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Leonid meteor stream from Ondřejov radar observations in 1965–1967

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Abstract. Results of Ondřejov radar observations of Leonid meteor shower in 1965–1967 are presented. Observations performed during previous returns of Leonid meteor showers indicate that both in 1965 and 1966 the peak activity was observed at almost the same solar longitude near $L_{\odot} = 235\overset{\circ}{.}17$. The activity pattern in 1965 showed two well pronounced peaks separated by 23 hours where the second one seemed to be the principal. This is true both with respect to activity as well as the flux. Our observations indicate that the main outburst of this Leonid return occurred in 1966, the activity ratio to 1965 was 1.2 while the corresponding ratio in fluxes was 3.7. The 1967 activity is characterized by a large scatter of observed hourly echo counts fluctuating around 15 which is slightly above the level in the intermediate years of Leonid activity. The dependence of the radio echo duration on the velocity, radiant position, the height of maximum ionization and the mass of particular meteoroid is also presented.

Key words: comets: individual: 55P/Tempel-Tuttle – meteors, meteoroids

1. Introduction

A high activity of the Leonid meteor stream is regularly observed on a 32–33-year cycle. Its 1998 display was of prime interest and a highlite event of the year. The observations were carried out using all possible methods including TV technique placed on the aircraft (Jenniskens & Butow 1998). Special expeditions for ground-based observations were operating in Mongolia (Rendtel & Molau 1999). The results from these campaigns were completed by visual (Arlt 1998), optical, TV, radio and radar observations from many locations all over the world. The results are still being analyzed. They will be used for the organization of observational campaigns in the forthcoming years. Some parameters of the stream associated with the return of parent comet 55P/Tempel-Tuttle in 1998 show different characteristics in contrast with previous activity in the nineteen sixties.

The Leonids observed by radar in 1957–1968 at The Springhill Meteor Observatory near Ottawa were discussed by McIntosh & Millman (1970). Ondřejov radar Leonids observations 1965–1967, partially published by Plavcová (1968), and by Brown et al. (1997) were reexamined to obtain comparable parameters of the stream with those from the present Leonid campaign monitored by the same meteor radar parameters of which were maintained identical since its installation in 1958.

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2. Equipment and observations

The meteor radar, located at Ondřejov Observatory ($49°55'$ N, $14°47'$ E), operates at a frequency of 37.5 MHz with a pulse length of $10\,\mu$s, a peak power of 20 kW, and a repetition frequency of 500 Hz. The beam-width of the antenna system is approximately $52°$ in the vertical plane and $36°$ in the orthogonal plane which is fixed at $45°$ elevation. A secondary lobe appears at about $15°$ elevation. The antenna is steerable in azimuth. Its beam was pointed during observations always to an azimuth differing by $180°$ from the azimuth of the Leonid radiant. Since the observing period is limited by the time when the shower radiant is above the horizon, the observations could be performed only from 23h LT (Local Time) until 14h LT. The radar records the meteor echoes in a range-time format on 35 mm film moving continuously with the speed of 5.6mm/min. The duration of each echo longer than 0.4 s is measured with an accuracy of ± 0.05 s.

3. Activity profiles

The background activity hourly rates for each hour in a particular year were determined for 13 echo duration intervals in the echo duration range $0.4 \leq T \leq 12.0$ s by means of the iterative method introduced by Šimek (1985). Such hourly rates were subtracted to obtain hourly shower echo rates for further analysis. Hourly shower echo rates for echo duration class $T \leqq 0.5$ s are presented in Figs. 1-3. Sporadic background rates were deduced from the observations in 1965–67 preceded the solar longitude $L_{\odot} = 233\overset{\circ}{.}992$ and followed $L_{\odot} = 236\overset{\circ}{.}255$ (J2000.0) (see Table 1) using a mean background model as described in Šimek (1985). This approach is generally accepted but we feel that it would be worth to comment the nature of echo counts referred to recorded particular meteor echo duration.

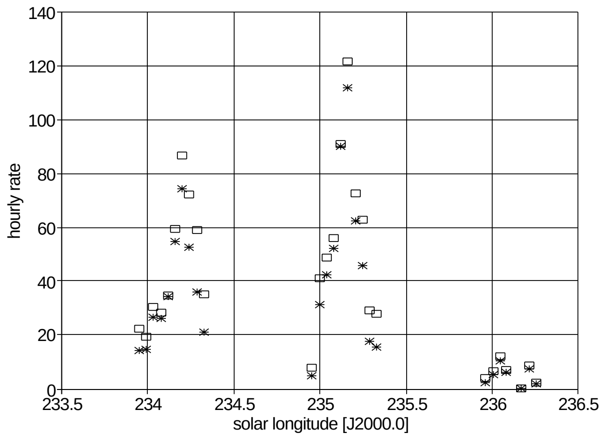

Fig. 1. The observed hourly rate of Leonid 1965 shower, represented by asterisks, and the hourly rate corrected for diurnal variation, depicted by open squares, as a function of solar longitude in degrees (J2000.0)

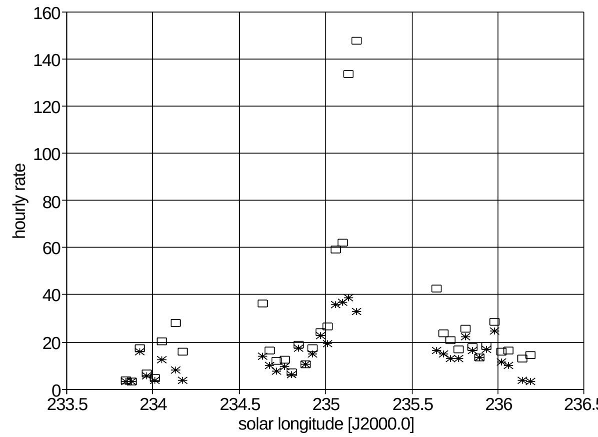

Fig. 2. The same as in Fig. 1 but for 1966

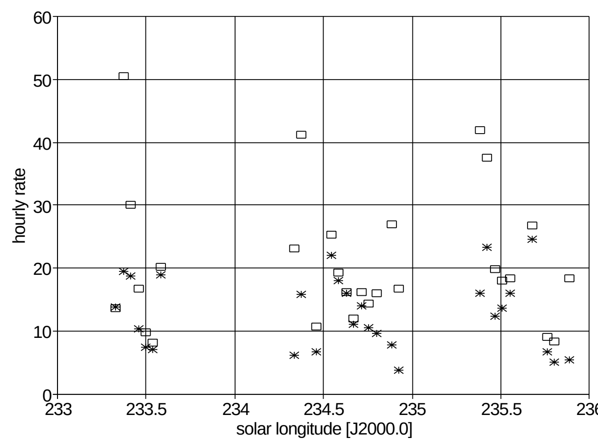

Fig. 3. The same as in Fig. 1 but for 1967

Table 1. Schedule of observations. Hours designate the beginnings of the entire hour.

Year	day	observations hours (LT)		background period (LT)	
1965	16	01–10			
	17	01–10			
	18	01–10		01–10	
	20	01–10		01–10	
1966	14		22–23		22–23
	15	00–12,	22–23	00–12,	22–23
	16	00–12,	22–23	00–12,	22–23
	17	00–12,	22–23		
	18	00–12			
1967	15		22–23		
	16	00–07,	22–23		
	17	00–12,	22–23		
	18	00–12,	22–23		22–23
	19	00–07		00–07	
	20		22–23		22–23
	21	00–12		00–12	

Verniani (1973) has derived from the statistics of observed sample of radar meteors the following expression for maximum electron line density in meteor trail, $\alpha_{\max}$, expressed in el/m,

$$\alpha_{\max} = 2.73 \times 10^{10}\ M_\infty^{0.92}\ V^{3.91}\ \cos z_{\rm r}, \qquad (1)$$

where M_∞ is the mass of the meteoroid before entering the atmosphere expressed in grams, V its velocity in km s^{-1}, and z_r is the zenith distance of the shower radiant. According to McKinley (1961)

$$\alpha_{\max} = \frac{32}{27} \times 1.41 \times 10^{16}\ T_{\rm D}\ \lambda^{-2}\ D, \qquad (2)$$

where $T_{\rm D}$ represents the diffusion-controlled duration of the radar echo, λ stands for the wavelength of the transmitted wave, and D denotes the ambipolar diffusion coefficient. Combining Eq. (1) and (2) (Šimek 1978) we have

$$M_\infty = 1.95 \times 10^6\ (T_{\rm D} D / \cos z_{\rm r})^{1.087}\ V^{-4.25}\ \lambda^{-2.17}, \qquad (3)$$

which shows pre-atmospheric mass of a meteoroid of given velocity as a function of $T_{\rm D} D/\cos z_{\rm r}$. The echo duration produced by a meteoroid of discrete mass is then

$$T_{\rm D} = 1.63 \times 10^{-6}\ M_\infty^{0.92}\ V^{3.91}\ \lambda^2\ D^{-1} \cos z_{\rm r}. \qquad (4)$$

Therefore, it is obvious that a meteoroid of discrete mass and velocity produces an echo duration controlled by the ratio $\cos z_{\rm r}/D$ where D depends on the height of the reflecting point. It follows that the recorded number of echoes with the same duration is produced by a conglomerate of meteoroids having different mass. Echo durations in our set of data appeared in the range of $0.20\,{\rm s} \le T_{\rm D} \le 0.89\,{\rm s}$, calculated according to Eq. (4) for $M_\infty = 10^{-2}$ g where the Leonid entering velocity $V = 72$ km s^{-1}, $\lambda = 8$ m for Ondřejov radar, and coefficient of ambipolar diffusion $D = 27.2\ {\rm m^2\,s^{-1}}$ for constant height of 105 km (see McKinley 1961). Since this duration interval of $T_{\rm D}$ includes very short overdense echo durations we neglect the small variability of echo heights affecting D. When comparing the series of hourly rates of a particular echo duration limit, they must be related to the same controlling conditions, i. e. for $z_{\rm r}$ and D. The R_f coefficients correcting recorded echo counts are presented in Table 2. They are the product of the iterative process (Šimek 1985, and Šimek & McIntosh 1986) applied to long-term data from observations of the Perseids. Since only

Table 2. Leonid zenith radiant angle, z_r, multiplying factors, f_m, eliminating the diurnal variation of the Leonid mass-distribution index, s, and inverse response function of the radar, R_f. Time is given in the local time (LT=UT+1). Since R_f factors for 0h, 13h and 23h designated by * are not available for relevant radiant zenith angles, corresponding values are estimated by extrapolation. Resulting corrected hourly rates are, therefore, uncertain.

LT	0	1	2	3	4	5	6	7
z_r	72.8	63.3	53.6	44.3	36.0	29.9	27.8	30.5
f_m	1.06	1.05	1.04	1.04	1.09	1.18	1.15	1.23
R_f	2.61	1.60	1.60	1.32	1.15	1.07	1.01	1.09
LT	8	9	10	11	12	13	23	
z_r	37.0	45.4	54.8	64.5	74.0	83.1	81.4	
f_m	1.23	1.12	1.02	1.00	1.03	1.03	1.00	
R_f	1.16	1.37	1.64	1.68	3.46*	4.50*	3.85*	

cumulative hourly rates for relevant echo duration and time are the starting parameters of the iterative process, R_f are products of all effects affecting meteor echo counts *de facto* involved in the distribution of observed hourly rates.

McIntosh & Millman (1970) normalized recorded rates "to remove the variation caused by changing elevation angle of the radiant h. For reasons discussed by McIntosh (1966) a simple sine function has been used and rates are normalized to $h = 30°$".

Corrected hourly shower echo rates are presented in Figs. 1–3. We can distinguish in 1965 two well pronounced maxima at $L_\odot = 234\overset{\circ}{.}201 \pm 0.021$, and $L_\odot = 235\overset{\circ}{.}165 \pm 0.021$ the widths of which at half maximum level are $0\overset{\circ}{.}18$ and $0\overset{\circ}{.}17$, respectively. Two peaks have also been recognized by McIntosh & Millman (1970). Since their observations were limited by the location of the Leonid radiant, both peak patterns were not especially pronounced, and McIntosh and Millman interpreted the resulting activity pattern as a single one having its peak within the observational break. Such a feature was not confirmed by our observation, and second activity peak at $L_\odot = 235\overset{\circ}{.}165$ indicates the maximum for 1965 display. Nevertheless, it should be mentioned that a single observation run of the Leonids is limited at our latitude to 14 hours which makes a description of whole activity pattern of the shower impossible.

The results of observations in 1966 were affected by the position of shower radiant near horizon when culminated Leonid activity similarly as for Canadian radar observations in 1965. The position of highest activity was found at $L_\odot = 235\overset{\circ}{.}182 \pm 0.021$.

The modest display of the Leonids 1967 is apparent from Fig. 3. The low rates as well as their fluctuations around the hourly rate of 25 remain rather the nature of the shower during intermediate Leonid period discussed by Brown et al. (1997). The shower radiant was below the horizon at the time of activity culminations in 1965 and 1966 at $L_\odot \simeq 235\overset{\circ}{.}17$. There are not many available reports of visual observations because of not good observational conditions due to the moonlight (see Brown 1999).

The cluster of Leonid particles encountering the Earth atmosphere in 1965–66 is characterized by the non-uniform structure along the parent comet orbit. Its nature was analyzed by McIntosh (1973) who explains it by the change of spacings between the comet and allocations of observed meteor showers along its orbit.

The maximum hourly rate in 1965 occurred at the same solar longitude as in 1966. The latter corrected value was higher than that in 1965 by the ratio $147.7/121.6 \simeq 1.2$.

4. Mass distributions and flux

The hourly echo rates obtained as described at the beginning of the previous section were used for the mass-distribution analysis. To eliminate fluctuations of fainter echoes the echo duration $T \geq 0.5$ s corresponding to a radio magnitude, M_r, of +1.3 calculated from Eq. (5) (cf. Šimek 1987)

$$M_\mathrm{r} = (0.74 \pm 0.02) - (1.90 \pm 0.04) \log T - \\ - (0.18 \pm 0.03)(\log T)^2 \quad (5)$$

was chosen as the lower limit for the mass-distribution analysis. The mass-distribution index, s, for overdense meteor echoes was inferred from the conventional formula (cf. Kaiser 1955)

$$\log N_\mathrm{c} = -\frac{3}{4}(s-1)\log T + \mathrm{const.}, \quad (6)$$

where N_c is the cumulative number of echoes having durations of at least T seconds. From the theory it follows that Eq. (6) is valid when ambipolar diffusion is the only process acting inside the ionized meteor path. Jones et al. (1990) recognized two principal regions corresponding to different dissipative processes operating in the ionized trail. While diffusion alone is dominant for echoes of shorter duration appearing at greater heights in the atmosphere, longer echo durations from meteors at lower heights are controlled mainly by different chemical and physical processes resulting different from the simple formula (6). Therefore, the mass-distribution index, s, is according to this model represented well by the slope of the initial linear portion of the $\log N_\mathrm{c}$ vs $\log T$ curve.

When the observations lasted only a fraction of an hour, N_c applied for calculation of s were recalculated for 60 minutes. Particular hours during which the observing time was less than 30 minutes were not used for the analysis.

The diurnal variation of the mass-distribution index, s, was described by Šimek (1993), Šimek & Pecina (1999), Pecina & Šimek (1999). The resulting diurnal patterns of s-parameter for shower echoes (i. e. the Perseids and the Geminids) and those for relevant sporadic background are characterized by similar patterns of relevant pairs. It is apparent that in all cases, s for the background in all particular hours are related to corresponding mean of the full cycle values of s by the same multiplying coefficient as that for the shower meteors. It indicates that such diurnal variation is neither due to the stream character nor the nature of sporadic radiants. This effect could be explained by diurnal variations of chemical and physical reactions in the atmosphere controlled by the solar radiation (cf. Jones et al. 1990). The mean

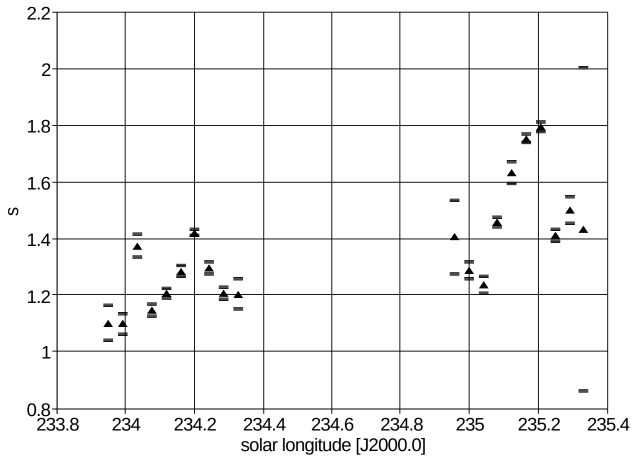

Fig. 4. The mass distribution index, s, for 1965 drawn as triangle, as a function of solar longitude (J2000.0). Horizontal lines designate the error bars

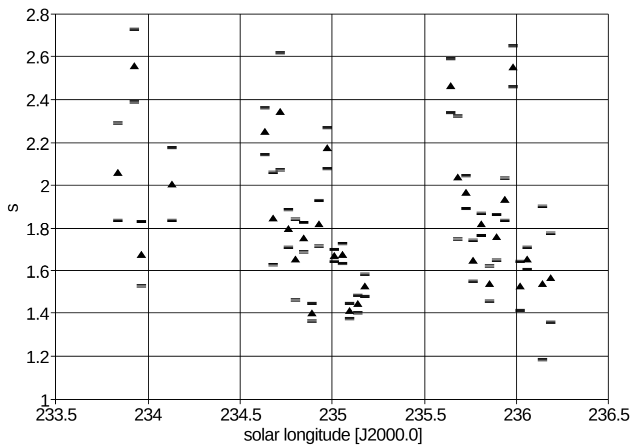

Fig. 5. The same as in Fig. 4 but for 1966

background mass index s for the Perseids and the Geminids have the same value of 2.17. We know the mass-distribution of the Leonid background for a fraction of the diurnal cycle between 23h and 14h only giving $s = 2.03$. Therefore, the above mean value $s = 2.17$ was ad hoc applied for the Leonids period, too. To obtain real s for the shower corrected for the diurnal variation, values of s calculated from observed shower data were multiplied by the ratio of 2.17/background value of s for each particular hour of observations. Correction factors, $f_{\rm m}$, Leonid zenith radiant angle, $z_{\rm r}$, at the middle of the interval, and multiplying factors, $R_{\rm f}$, discussed in the Sect. 4, are listed in Table 2.

The resulting patterns of the Leonid mass distribution index, s, vs the solar longitude, $L_\odot$(J2000.0) in 1965 and 1966 are presented in Figs. 4-5.

4.1. 1965

Mass-distribution indices indicate particular difference in both analyzed years. Leonids 1965 are characterized by generally lower mass-coefficient indicating higher content of large particles shown already by McIntosh (1973). An average value on November 16 in the period 02h-07h (i.e. six hours before maximum hourly rate) is $s = 1.20$, and $s = 1.49$ one day later. Comparable results were derived from radar observations at Springhill published by McIntosh (1966, Fig. 11) which yields $s = 1.22$ and $s = 1.61$ at the same days. The maximum observed hourly rate of 111.7 for echo duration $T \geq 0.5$ s appeared at Ondřejov on Nov. 17 at 7h LT with $s = 1.75$.

4.2. 1966

Observation in 1966 resulted in a higher average s-values of 1.63 on November 17 (calculated similarly as in 1965), and of 1.57 on November 18 when the missed 11h value was approximated by $s = 1.60$. A maximum hourly rate of 38.6 at 12h is associated with $s = 1.44$. Mass-index derived from McIntosh & Millman (1970, Fig. 8) for Leonid echo counts for November 17, 1966 gives $s = 1.64$ which perfectly fits with our result. Such values of s correspond with "slightly higher content of intermediate sized particles" (McIntosh 1973).

The differences of s indicate higher contribution of longer echoes in 1965 while in 1966 the activity of shorter echoes is dominant. The cluster of Leonid meteoroids encountering the Earth's atmosphere in 1965–66 is characterized by non-uniform structure along the parent comet orbit.

4.3. 1967

Because of low recorded hourly echo counts mean mass indices for November 15/16 $s = 2.15 \pm 0.04$, November 16/17 $s = 1.76 \pm 0.05$, and November 17/18 $s = 2.14 \pm 0.06$ are determined. These results indicate s-values on both marginal days close to $s = 2.17$ for sporadic background. Lower s on November 16/17 supports above conclusion that the culmination of the shower activity could appear after $L_\odot = 235^\circ$ when the radiant was below the horizon.

4.4. The flux

The flux was computed according to Pecina (1982). Its determination is based on the comparison of observed hourly rates with the theoretical rates as expressed by the formula

$$N(t_1, t_2, T_1, T_2) = (s-1) m_0^{s-1}\, \Theta_{\rm m_0}\, F(s; t_1, t_2, T_1, T_2), \quad (7)$$

where $N(t_1, t_2, T_1, T_2)$ represents theoretical rates corresponding to those observed during the time interval $[t_1, t_2]$ within the duration interval $[T_1, T_2]$, s is the mass distribution index, m_0 is the limiting mass to which the flux, $\Theta_{\rm m_0}$ is related, and the function $F(s; t_1, t_2, T_1, T_2)$, expressed by the integral, bears the information of mutual orientation of the shower radiant with respect to the antenna pattern. The time dependence of $F(.)$ is due to the dependence of integration limits within the echo plane on this configuration. The function $F(.)$ takes also into account the fact that the region within the echo plane contributing to N differs for different duration classes. The flux is nonlinear function of s. The higher the value of s the higher value of flux. We were interested in the hourly course of the Leonid's flux

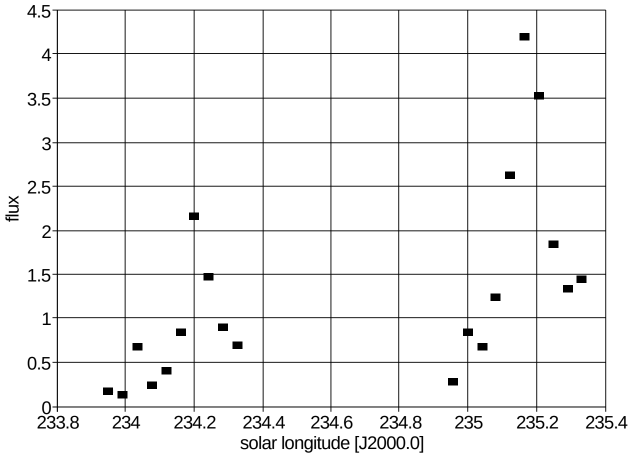

Fig. 6. The 1965 Leonid flux as a function of solar longitude, $L_\odot$ (J2000.0). It is expressed in units of $10^{-12}\mathrm{m}^{-2}\mathrm{s}^{-1}$

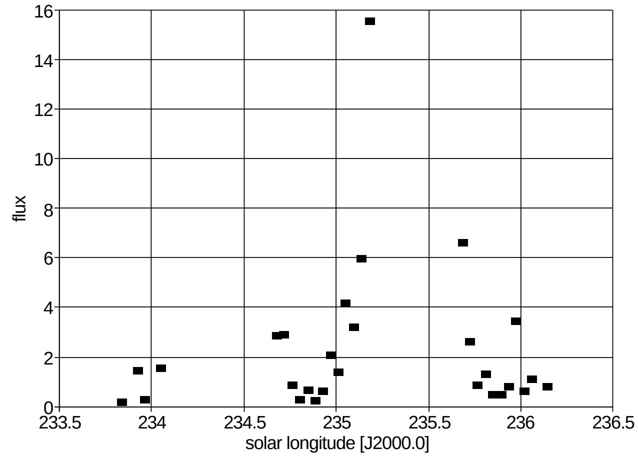

Fig. 7. The same as in Fig. 6 but for 1966

so we have computed these quantities. Since hourly values of s are determined on one hour base only for 1965 and 1966 the hourly flux was computed for these years. The mass distribution indices from Fig. 4 and 5 were employed. Other parameters we needed for computation were the ablation parameter, σ, and shape-density coefficient, $K = A\Gamma\delta^{-2/3}$. The ablation parameter was set to $\sigma = 0.1\,\mathrm{s}^2\,\mathrm{km}^{-2}$ (Spurný et al. 2000) while $K = 0.0597$ (in SI units). The s-values corrected for diurnal variation were used for flux computation. All values of flux are related to $m_0 = 10^{-5}$ kg. This value is close to the lower duration value of the duration interval considered. The flux is drawn in Fig. 6 and 7. The higher values of flux in 1966 are mainly due to higher values of s as compared with corresponding values in 1965 (compare Fig. 5 with Fig. 4), as it was mentioned above. The standard deviations of the flux values depend mainly on standard deviations of mass distribution index, s. The resulting relative standard deviations of flux grouped around 10% of their values.

5. Conclusions

We can deduce from our observations during previous returns of Leonid meteor shower that both in 1965 and 1966 years the peak activity was observed at almost the same solar longitude near $L_\odot = 235\overset{\circ}{.}17$. The activity pattern in 1965 showed two well pronounced peaks separated by 23 hours where the second one appeared to be the principal. This is true both with respect to activity as well as the flux. Our observations indicate that the main outburst of this Leonid return occurred in 1966 the activity ratio to 1965 was 1.2 while the corresponding ratio in fluxes was 3.7. Since the maximum activity peak in 1966 was deduced from an uncertain correction for high $z_\mathrm{r} = 74°$ we suggest that the latter value is closer to reality. The 1967 activity is characterized by a large scatter of observed hourly echo counts fluctuating around 15 which is slightly above the level in intermediate years of Leonid activity (Brown et al. 1997). We confirmed that single station observation of the Leonid shower limited to the period when the radiant is above the horizon cannot yield a complete picture of the activity pattern. Organization of international Leonid watch during the 1999 return promised a better picture of the stream.

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References

Arlt R., 1998, WGN 26, 239
Brown P., 1999, Icarus 138, 287
Brown P., Šimek M., Jones J., 1997, A&A 322, 687
Jenniskens P., Butow S., 1998, WGN 26, 249
Jones J., McIntosh B.A., Šimek M., 1990, J. Atmos. Terr. Phys. 52, 253
Kaiser T.R., 1955, In: Kaiser T.R. (ed.) Meteors. Pergamon Press, London, p. 119
McIntosh B.A., 1966, Can. J. Phys. 44, 2729
McIntosh B.A., 1973, In: Hemenway C.L., Millman P.M., Cook A.F. (eds.) Evolutionary and Physical Properties of Meteoroids. NASA SP-319, Washington, D.C., 193
McIntosh B.A., Millman P.M., 1970, Meteoritics 5, 1
McKinley D.W.R., 1961, Meteor Science and Engineering. McGraw-Hill, New York
Pecina P., 1982, Bull. Astron. Inst. Czechosl. 33, 1
Pecina P., Šimek M., 1999, A&A 344, 991
Plavcová Z., 1968, In: Kresák L., Millman P.M. (eds.) Physics and Dynamics of Meteors. D. Reidel, Dordrecht, p. 432
Rendtel J., Molau S., 1999, WGN 27, 24
Spurný P., Betlem H., van't Leven J., et al., 2000, Meteoritics and Planetary Sciences 35, 243
Šimek M., 1978, Bull. Astron. Inst. Czechosl. 29, 331
Šimek M., 1985, Bull. Astron. Inst. Czechosl. 36, 270
Šimek M., 1987, Bull. Astron. Inst. Czechosl. 38, 80
Šimek M., 1993, In: Štohl J., Williams I.P. (eds.) Meteoroids and Their Parent Bodies. Astronomical Institute, Slovak Academy of Sciences, Bratislava, 277
Šimek M., McIntosh B.A., 1986, Bull. Astron. Inst. Czechosl. 37, 146
Šimek M., Pecina, P., 1999, Planet. Space Sci. 47, 281
Verniani F., 1973, J. Geophys. Res. 78, 8429