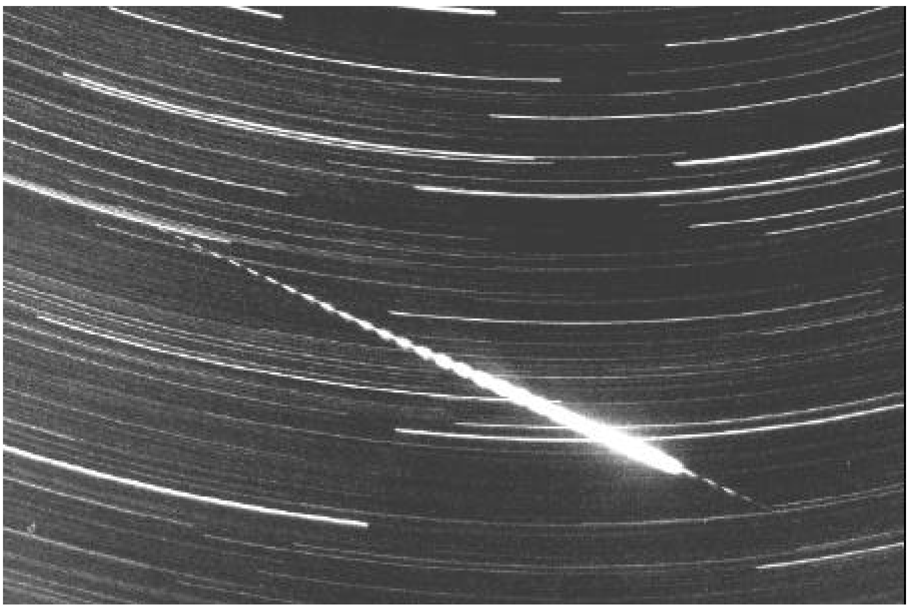
Table 2 shows that for all of recorded cases the diffuse structures have dimensions in orders of kilometers. We should point out that these dimensions are minimum values, because we

observed each individual structure only from one observing site. Therefore we are able to determine only distances as they would be perpendicular on the line of sight.
These structures have been reported never before; only Murray et al. (1999) described a nebulous appearance for one bright Leonid meteor and estimated width of this event in order of hundreds of meters.
We emphasize that instrumental effects are excluded for these cases as meteors which perform the same brightness lower in the atmosphere detected with the same technique show sharp, drop-like classical ablation images regardless of their position in the field.

3.3. LN98023 fireball. A detailed study of the observed phenomenon

The LN98023 fireball is the brightest event from all of cases from which the beginnings were recorded by the LLTV technique. It reached -12.5 maximum absolute magnitude and its picture taken by the fish-eye photographic camera at Xinglong observatory is presented in Fig. 2. The diffuse features near the luminous trail of fireball are caused by the long enduring train, which was visible on the all-sky video record at least 30 minutes after the fireball passage. This is the best case for which the diffuse phase with all types of structures was recorded by 85 mm LLTV camera at Lin Ting Kou observing site. For this reason we will describe the evolution of the diffuse phase and individual structures observed for this extraordinary case in more detail then for the others cases. Its exceptionality consists also in the recorded range of heights and magnitudes. We have data on this fireball from the

Fig.2. LN98023 Leonid fireball photographed by 3.5/30 mm fish-eye camera at Xinglong



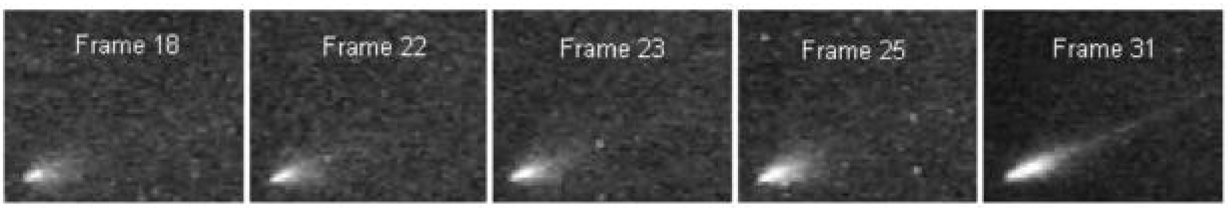
beginning altitude of 195 km down to terminal height of 73 km, which corresponds with a range of apparent magnitudes from +6.3 to -12.3! Basic atmospheric data for the LLTV video record are presented in Table 3. **NF** is the frame number, **T** is the corresponding time, **H** is the observed height and $\mathbf{M_{app}}$ is the apparent magnitude. In the last column the observed structures are described with different letters. D means diffuse appearance, C means comet-like appearance, J and A correspond with observation of jets and arcs, T means a formation of the meteor train and I means observation of the intermediate phase.

Table 3. Atmospheric data on LLTV video record of LN98023 fireball

NF	**T** (s)	**H** (km)	**M$_{app}$**	Observed structure	**NF**	**T** (s)	**H** (km)	**M$_{app}$**	Observed structure
1	0.00	195.0	6.3	D	17	0.64	160.9	2.1	D,C
2	0.04	192.8	4.9	D	18	0.68	158.6	2.1	D,C
3	0.08	190.7	4.9	D	19	0.72	156.7	2.0	D,C
4	0.12	188.7	3.9	D	20	0.76	154.2	1.9	D,C
5	0.16	186.6	4.2	D	21	0.80	152.4	1.9	D,C,J
6	0.20	184.2	4.1	D	22	0.84	150.4	1.8	D,C,J,A
7	0.24	182.3	4.8	D	23	0.88	148.2	1.7	D,C,J
8	0.28	180.2	4.9	D	24	0.92	146.1	1.5	D,C,J
9	0.32	177.9	4.7	D	25	0.96	144.0	1.4	D,C,J
10	0.36	176.0	4.1	D	26	1.00	142.0	1.3	D,C,J
11	0.40	173.8	3.5	D	27	1.04	139.7	1.2	D,C,J
12	0.44	171.5	3.4	D	28	1.08	137.7	1.0	D,C,T?
13	0.48	169.4	3.1	D	29	1.12	135.6	1.0	C,T
14	0.52	167.3	2.8	D	30	1.16	133.6	0.9	C,I,T
15	0.56	165.1	2.6	D,C	31	1.20	131.7	0.8	I,T
16	0.60	163.1	2.4	D,C	32*	-	130.5	-	-

The total length of LLTV record is 1.20 seconds which corresponds with the total number of 31 frames. On the last frame no. 32 is the meteor partly out of the field of view. The fireball becomes visible on LLTV record near the center of field of view as a faint +6.3 magnitude diffuse object. After a short and relatively steep beginning increase in brightness a significant

Fig. 3. Typical diffuse structures for LN98023 fireball recorded by LLTV system



0.1s long decrease of about one magnitude occurred (Fig. 7). After this short but well defined minimum of brightness (observed also for several other cases), the brightness of meteor gradually grows and at an altitude of 167 km the first sign of comet-like appearance becomes visible. This quickly changing structure with head and tail is visible up to an altitude of 135 km, where the meteor train starts to form and the diffuse structure is gradually disappearing. On the last frame (no.31) the diffuse phase is evidently not so dominant. Typical diffuse structures for LN98023 fireball are presented in Fig.3, but details are not so nicely visible like on the original record. The comet-like structure is the most developed in the interval of frames from 18 to 27 and on the frame 22 an arc of minimum distance from the brightest part of meteor head of 2 km is visible (Fig. 1, Fig.3, frame 22). On the following frame 23 at least two significant jets are detectable with a minimum distance from the brightest part of the meteor head 5.9 and 5.3 km having significant transverse components. Let we define the XY rectangular coordinate system with its origin in the brightest point of a meteor head and X-axis grows in the direction of meteor radiant (opposite direction of meteor flight) and Y-axis

is positive above the plane containing a meteor path and an observer. In this coordinate system the position of the most distant detected point on the first jet is defined with coordinates x = 4.8 km and y = 3.5 km.
Similarly for the second jet are these coordinates: x = 4.8 km and y = 2.3 km.
Very probably these jets were connected with the arc observed on the preceding frames 21 and 22 as they were detected in the same region in respect to the meteor head. Several different jets were detected also on another frames. The longest jet was detected on the frame 25 up to a minimum distance of 7 km from the brightest point of the meteor head with a transverse component of 5 km! It is very difficult to explain this observational fact and to find the mechanism which can separate material from the meteoroid so widely transverse to the motion of the meteoroid.

3.4. Light curves of video records

The photometric procedure used for a determination of apparent magnitudes of meteors from video records was developed by Pavel Koten and consists of two parts. During the first part the calibration curve is constructed, in the second part the meteor signal is measured and a meteor brightness is determined for each frame. After dark image subtraction, flat-fielding and reduction, our software identifies positions of stars on the image which are used for the calibration. This operation is also useful for the computation of a meteor position. The signal of stars is determined as the summation of pixel intensities over a defined square area around the star minus background. The logarithm of this value and the catalogue magnitude is recorded for each star and the calibration curve can be computed. Similarly the signal of the meteor is measured as the summation of intensity of corresponding pixels minus background. Finally, the apparent magnitude of the meteor is computed using the calibration curve.

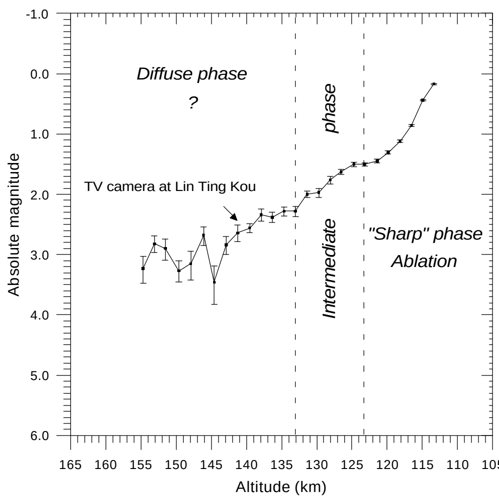


Fig. 4. Lightcurve of the LN98013 fireball

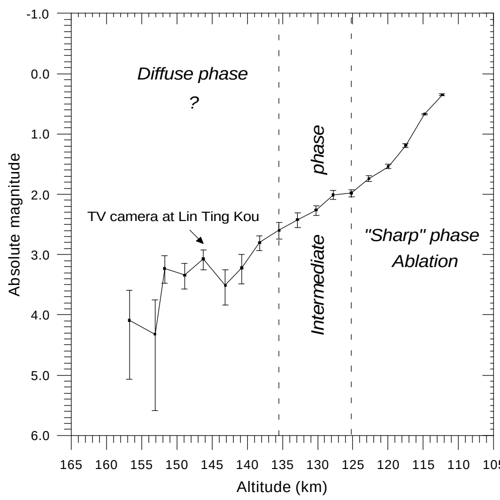


Fig. 5. Lightcurve of the LN98035 fireball

The light curves based on video records are presented for all seven cases on Figs. 4-8. For practically all cases a decrease in brightness is observed shortly after the beginning. The three cases LN98013, LN98035 and LN98036, with about the same maximum absolute magnitude (~ –7) may be well compared. Their records show a minor decrease in brightness of a half of magnitude at an altitude of about 145 km (Figs. 4-6). A similar feature is shown in the case of LN98023 which was much brighter (absolute maximum magnitude –12.5) where a decrease

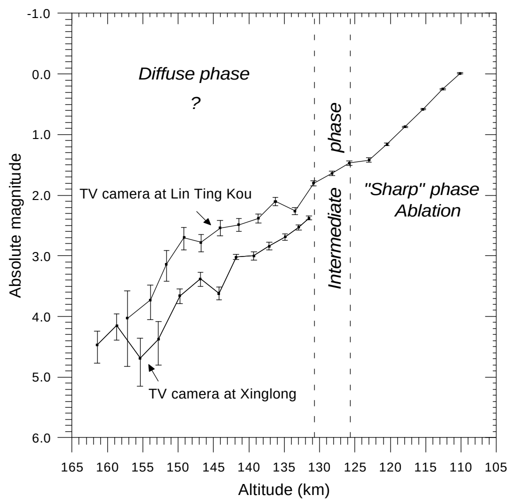


Fig. 6. Lightcurves of the LN98036 fireball

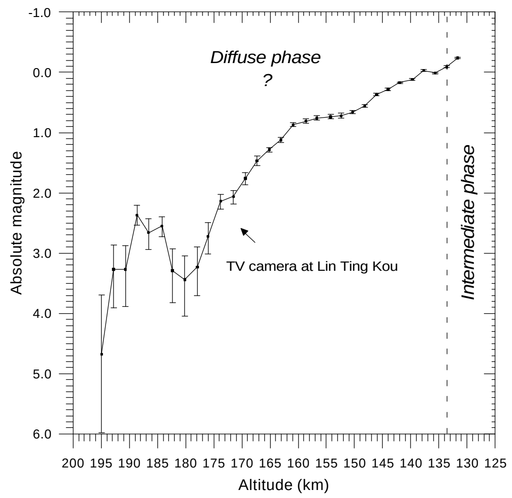


Fig. 7. Lightcurve of the LN98023 fireball

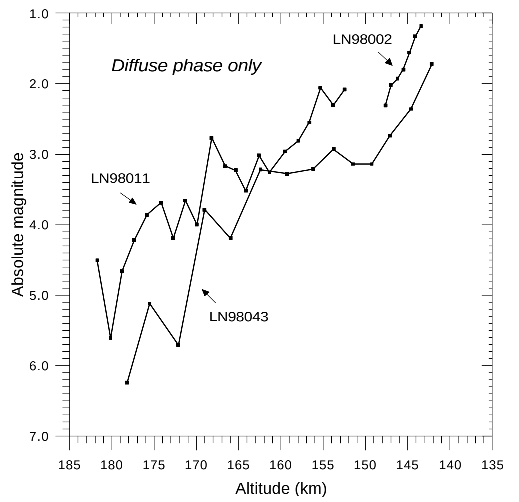


Fig. 8. Lightcurves of the LN98002, LN98011 and LN98043 fireballs

of one magnitude is present at a height of 180 km (Fig.7). In all cases this decrease is approximately 15 km in height below the first detection of the meteor.

After the classical ablation has taken over the process, the brightness increases almost linear with time. This early beginning of the ablation phase at an altitude of about 125 km coincides nearly with the recording limit of the classical photographic cameras.

Both, the diffuse and the "sharp" ablation phases are recorded for the three above mentioned cases only. On Figs. 4-6 we can see gradually increasing brightness without any discontinuity during the intermediate phase. In so far the ablation of meteors is a well known and described process, the diffuse phase is not yet understood at all.

4. Conclusions

We confirm our previous discovery of extreme beginning heights of bright Leonids up to height of 200 km and probably higher as all LLTV recorded beginnings are more than 10 km

higher than all-sky video beginnings published in Spurny et al. (2000). These extreme high parts of bright meteors are visible on video systems only. Detailed images show diffuse comet-like structures with jets and in one (the brightest) case we detected also well developed arc with a minimum dimension of 2 km. Material formed in jets is ejected from the meteoroid at a very high speed and reaches distances up to the order of kilometers from the meteoroid within one video frame (0.04 s). The intermediate phase is completely recorded for three cases. Its typical duration is between 0.1 to 0.2 seconds and during this period brightness of meteor gradually grows without any discontinuity. We observe fast change of diffuse comet-like shape into a sharp drop-like shape with a parallel formation of a meteor train. It is not possible to explain the processes observed during the diffuse phase by the standard ablation model. They are very probably connected with electromagnetic processes in upper atmosphere and with the more complicated structure of entering bodies with the cometary origin. These bodies are probably composed from different kinds of material which is conserved in different layers of the initial meteoroid. We need further studies and observations to better understand these new processes connected with the early period of interaction of interplanetary bodies with the Earth's atmosphere.
Due to its diffuse apparition and possibly its spectral composition these features stayed not revealed for current photographic techniques. Video shots with higher resolution of the beginnings of very bright fireballs can be obtained at rare occasions only. The 1998 Leonid fireball outburst rewarded the Dutch-Czech expedition with seven of those “lucky shots”.

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