

# Observations of Leonids 2009 by the Tajikistan Fireball Network

G. I. Kokhirova · J. Borovička

**Abstract** The fireball network in Tajikistan has operated since 2009. Five stations of the network covering the territory of near eleven thousands square kilometers are equipped with all-sky cameras with the Zeiss Distagon "fish-eye" objectives and by digital SLR cameras Nikon with the Nikkor "fish-eye" objectives. Observations of the Leonid activity in 2009 were carried out during November 13-21. In this period, 16 Leonid fireballs have been photographed. As a result of astrometric and photometric reductions, the precise data including atmospheric trajectories, velocities, orbits, light curves, photometric masses and densities were determined for 10 fireballs. The radiant positions during the maximum night suggest that the majority of the fireball activity was caused by the annual stream component with only minor contribution from the 1466 trail. According to the PE criterion, the majority of Leonid fireballs belonged to the most fragile and weak fireball group IIIB. However, one detected Leonid belonged to the fireball group I. This is the first detection of an anomalously strong Leonid individual.

**Keywords** observations · fireball · atmospheric trajectory · radiant · orbital elements · light curve · density · porosity

## 1 Introduction

Leonids are a well known meteor shower capable of producing meteor storms around November 17. The parent body is comet 55P/Tempel-Tuttle. Complex observations of Leonids were performed both by ground-based and aircraft facilities during 1998-2002 and in 2006 in connection with the high activity of the shower at this period. Owing to extensive observational data, very important results were obtained which significantly complemented meteor physics and dynamics and physical properties of cometary meteoroids. For the first time, extraordinary high beginning altitudes of the luminosity of the Leonid meteors were registered, among which some reaching the limit of almost 200 km, and are a result of both physical-chemical features of Leonid meteoroids and conditions of ablation at such altitudes (Spurny et al. 2000a, Spurny et al. 2000b, Koten et al. 2006).

According to several authors (Vaubailon et al. 2005, Maslov 2007, Lyytinen and Nissinen 2009), high activity of the Leonids was predicted also in 2009.

In this work, the results of the photographic observations of the meteor shower Leonids in 2009 in Tajikistan are presented.

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## 2 Observational Data

The photographic observations of the Leonids activity in 2009 were carried out during November 13-21, by the fireball network which consists of 5 stations situated in the south part of the Tajikistan territory and covering the area of near eleven thousands square kilometers (Babadzhanov and Kokhirova 2009b). The mutual distances between them range from 53 to 184 km. All stations of the network are equipped with all-sky cameras with the Zeiss Distagon "fish-eye" objectives ( $f = 30$  mm,  $D/f = 1:3.5$ ) using sheet films  $9 \times 12$  cm and by digital SLR cameras "Nikon D2X" and "Nikon D300" with the Nikkor "fish-eye" objectives ( $f = 10.5$  mm,  $D/f = 1:2.8$ ).

As a result of observations, 16 Leonid fireballs have been photographed, from which 9 were registered on the night of maximum activity of November 17/18. Among all, 3 fireballs have been photographed from five stations, 1 – from four, 2 – from three, 7 – from two, and 3 – from one station.

The time of fireball appearance was determined by the method of combination of fireball images obtained by fixed and guided cameras, or by the digital fireball image. During the maximum night, double station video observations were performed simultaneously (Koten et al., in preparation). For six fireballs reported here, more precise times of appearance could be extracted from the video tapes. Here we present precise data of only 10 photographed fireballs for which the coordinates of radiants, heights, velocities, light curves, and orbital elements were determined. The geometrical conditions for the other three double-station fireballs were not good enough to compute reliable trajectories. Fireball photographs were measured using the Ascorecord device. Digital fireball images were measured using the Ascorecord measuring software "FISHSCAN" developed by J.Borovička for measurements of scanned photographs of fireballs registered by all-sky cameras.

Astrometric reduction procedures are the same as that used by the European Fireball Network, which allows determination of the position of an object at any point of photographic frame with the precision of one arc minute or better (Borovička et al. 1995, Babadzhanov et al. 2009).

## 3 Atmospheric Trajectories

The basic parameters of atmospheric trajectories of fireballs are given in Table 1, which contains the following data: the number of the fireball; the number of stations whose fireball photographs were involved in reduction; the type of camera which registered a fireball; date, the time of the fireball passage in UT;

- $L_{\odot}$  is the longitude of the Sun corresponding to the time of the fireball passage (J2000.0);
- $v_B$  and  $v_E$  are the velocities at the beginning and at the end of the luminous trajectory;
- $h_B$  and  $h_E$  are the beginning and the terminal heights of the luminous trajectory above the sea level;
- $l$  is the total length of the luminous trajectory;
- $M_P$  is the maximum absolute magnitude of the fireball;
- $m_{\infty}$  is the initial mass of the meteoroid;
- $m_E$  is the terminal mass of the meteoroid;
- $PE$  is the empirical end height criterion for fireballs; the type of fireball according to Ceplecha and McCrosky (1976) classification. The standard deviations given for the beginning and the terminal points reflect the precision in computing the heights and positions of fireballs in the atmosphere. In Table 1, FC means fireball camera and DC – digital ones.

**Table 1.** Data of the atmospheric trajectories of the fireballs.

Fireball No.	TN171109A	TN171109B	TN171109C	TN171109D	TN171109E	TN171109F	TN171109G	TN131109	TN191109	TN211109
Number of stations, type of camera	5 stations FC 2 stations DC (5 total)	5 stations FC	3 stations FC 1 station DC (3 total)	2 stations DC	2 stations DC	4 stations FC	5 stations FC	2 stations FC 1 station DC (2 total)	2 stations FC 2 stations DC (3 total)	2 stations FC 1 station DC (2 total)
Date, 2009	November 17	November 17	November 17	November 17	November 17	November 17	November 17	November 13	November 19	November 21
Time (UT)	20h39m09s ±10s	20h49m56s ±2s	21h10m25s ±2s	21h24m05s ±2s	22h17m14s ±2s	22h37m37s ±2s	23h35m27s ±2s	22h09m01s ±15s	22h14m41s ±15s	21h47m39s ±15s
$L^\circ$	235.504	235.511	235.526	235.535	235.572	235.590	235.627	231.535	237.589	239.590
$v_\infty$ (km s <sup>-1</sup> )	71.84±0.05	72.07±0.17	71.45±0.38	71.77±0.18	71.71±0.60	71.59±0.53	70.57±0.49	71.80±0.16	70.38±0.36	71.78±0.03
$h_B$ (km)	111.21±0.01	112.38±0.02	107.66±0.09	114.56±0.02	114.06±0.01	106.45±0.29	106.68±0.01	108.50±0.04	104.26±0.01	110.33±0.02
$v_E$ (km s <sup>-1</sup> )	71.84±0.05	72.07±0.17	71.45±0.38	71.77±0.18	71.71±0.60	71.59±0.53	70.57±0.49	71.80±0.16	70.38±0.36	71.78±0.03
$h_E$ (km)	91.03±0.00	91.51±0.04	91.05±0.07	98.91±0.02	77.84±0.01	89.04±0.28	87.01±0.01	91.14±0.03	91.05±0.02	98.20±0.01
$l$ (km)	51.2	50.3	32.9	29.9	55.1	24.7	23.8	26.4	19.9	21.2
$M_{max}$	-7.2	-8.5	-8.3	-3.7	-3.4	-9.1	-8.3	-8.0	-6.3	-7.5
$m_\infty$ (kg)	0.007	0.019	0.020	0.0002	0.00025	0.017	0.007	0.008	0.002	0.004
$m_E$ (kg)	0	0	0	0	0	0	0	0	0	0
$PE$	-5.64	-5.90	-5.99	-5.76	-4.40	-5.98	-5.75	-5.82	-5.67	-6.34
Type	IIIA	IIIB	IIIB	IIIB	I	IIIB	IIIB	IIIB	IIIA	IIIB

Note that for all fireballs it was impossible to determine decelerations along the trajectories reliably. The cameras are not particularly suitable for studying velocities of very fast meteors like Leonids, since the shutter frequency is relatively low (12–15 breaks per second). In some cases we had to rely on 3 or 4 shutter breaks. Therefore, only average velocities were computed and were assumed to be equal to the initial velocities.

One digital camera was equipped with symmetrical two-blade shutters rotating with the frequency 370 rotations per minute in front of the objective. In the fireball cameras, the shutter is placed near the focal plane.

#### 4 Photographic Beginning and End Heights of Visible Fireball Trajectories

It is undoubted now that the limit of beginning heights of photographic high-velocity meteors reaches 200 km. This fact was confirmed due to observations of the Leonids storm and outbursts during 1998-2002. Use of the more sensitive than photographic techniques provided a large number of meteors registered at the beginning heights between 130-200 km (see, e.g., Spurny et al. 2000a, Spurny et al. 2000b, Koten et al. 2006).

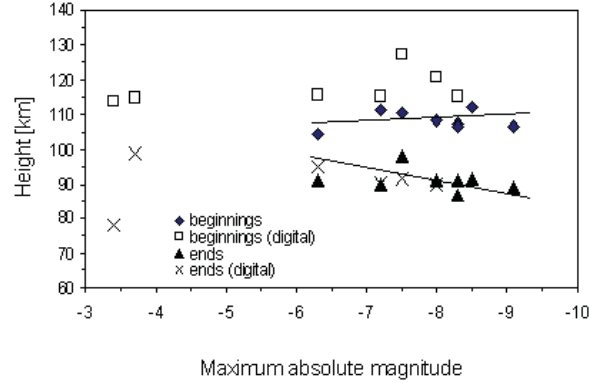
Our observational equipment does not allow us to record meteors at such heights because for the film's sensitivity  $I = 125$  ISO units the limiting magnitudes of registration of meteors is equal to about -4 magnitudes. While, as was shown by Spurny et al. (2000a) and Koten et al. (2006), a brightness of meteors at heights above 130 km is more than 0 magnitude, as a rule.

The range of beginning heights of fireballs under investigation photographed by all-sky cameras is between 112-104 km. On observations from the same point it is revealed that the beginning height registered by the digital camera is equal to 128-114 km. This difference is caused by greater sensitivity of the digital camera. The standard range of terminal heights is 98-87 km for all-sky cameras and is practically the same for digital ones. One case of terminal height of 77.8 km was fixed only by digital camera.

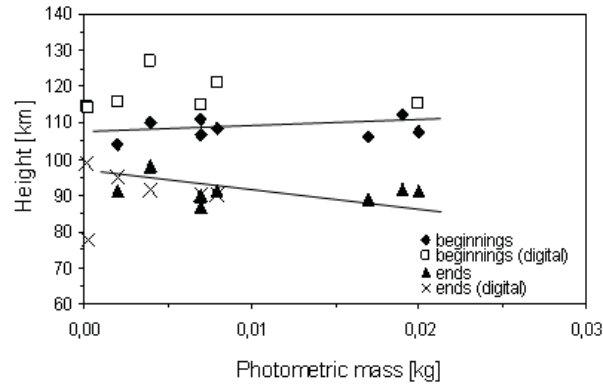
From all-sky photographic records of Leonid fireballs Shrbeny and Spurny (2009) obtained the value  $111 \pm 5$  km for beginning height for the range of maximum absolute magnitudes from -3 to -14, and concluded that this is the limiting altitude of all Leonids registration by the all-sky cameras.

Spurny et al. (2000b), investigating photographic and TV heights of high-altitude Leonid meteors ( $H_b > 116$  km), found that photographic beginning height of a meteoroid weakly depends on its initial mass or maximum absolute magnitude. But they revealed relatively strong correlation on end heights, namely, very bright Leonid meteors, and consequently with greater mass, penetrate more than 20 km deeper than the faintest ones.

We plotted the same graphs using our data (Figures 1 and 2). The greatest magnitude and initial mass of described fireballs are  $M_{max} = -9.0$  and  $m_{\infty} = 0.02$  kg i.e. our data represents a half of the data range used by Spurny et al. (2000b).



**Figure 1.** The Leonid beginning and terminal heights as a function of maximum absolute magnitude.



**Figure 2.** The Leonid beginning and terminal heights as a function of initial mass.

Nevertheless, gradual dependences of beginning and terminal heights on maximum absolute magnitude and initial mass can be seen clearly. However, the fireball TN171109E with maximal magnitude  $-3.4$  and initial mass of only  $2.5 \times 10^{-4}$  kg was quite anomalous in this respect because it penetrated to the terminal height of 77.8 km, much deeper than more massive bodies.

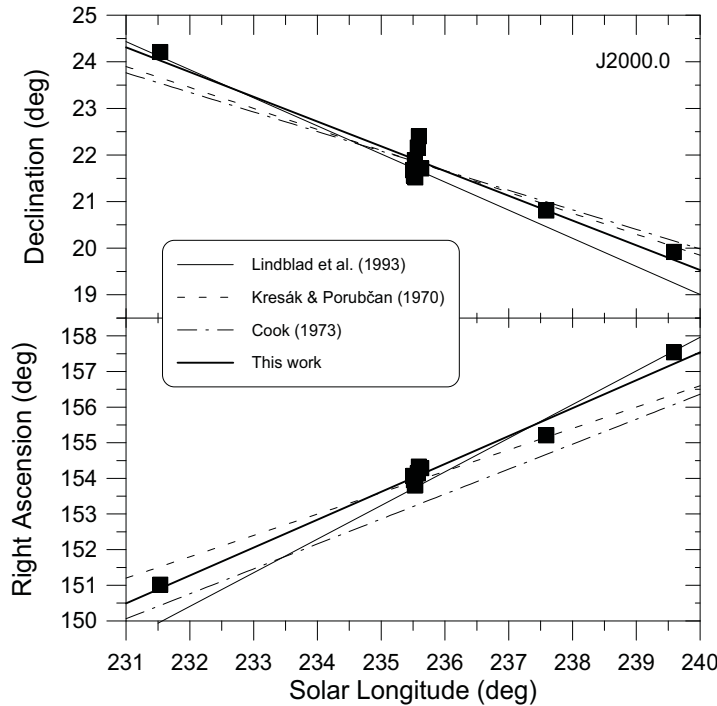
## 5 Radiants and Heliocentric Orbits of Fireballs

Table 2 gives the results of determination of the coordinates of radiants and heliocentric orbits of the Leonid fireballs with their standard deviations. Here:

- $\alpha_R, \delta_R$  are the right ascension and declination of the apparent radiant of fireball at the time of observation;
- $z_R$  is the zenith distance of the apparent radiant;
- $Q_P$  is the convergence angle between two planes (for multi-station fireballs the largest angle from all combinations of planes);
- $v_\infty$  is the initial (preatmospheric) velocity;
- $\alpha_g, \delta_g$  are the right ascension and declination of the geocentric radiant of fireball in J2000.0 equinox;

- $v_g$  is the geocentric velocity;
- $v_h$  is the heliocentric velocity;
- $a, e, q, Q, \omega, \Omega, i$  are the orbital elements in J2000.0 equinox.

The results of determination of the coordinates of radiant of Leonid fireballs photographed during November 13-21, 2009, in dependency on longitude of the Sun, are illustrated in Figure 3 and compared with previously published radiant drifts. Using only our data, the daily radiant drift was found to be  $\Delta\alpha = 0.78^\circ$  and  $\Delta\delta = -0.53^\circ$ . Maximum activity of Leonids occurred on the night of November 17/18 at the Solar longitude near  $235.55^\circ$ . The enhanced activity was predicted to be produced by two meteoroid trails ejected from the parent comet in 1466 and 1533, respectively. The annual Leonid shower was expected to peak approximately at the same time but with much lower activity.

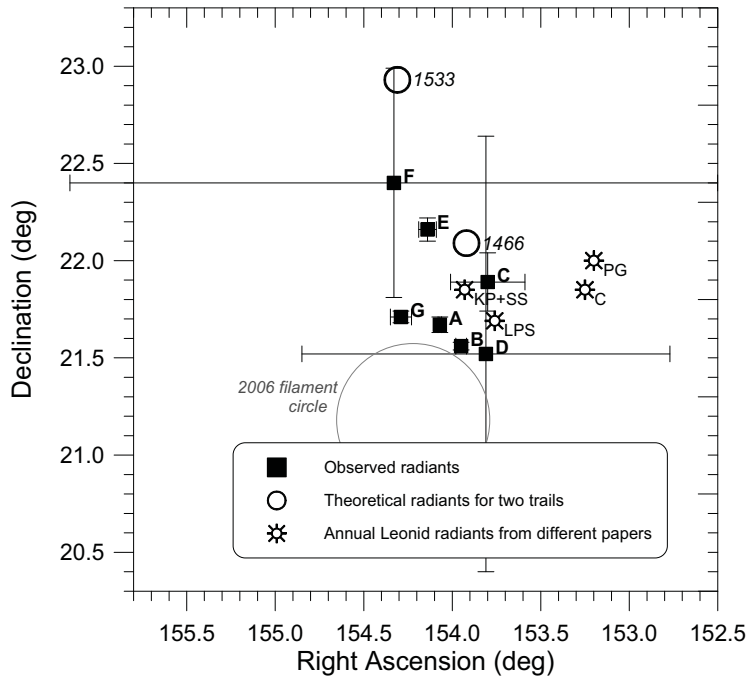


**Figure 3.** Drift of Leonid radiant as a function of Solar longitude. Our observations are compared with three published drifts as quoted in the book of Jenniskens (2006). Linear fit to our data is also shown. All coordinates are given in the equinox J2000.0.

Figure 4 shows the radiant positions of Leonids observed that night together with the predicted radiants for the 1466 and 1533 trails (Vaubaillon et al. 2009), the radiant of the annual shower according to various authors, and the so-called filament circle along which the radiants were spread during 2006 Leonids (Jenniskens et al. 2008). The radiants of two Leonids (D and F) have too large error to judge their origin. The radiant C, with moderate error, lies in between the annual radiant and the 1466 trail. Quite precise radiants A, B, and G lie closer to the annual shower or to the filament circle. Radiant E is the only one, which can be attributed with some confidence to the 1466 trail. None of the seven fireballs can be firmly attributed to the 1533 trail.

**Table 2.** Coordinates of radiants and heliocentric orbits of the fireballs.

Fireball No.	TN171109A	TN171109B	TN171109C	TN171109D	TN171109E	TN171109F	TN171109G	TN131109	TN191109	TN211109
$\alpha'_R$	153.87±0.04	153.77±0.02	153.70±0.14	153.73±1.11	154.17±0.01	154.42±0.58	154.51±0.03	151.04±0.09	155.26±0.07	157.51±0.07
$\delta'_R$	21.76±0.01	21.65±0.03	21.96±0.21	21.58±1.03	22.18±0.01	22.44±1.81	21.73±0.06	24.23±0.07	20.85±0.03	19.99±0.02
$\cos z_R$	0.390	0.412	0.503	0.523	0.655	0.705	0.828	0.658	0.663	0.572
$Q'_p$	74	55	25	5	33	17	74	51	62	58
$\alpha'_g$	154.07±0.04	153.95±0.02	153.81±0.15	153.81±1.12	154.14±0.02	154.33±0.59	154.29±0.03	151.02±0.09	155.21±0.07	157.54±0.07
$\delta'_g$	21.66±0.01	21.56±0.03	21.89±0.21	21.52±1.04	22.16±0.01	22.40±1.83	21.71±0.06	24.21±0.08	20.81±0.03	19.92±0.02
$v_\infty$ (km s <sup>-1</sup> )	71.84±0.05	72.07±0.17	71.45±0.38	71.77±0.18	71.71±0.60	71.59±0.53	70.57±0.49	71.80±0.16	70.38±0.36	71.78±0.03
$v'_g$ (km s <sup>-1</sup> )	70.64±0.05	70.87±0.17	70.26±0.38	70.59±0.18	70.56±0.60	70.47±0.54	69.50±0.50	70.66±0.16	69.22±0.37	70.61±0.04
$v_h$ (km s <sup>-1</sup> )	41.35±0.05	41.56±0.17	40.99±0.38	41.26±0.25	41.34±0.60	41.31±0.60	40.24±0.50	41.64±0.16	39.85±0.36	41.23±0.04
$a$ (AU)	10.44±0.49	13.15±2.80	7.73±2.11	9.61±2.12	10.40±6.04	10.05±5.66	5.05±1.15	14.91±3.38	4.28±0.60	9.21±0.28
$e$	0.906±0.004	0.925±0.016	0.873±0.035	0.897±0.023	0.905±0.055	0.902±0.055	0.805±0.044	0.934±0.015	0.770±0.032	0.893±0.003
$q$ (AU)	0.984±0.000	0.984±0.000	0.985±0.001	0.985±0.004	0.985±0.000	0.984±0.003	0.983±0.000	0.983±0.000	0.986±0.000	0.984±0.000
$Q$ (AU)	19.90±0.98	25.32±5.59	14.48±4.23	18.23±4.24	19.81±12.08	19.11±11.32	9.12±2.30	28.85±6.76	7.58±1.20	17.44±0.56
$\omega^\circ$	171.78±0.13	172.13±0.11	172.81±0.58	172.46±3.78	172.48±0.30	172.26±3.19	170.94±0.35	170.80±0.30	173.85±0.29	172.98±0.21
$Q'$	235.50±0.00	235.51±0.00	235.53±0.00	235.53±0.00	235.57±0.00	235.59±0.00	235.63±0.00	231.53±0.00	237.59±0.00	239.59±0.00
$i^\circ$	162.35±0.03	162.63±0.06	162.09±0.35	162.72±1.77	161.53±0.11	161.01±2.89	161.94±0.14	160.04±0.13	162.80±0.09	163.07±0.06



**Figure 4.** Leonid radiants during the maximum on November 17, 2009. The observed radiants are shown with their errors and compared with theoretical radiants for the 1466 and 1533 trails (Vauballion et al. 2009), with the annual Leonid radiant at Solar longitude  $235.55^\circ$  according to Cook (1973) (C), Kresák and Porubčan (1970) (KP), Lindblad et al. (1993) (LPS), Porubčan and Gavajdová (1994) (PG), and Shrbený and Spurný (2009) (SS), radiant almost identical to (KP). The filament circle as observed in 2006 (Jenniskens et al. 2008) is also shown. All coordinates are given in the equinox J2000.0.

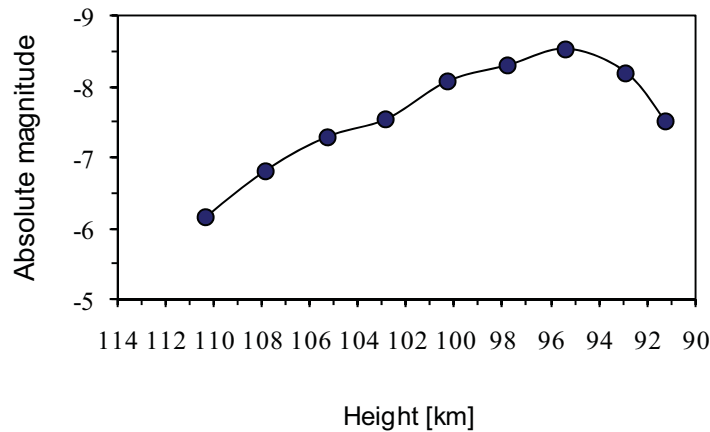
The mean geocentric radiant of Leonid fireballs on November 17/18, 2009 is  $\alpha = 153.66^\circ \pm 0.17^\circ$  and  $\delta = 22.11^\circ \pm 0.31^\circ$ , and is very close to the mean radiant values of Leonid fireballs in 1998  $\alpha = 153.63^\circ$ ,  $\delta = 22.04^\circ$  for  $L_\odot = 235.1^\circ$  (Betlem et al. 1999) and in 1999–2006  $\alpha = 153.6^\circ \pm 0.4^\circ$ ,  $\delta = 22.0^\circ \pm 0.4^\circ$  for  $L_\odot = 235.1^\circ$  (Shrbeny and Spurny 2009).

## 6 Light Curves of Fireballs

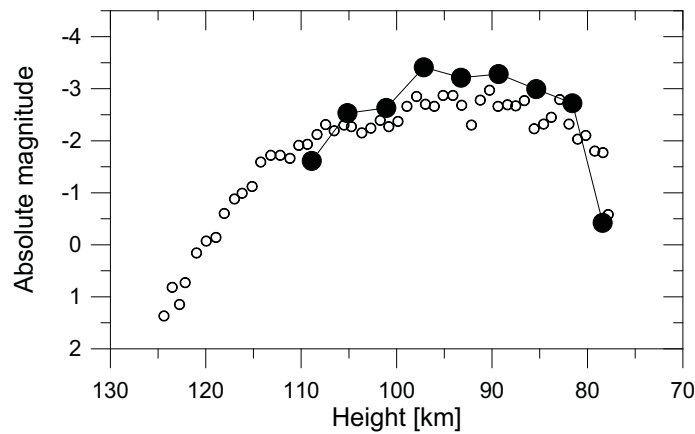
The photometry of Leonid fireballs was performed by the method developed for photographs taken by the Czech fish-eye camera (Ceplecha 1987). This method allows determine a brightness of fireball with the photometric precision of  $\pm 0.2$  stellar magnitudes in the whole field to a zenith distance to  $70^\circ$ . Negatives, where fireball images have the best quality and the greater number of breaks, were used for photometry. The photometry of two fireballs observed only by the digital cameras was performed with the FISHSCAN program.

Maximum absolute magnitudes and initial photometric masses are given in Table 1. The maximum absolute magnitude ranges between  $-3.4$  and  $-9.1$ , the masses are between 0.2 and 20 grams. The typical observed light curve of the fireball TN171109B is presented in Figure 5. We also present the light curve of deeply penetrating fireball TN171109E in Figure 6. All registered fireballs have smooth light curves with no significant flares. Almost all curves have asymmetric shape and the maximum points shifted towards to the end of luminosity.





**Figure 5.** Observed light curve of Leonid fireball TN171109B.



**Figure 6.** Observed light curve of Leonid fireball TN171109E. The empty circles are approximate magnitudes from the spectral video camera.

## 7 Physical Properties of Leonid Meteoroids

The values of the  $PE$  criterion given in Table 1 and calculated by the following expression:

$$PE = \lg \rho_E - 0.42 \lg m_\infty + 1.49 \lg v_\infty - 1.29 \lg \cos z_R,$$

where  $\rho_E$  – is the air density ( $\text{g/cm}^3$ ) at the  $h_E$  – the terminal height of the fireball visible trajectory, indicate the penetration ability of a meteoroid;  $m_\infty$  is given in grams and  $v_\infty$  in km/s. For the majority of fireballs the  $PE$  values are typical for the fireballs of type IIIB according to Ceplecha and McCrosky (1976) classification or they lie close to the IIIA/IIIB boundary ( $PE = -5.70$ ). The fireballs of group IIIB are produced by the meteoroids with the lowest bulk density equal to  $\delta = 0.2 \text{ g/cm}^3$ , and represent the weakest cometary material. The fireball TN171109E was classified as type I, which is the absolute exception among Leonids and quite unusual for fireballs on cometary orbits. Type I fireballs are

normally associated with stony meteoroids of density about  $3.5 \text{ g/cm}^3$ . The existence of different fireball types among the Leonid fireballs was also confirmed by Shrbeny and Spurny (2009). They recognized fireballs corresponding to types II, IIIA, and IIIB according to the *PE* criterion and made a conclusion on non-homogeneity of the parent comet.

Babadzhanov and Kokhirova (2009a) on the basis of photographic observations of Leonids determined mean bulk density equal to  $\delta = 0.4 \pm 0.1 \text{ g/cm}^3$ , and mean mineralogical density of  $\delta_m = 2.3 \pm 0.2 \text{ g/cm}^3$  of these meteoroids. Using the relation between these densities, the porosity of Leonid meteoroids was calculated to  $p = 83\%$ . These confirm the very porous and fragile (weak) structure of the Leonid meteoroids. It turned out that density and porosity of Leonid meteoroids are very similar to those of Draconid meteoroids, which also were found to be porous aggregates of constituent grains with bulk density of  $\delta = 0.3 \text{ g/cm}^3$  and porosity of  $p = 90\%$  (Borovička et al. 2007).

The value of mean bulk density  $\delta = 0.2 \text{ g/cm}^3$  of Leonid meteoroids under investigation obtained according to the calculated values of *PE* criterion and fireball type, is in good agreement with mentioned results of investigation of density and porosity of cometary meteoroids. The nature of TN171109E with likely much larger bulk density is puzzling in this context. Nevertheless, small strong constituents penetrating much deeper than the majority of the meteoroid were observed in Leonids before (Spurný et al. 2000a, Borovička and Jenniskens 2000). TN171109E is the first case where a whole Leonid meteoroid was so strong that it was classified as type I meteoroid.

## 8 Conclusions

As a result of photographic observations by the Tajikistan fireball network during November 13-21, 2009, 16 Leonid fireballs were registered, from which 9 fireballs were captured at the night of maximum on November 17/18. This number confirms the forecasted enhanced activity of Leonids in 2009.

The results of determination of precise atmospheric trajectories, velocities, initial masses and orbits of 10 Leonid fireballs are presented in this study.

The daily radiant drift of Leonids was found to be  $\Delta\alpha = 0.78^\circ$  and  $\Delta\delta = -0.53^\circ$ . The radiant positions during the maximum night suggest that the majority of the fireball activity (i.e. the majority of flux of Leonid meteoroids larger than 0.2 g) was caused by the annual stream component with only minor contribution of the 1466 trail. According to the *PE* criterion, the majority of Leonid fireballs belonged to the most fragile and weak fireball group IIIB, corresponding to the meteoroid mean bulk density of about  $0.2 \text{ g/cm}^3$  and porosity of 80–90%. However, one detected Leonid of a size of about 5 mm belonged to the fireball group I and likely had a bulk density of few  $\text{g/cm}^3$ . This is the first detection of an anomalously strong Leonid individual.

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