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Radar observations of the Leonids: 1964–1995

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Abstract. Activity of the Leonid meteor stream is analyzed from radar data collected in the Czech Republic over a 30-year interval and Canada from 1964–1967. The shower shows pronounced activity during the 1964–1967 time period, with large meteoroids abundant in the 1965 shower. The filament causing the 1966 Leonid storm is present in 1965, but absent in 1967. The mean activity of the shower during the interval 1970–1993 is found to be near or below the level of the sporadic background. The 1994 and 1995 showers were well above the mean activity of the 1970–1993 period and displayed heightened activity for at least one full day near maximum during each return. A reanalysis of the 1966 Leonid storm from radar records shows the radar flux profile to have a Gaussian shape and suggests a lower limit for the peak corrected flux for meteoroids brighter than magnitude +6.8 of 39±2 km^{-2} hour^{-1} using s=2.0 in agreement with visual observations which reported a peak ZHR of ≈ 150 000 at the time of the shower maximum.

Key words: Leonids – meteoroids – Radar – astronomy – Comets: individual: 55P/Tempel-Tuttle

1. Introduction

The Leonid meteor shower is among the most variable in activity of any stream currently visible from Earth. The large meteor displays which accompany the return to perihelion of the parent comet, 55P/Tempel-Tuttle, every 33 years are among the strongest recorded (Kresák, 1993). Indeed, nearly half of all the meteor storms reported during the last 1000 years are associated with the Leonids (Beech et al., 1995). Recent numerical modelling of the stream has explained some of the more basic features of the Leonids (cf. Wu & Williams, 1993; Brown and Jones, 1996), while other authors have used the recorded pattern of past storms/outbursts and the comet - Earth geometry to better understand the distribution of meteoroids in relation to Tempel-Tuttle's location and orbit (Yeomans, 1981). A more comprehensive understanding of the stream is desirable in part to study the evolutionary behavior of young stream's in general and learn more about the parent comet-meteoroid relationship. It is also important from a practical standpoint, in view of the suggestion that satellites in Earth orbit could be at risk from Leonid storms in the latter half of the 1990's (Brown et al., 1996).

The first step in understanding the stream is obtaining accurate observational information concerning the shower. Orbital data for the Leonids has recently been presented by Lindblad et al. (1993) and visual observations of the shower by various authors (cf. Brown, 1994; Zvolánková, 1995). A detailed record of the stream's activity from radar observations during the 1960's is given in McIntosh and Millman (1970). This latter reference is also the primary source for information concerning relative activity levels of the shower during the 1960's. The 1966 Leonid storm has been quoted as having zenithal hourly rate (ZHR) values close to 150 000 (Milon, 1967; Bronsthen, 1968), though this figure has been recently questioned by Jenniskens (1995). A determination of the actual peak flux value reached during the 1966 storm is of great interest for those modelling the stream and also those concerned with satellite intereference from the shower later in the decade.

Here we present observational results from long-term monitoring of the Leonids with the Ondřejov radar and supplement these with similar radar data available from the Springhill, (Canada) patrol radar. Some Ondřejov radar results from the 1960's for the Leonids have previously been presented by Plavcová (1968) concerning mass indices and relative flux as well as for Springhill by McIntosh and Millman (1970). Here we concentrate on the activity profile for the stream for each year in the interval 1964–1967 as well as deriving a quiet-time profile of shower activity from observations made between 1970–1993. The higher activity from the shower noted by visual observers in 1994 and 1995 (Brown, 1995; Brown and Rendtel 1995; Jenniskens, 1996) is also apparent in the Ondřejov radar record and is discussed. Uncorrected rate values from the 1966 storm observed at Springhill are analyzed and corrected for both initial train radius biases and the radar response function to yield a true flux profile of the stream near the time of the peak in 1966.

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2. Observations and data reduction

The observations made from Ondřejov (49° 54′ 38″N, 14° 47′ 01″ E) were carried out at 37.5 MHz using a 20 kW peak power transmitter with a pulse repetition frequency (PRF) of 500 Hz and recorded on moving film for later analysis. Further details of the radar are given in Plavcová and Šimek (1960); Šimek (1965) and by Hajduk (1965).

The activity of the shower was monitored for the years 1964–1967, 1970–1971, 1982–1983 and 1988–1995 excepting 1991. As this interval contains radically different shower activity, the observational data were divided into three sets: yearly observations from 1964–1967, a combined dataset from 1970–1993 constituting the average quiet-time profile of the stream and data from 1994–1995 which showed enhanced activity.

To supplement the observations in the interval 1964–1967, original raw radar data from the Springhill (45° 11′ 48″ N, 75° 28′ 24″N) patrol radar were also used. These observations were made at 32.8 MHz using a 20 kW peak power transmitter operating with a PRF of 118 Hz and possesing an omnidirectional gain pattern. Details of the radar can be found in Neale (1966). Since both radars are at relatively low latitudes neither is able to follow the low-declination Leonid radiant ($\delta = 22°$) over the entire day.

The gain pattern for Springhill is isotropic in azimuth and broad in elevation as expected for a fixed crossed dipole antenna. In contrast, the Ondřejov antenna consists of two colinear arrays, each having three half-wave dipoles which produce a radiation pattern 36° broad in azimuth and 52° in extent in altitude to the half-power points. The Ondřejov radar is fixed at 45° elevation, but is steerable in azimuth. The limiting radio magnitudes for Springhill and Ondřejov are +6.8 and +8.5 respectively.

To determine the shower activity from the Ondřejov records, an iterative process was chosen similar to that used for the analysis of the Perseids (Šimek and McIntosh, 1986) and Geminids (Šimek, 1985). The procedure involves measuring all echoes with duration more than 1 second from the film record and correcting the rates to an equivalent hourly measure. Only intervals longer than 0.5 hours were used. Shorter duration echoes are most heavily affected by variations in film quality and terrestrial noise and hence are not used here. This echo duration corresponds to Leonid meteors brighter than magnitude +1 according to Šimek (1987a). Using the mass-magnitude-velocity relation of Jacchia et al. (1967) this corresponds to a Leonid of mass 3 mg. The antenna-beam is steered such that the maximum in the gain pattern is always 180° from the Leonid radiant in azimuth.

In an effort to eliminate the effects of the sporadic background and correct for the antenna pattern – radiant geometry we assume that the profile of the Leonids is stable over many years and that the sporadic background shows a similar variation throughout each day and also from day-to-day close to the time of the shower maximum. The only free parameter for the sporadic background is the magnitude of the variation from one year to the next; this constant multiplier is also assumed to affect shower rates. That the sporadic rate as measured by radar can vary significantly from year to year has been established from past observations (cf. Lindblad, 1978), the phenomenon possibly being related to variations in the conditions of the upper atmosphere (Hughes, 1976). We attempt to remove this effect on the observed Leonid rates by assuming the sporadic variations are of a similar magnitude to those affecting the stream. Clearly, the high velocity of the Leonids makes this only an approximate solution, but this is the only one available to us.

Table 1. Mean hourly sporadic rate for the Ondřejov radar during the Leonids from 1964–1995. The local time is 1 hour ahead of Universal Time (UT). The Leonid radiant transits at 6 local time.

Local Time (LT)	Sporadic Rate
0	10.0±0.7
1	8.6±0.7
2	8.6±0.7
3	10.0±0.8
4	10.5±0.9
5	11.4±0.8
6	11.2±1.1
7	13.0±0.9
8	9.4±0.9
9	9.5±1.3
10	7.1±0.9
11	9.2±0.8

The assumption that the Leonid activity profile is constant is valid only during those years when the storm-causing portion of the stream is not encountering the Earth. In the time interval of our study this corresponds to 1970–1993 and thus our procedure is only valid in this time span. We derive a mean sporadic rate as a function of local time from observations in all years prior to $\lambda_\odot = 234\overset{\circ}{.}71$ and after $\lambda_\odot = 235\overset{\circ}{.}9$ (both refered to equinox 2000.0 which we use throughout). This is our best estimate of the central core of activity of the Leonids based on visual observations. The implicit assumption is that significant Leonid activity occurs inside this interval well above the sporadic background. We will examine the validity of this assumption later. The resulting mean sporadic rate averaged over all years of observation is given in Table 1.

From the raw hourly rates, these mean sporadic rates are subtracted throughout the period of activity of the shower to produce raw shower rates. These raw shower rates from many different years are pooled to produce a mean activity profile for the stream after correction for the antenna response function and scaled in accordance with the mean activity of the sporadic background for a given year as discussed earlier. In general, the specular nature of the echo process for the analyzed trails requires a correction for the effective collecting area (via the response function) before a comparsion of the flux throughout the activity of the shower can be properly derived from the observed rates. Provided the radiant-antenna geometry remains constant during all years of Leonid observations it is possible to iteratively solve for the mean profile and the response function. Details of this process are given in Šimek (1985).

The radar response function describes the efficiency with which the radar is able to detect meteor echoes over the investigated magnitude interval emanating from a specific radiant. This function will depend on radar specific terms such as the gain pattern of the antenna, the power of the transmitter, the wavelength used and the range to the echo. Other factors such as the radiant elevation and mass distribution of the meteoroids also have an affect. Recent detailed derivations for the response function can be found in Brown and Jones (1995) and Elford et al. (1994). In our case, the value of R_f represents the inverse efficiency of detection of meteors from a specific radiant - i.e. the inverse of the response function.

Since the Leonid activity does not greatly exceed the background for a sufficient length of time, it is not possible to use this procedure to solve for the antenna response function directly. For the echo class under consideration ($\tau > 1s$) it is clear that only overdense echoes are being measured and hence some uncertainty exists as to how much correction needs to be applied under the assumption that the scattering from the initial trail is specular. To address both of these problems we examine the response function calculated from the mean profile for the Perseids (Šimek, 1987b). This is shown in Fig. 1. This response function can be compared to that for the Geminids found using the same technique (Šimek, 1987) but for echoes with $\tau > 0.4s$. The shape of the response curve is dramatically different suggesting that the effects of specular scattering are still important for underdense/transition echoes having $\tau > 0.4s$, though the meteor velocity and mass index are also important in calculation of the response function.

The response function found for the mean Perseid profile is for the same echo class considered here and hence the conclusions should be applicable to the Leonids since both showers have similar geocentric velocities (if specular reflection is still important). Also shown is the scaled curve for a correction of the form $\frac{1}{sin(\theta)}$ where θ is the radiant altitude. This correction would correspond to a purely geometric correction and would indicate no need for corrections of the collecting area under assumption of specular reflection. It can be seen that the curve assuming a purely geometrical correction matches the individually measured values for R_f and hence we conclude that these overdense echoes are long enough in duration to be distorted by upper atmospheric winds or other processes such that reflection is non-specular to the point of being isotropic. This also means that we may use this geometric correction for the Leonids and need not compute the response function for the shower directly.

For the Springhill data the echo class used corresponded to $\tau > 8s$ or equivalent magnitude brighter than -2 according to McIntosh and Millman (1970). For these data, the background correction was made assuming that activity two days after the Leonid maximum during the 1964–1967 interval was entirely sporadic and hence these rates were subtracted from those during the Leonid activity period in each year and then corrected for radiant elevation to derive shower rates.

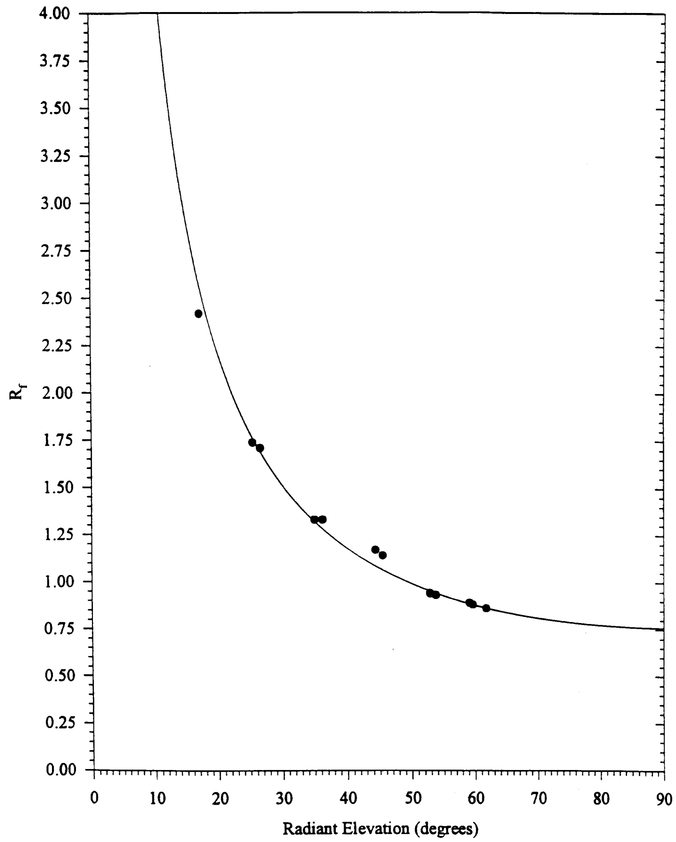

Fig. 1. The inverse of the response function (R_f)for Ondřejov for the Perseid shower for echoes with $\tau > 1s$ as given by Šimek (1987b). The radiant only traverses the region $18 < \theta < 62$ from Ondřejov during observations, where θ is the radiant elevation angle. The symbols • are measured values for R_f for the Perseids and the solid line corresponds to the theoretical values for a $\frac{1}{sin(\theta)}$ correction. The solid curve has been scaled to equal the measured R_f at the highest radiant elevation angle.

3. Results and analysis

3.1. The Last Leonid Epoch: 1964–1967

The observations were broken into three different periods; 1964–1967 when higher activity associated with the April 30 1965 perihelion passage of 55P/Tempel-Tuttle predominated, 1970–1993 when no significant change in Leonid activity was noted and 1994–1995 during which enhanced activity associated with the Feb 28 1998 perihelion passage of the comet.

For the interval 1964–1967, data from both Ondřejov and Springhill were used. The raw hourly counts are shown in Fig. 2. Note that the difference in echo classes for Ondřejov and Springhill as well as differing antenna patterns make comparison of the absolute activity from the curves difficult. These same data corrected for the sporadic background and radiant elevation as described in the previous section are shown in Fig. 3. Where individual datum points are not shown, the shower activity was below background.

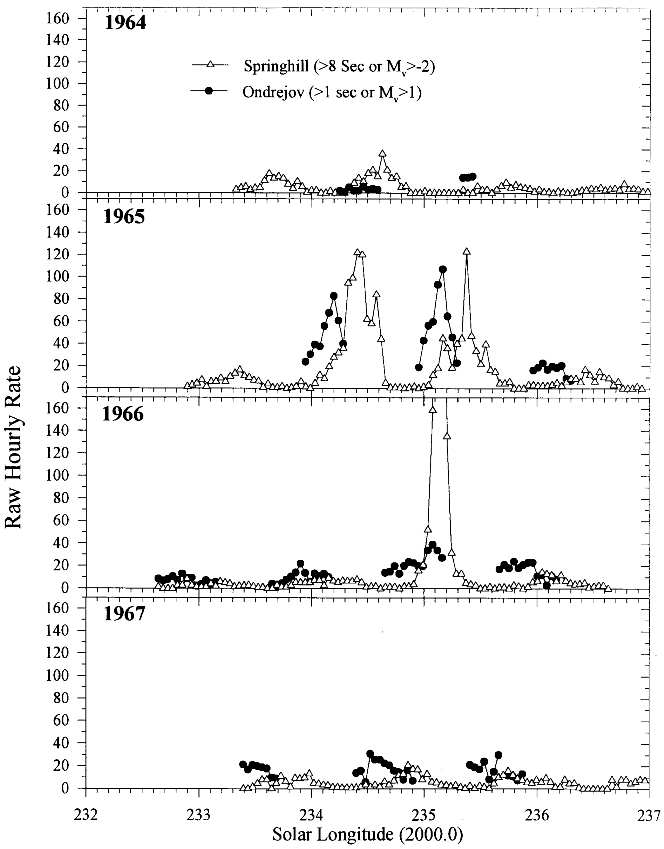

Fig. 2. Observed hourly echo rates from Springhill (△) and Ondřejov (•) from 1964- -1967. The echo class for Springhill is $\tau > 8s$ or magnitude > -2 and $\tau > 1s$ or magnitude $> +1$ for Ondřejov.

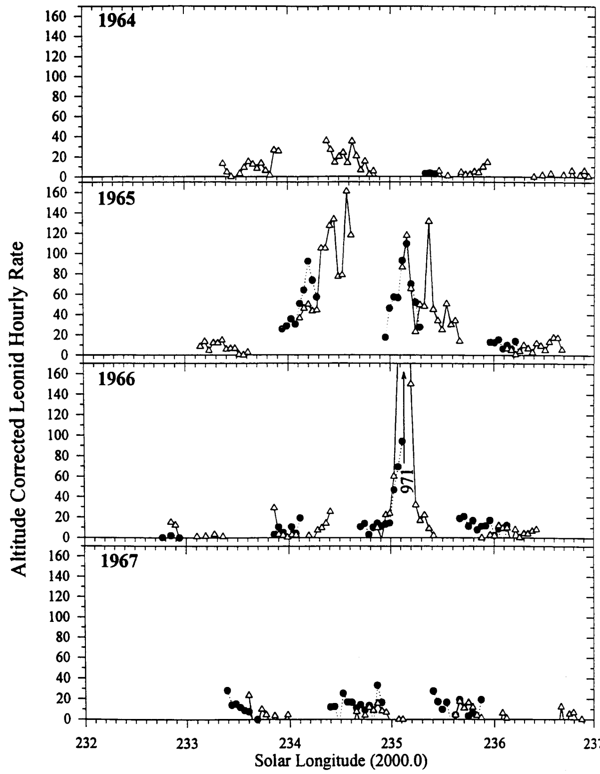

Fig. 3. The echo data from Fig. 2 corrected for the sporadic background and radiant elevation. Symbols are the same as Fig. 2.

Significant shower activity in 1964, particularly between $\lambda_\odot = 233\overset{\circ}{.}5$–$235\overset{\circ}{.}0$ is evident from Springhill. The 1965 shower activity is very pronounced and is more than an order of magnitude above background in many intervals. The main activity appears between $234\overset{\circ}{.}0$– $236\overset{\circ}{.}0$ and shows a very broad maximum near $\approx 234\overset{\circ}{.}5$. The two day long shower activity was dominated by large meteoroids in 1965 as measured by McIntosh and Millman (1970) from Springhill data alone. They computed a mass index of s=1.6 based on the observed distribution of echo durations above 1 second (corresponding to a magnitude of 0 for Springhill). Of interest are features near $234\overset{\circ}{.}12$ and $235\overset{\circ}{.}16$ which appear to be local maxima in both Springhill and Ondřejov data. The Springhill data also shows a complex series of short-duration peaks near $234\overset{\circ}{.}35$, $234\overset{\circ}{.}5$, and $235\overset{\circ}{.}35$ not covered by Ondřejov's observational intervals. The peak near $\lambda_\odot = 235\overset{\circ}{.}16$ is at precisely the position of the 1966 storm maximum and indicates that the material from that filament was more than a year in total duration at Earth's orbit.

In 1966, no broad plateau of activity in these large meteoroids is seen, but the 1966 storm peak at $\lambda_\odot = 235\overset{\circ}{.}16$ is visible in both sets of data. From Ondřejov, the radiant was less than 10° altitude at the peak and thus rate corrections are highly uncertain. Significant increases in the shower rate are visible in the radar record almost 3 hours before the storm maximum in agreement with visual observations (Milon, 1967).

The 1967 profiles show no clear peak in activity and no indication of any activity much above the levels recorded in 1964. The location of the 1966 maximum ($\lambda_\odot = 235\overset{\circ}{.}16$) is barely covered in 1967 Springhill data, and occurred with the radiant less than 10° above the horizon. Any large enhancement should still have been noted, however, and it thus seems that all traces of the material causing the 1966 and 1965 enhancement at $\lambda_\odot = 235\overset{\circ}{.}16$ had disappeared by 1967.

3.2. Quiet-time profile: 1970–1993

To derive the quiet-time profile for the Leonids, the procedure outlined in Sect. 2 was used. The resulting shower profile in units of corrected radar hourly rates to a limiting magnitude of +1 is shown in 4. The most evident feature of the profile is its apparent lack of clear features. The iteration process used to derive the shower profile assumes that the activity of the shower is similar from year to year. However, this technique breaks down when the fluctuations in the sporadic background begin to overwhelm the signal from the shower. Indeed, Brown (1994) concluded that the Leonids were at or below background for the entire period of their activity based on a mean visual profile from 1988–1993 (also shown in Fig. 4), consistent with this radar picture. The peak activity found by Brown (1994) was located between $235\overset{\circ}{.}0$– $236\overset{\circ}{.}0$. This is not in contradiction to the mean shower profile found here, which shows a systematic drop in activity

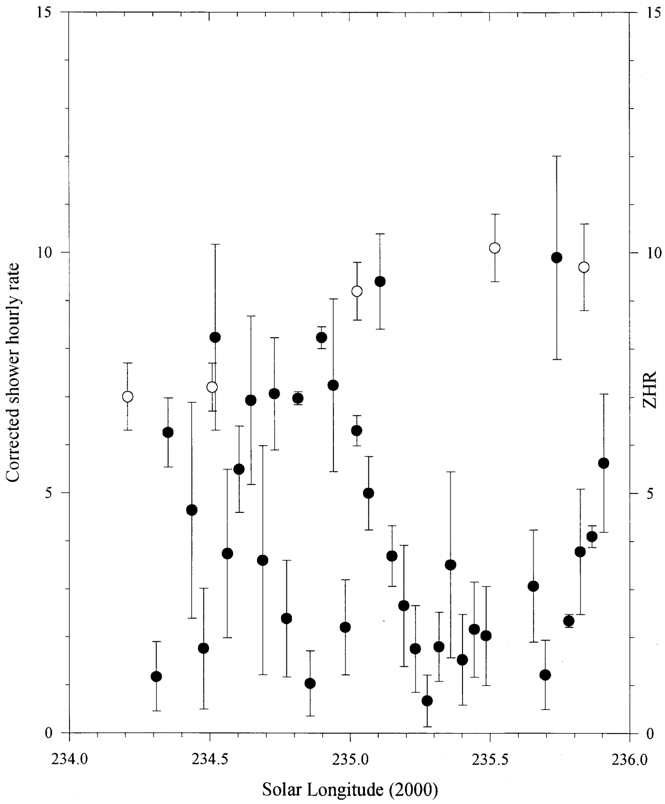

Fig. 4. The mean Leonid shower profile from combined observations 1970–1993 (•). The error bars represent the standard deviation of the individual activity values used to compute the average for any point. The activity is given in meteors per hour brighter than magnitude +1. For comparison, the mean shower ZHR derived from visual observations analyzed by Brown (1994) is also shown ◦.

from ≈235°.0–235°.3. The temporal resolution of the radar profile is higher than for the visually derived ZHR curve and hence this feature, if real, would be smeared out in the visual profile. However, the radar shower profile is too noisy to locate any maximum unambiguously. A single datum at 235°.11±0°.02 is several times error margins above the falling trend and may represent some of the newer activity from recent ejecta as seen during the 1960's near 235°.16. Alternatively, the shower may be more variable across the stream for the larger radar meteors than for the smaller visually observed meteors.

The activity of the Leonids in each year where observations were made from 1970–1993 is given in Table 2. The values represent the unnormalized multipliers for the shower rates in a given year needed to best match the observed shower rates to the mean profile after allowance for the absolute level of the strength of the sporadic background in a given year. The values here are a relative mean multiplier of activity in a given year and represent the equivalent relative average change in integrated flux of the stream in a particular year throughout the period of activity of the shower we have adopted. This measure would be physically similar to an integration of the flux curve over 10 hour periods randomly chosen near the peak of shower (corresponding to the distribution of times the shower can be observed each year from

Table 2. The relative activity levels for the Leonids from 1970–1993. These values represent the unnormalized multiplier of best-fit between the observed shower levels in a given year and the mean profile after correction for the sporadic background. These values should be physically interpreted as the relative difference in the fluence of Leonids to magnitude +1 in the solar longitude interval 234°.71 – 235°.9 in different years.

Year	Activity level
1970	0.16
1971	0.19
1982	0.23
1983	0.42
1988	0.90
1989	0.43
1990	0.60
1992	0.92
1993	0.21

Ondřejov) and summed for each year. Since we do not have the absolute collecting area for the radar, we are unable to calculate an absolute value of the flux from the shower, but can derive these relative values of the integrated flux (fluence) over the showers period of activity by keeping all other parameters in the observations constant. Some of the variation in these years may be ascribed to the time observations were made relative to the peak time – this can have a strong affect on the final values. Other factors such as solar related changes to the upper atmosphere may also affect echo rates (cf. Hughes, 1976). The factor of 5 variation throughout these years in activity is, in many cases, the result of these effects rather than a true indication of flux changes within the stream.

3.3. Recent activity: 1994–1995

The first enhanced activity of the current Leonid cycle took place at the 1994 shower return (cf. Jenniskens, 1996). The presence of the full moon, however, hindered visual observations of the stream. Heightened activity was also detected by visual observers during the 1995 Leonid return, though these rates were probably below those of 1994 (Brown, 1996).

The radar shower profiles for 1994 and 1995 are shown in Fig. 5 and Fig. 6 respectively. These values have been corrected for the sporadic background in the same manner discussed earlier and have been multiplied by the sporadic multiplier for each year to represent actual shower hourly rates. Also shown are the visual ZHR's as found for the 1994 return by Brown (1995) and for 1995 by Brown (1996). The large error margins for the ZHR's in 1994 are due to the presence of the full moon.

For the 1994 return, the visual data indicate a very strong return, with ZHR's approaching 100. The multiplier of best fit for 1994 was 0.96, which is higher than in any year of observation after 1970 (see Table 2) supporting this visual result. The high rates recorded by visual observers after 235°.5 are generally in agreement with the radar data which also shows a peak near 235°.85, in agreement within the error margins with the visual peak at 235°.7± 0°.1. Some differences between the two

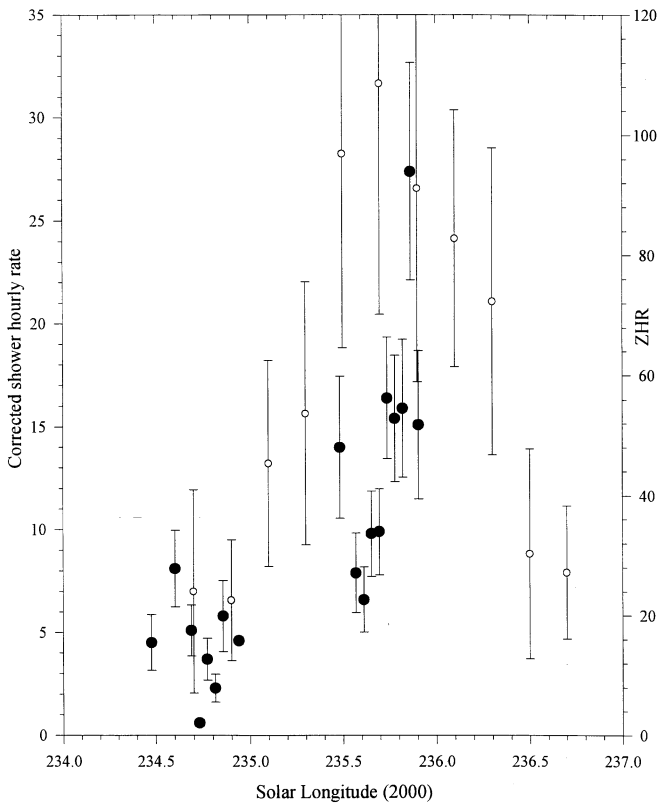

Fig. 5. Radar Leonid activity from Ondřejov data for 1994 (•). The values are given in equivalent hourly rates to a limiting magnitude of +1. For relative comparison the visual ZHR's presented in Brown and Rendtel (1995) are also shown (∘) averaged in bins of 0°.4, with each successive bin shifted by 0°.2.

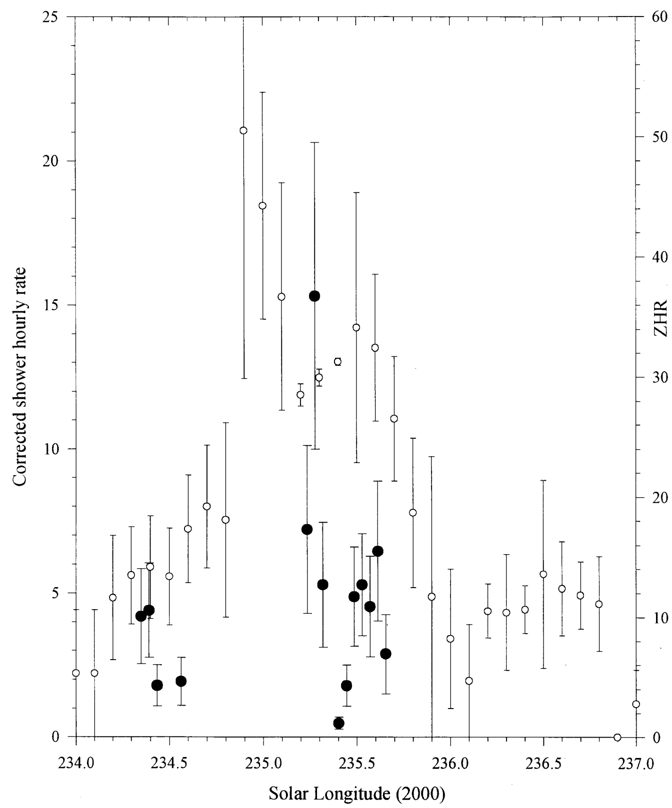

Fig. 6. Radar Leonid activity from Ondřejov data for 1995 (•). The values are given in equivalent hourly rates to a limiting magnitude of +1. For relative comparison the visual ZHR's from Brown (1996) are also shown (∘).

profiles are attributable to small number statistics for the radar data, systematic errors due to the inapplicability of the ZHR correction formulae for moonlight conditions and the large difference in limiting magnitude between the visual data and the radar observations.

In general, the major features of the visual and radar profile also agree in 1995. The shower was considerably weaker in 1995 as compared to 1994, but still several times normal activity according to the visual observations. The multiplier of best fit in 1995 for the radar data was 0.69, which indicates that only 70% as many shower meteors brighter than +1 in total over the interval of observation were detected in 1995 as compared to 1994. The activity before $\lambda_\odot$ = 235°.00 is low for both sets of data, with significant activity most apparent near $\lambda_\odot$ = 235°.5. The feature near $\lambda_\odot$ = 235°.0 in the visual data is from only two observers and is probably spurious.

3.4. The 1966 storm from Springhill radar data

In an effort to improve the determination of the true flux during the 1966 meteor storm, the radar rate data from Springhill were re-examined. In particular, all raw-echo rates to the limiting sensitivity of the system were utilized. McIntosh and Millman (1970) in their analysis of these data indicate that the large number of echos (particularly overdense) make saturation effects important near the time of peak of the shower in 1966. They estimated 30% as the correction factor for obscuration of underdense trails by the numerous persistent echoes visible on the film at the peak of the storm, with lesser obscuration values on either side of the maximum. The high-power (2–3 MW) radar record is completely saturated at the time of the peak and no useful information is deriveable from this source.

Since we have no indication as to what are the actual corrections due to saturation effects, we eliminate all such corrections in this analysis and use only the raw rate data. By using the recorded echo values and the collecting area for the Springhill radar as recently computed by Brown and Jones (1995) we may estimate the corrected number of echoes recorded by the system. We note that Plavcová (1968) found s=1.5 for the Leonids in 1966 from Ondřejov radar data. System specific variations between the two radars would seem to dictate that use of an s value derived from the radar data being analysed is most appropriate. McIntosh and Millman (1970) found s=2.2 from the duration distribution for overdense trails with $\tau > 1s$. However, since the mass index decreases at lower masses we also present results for s=2.0 as the 2.2 value only strictly applies to meteors of magnitude 0 and brighter while from Brown and Jones (1995), the limiting sensitivity of the Springhill radar is equivalent to radio magnitude +6.8. We note that by assuming no correction for saturation effects that our estimated flux will be lower than the true flux.

To determine the true flux from this value, we need only correct for the effects of initial trail radius. Greenhow and Hall (1960) were among the first to point out that a large attenuation in reflected signal would occur once the train radius of an underdense meteor trail at the reflection point became comparable to the radar wavelength. This leads to some fraction of echoes being undetected. Since the initial trail radii increase with height, higher velocity, small meteoroids are most affected by this bias. Jones (1983) analyzed the velocity dependence of the correction determined by Greenhow and Hall and found an empirical relation between the fraction (f) of detected echoes, the radar wavelength used and the meteoroid velocity of

$$f = a\lambda^b$$

where a and b depend on veolcity. By extending the velocity dependence of (1) to 70 km s^{-1} from the data given in Jones (1983) we find a=3.4×10^{-5} and b=3.211. Using these coefficients and (1), we find at Leonid velocities for Springhill (f=32.8 MHz) that only about 5% of Leonid echoes are actually detected.

To provide a comparison with the Greenhow and Hall method we have independently analyzed this problem. Due to system geometry, the specular point falls randomly on the trail and for a radar echo to be detected the electron line density at this point must exceed the sensitivity threshold of the system. This introduces one bias into the determination of a trail radius correction. Based on the information from TV meteors given by Sarma and Jones (1985), which samples the same mass range as the Springhill radar data, the trail lengths for such faint TV meteors is found to be considerably shorter than theory suggests (cf. Kaiser, 1954). Using the Sarma and Jones (1985) height data (which are normalized for velocity, mass, and entry angle) we derive an r.m.s spread in the height range at these small meteoroid masses of 6.24 km. This scatter is due entirely to differences in the physical (i.e. composition or shape) character of the meteoroids. A further r.m.s error of 2.65 km is found for the spread in heights due to the random locations of the specular points, producing a final r.m.s height variance of 6.78 km. Since the physical makeup variation and location of the specular point are assumed random, we assume to first order that the height distribution for the Leonids in this mass range is Gaussian. More details of this method will be given in Jones (1997). Height distributions at low frequencies found by Steel and Elford (1991) are free of initial train radius bias and are very near Gaussian in shape; hence we feel justified using this in the absence of more definitive height distribution information specific to the Leonids.

Using this technique we find that 14% of the meteors are detected using an s value of 2.2, 20% for s=2.0 and twice this value at s=1.5. Clearly, this value is very sensitive to s, increasing steeply as s decreases. Since no accurate measurements of s for the Leonids were made in the magnitude range near the Springhill limiting sensitivity during the 1966 storm, it is only possible to estimate that the true value of s at our limiting sensitivity was close to 2 (lower than at the brighter magnitudes and comparable to the sporadic background). For accurate flux measurements for forthcoming Leonid returns, accurate measures for the mass distribution at low masses is desirable.

The echo rate data corrected for collecting area and initial train radius is shown in Fig. 7 for both s=2.2 and s=2.0. At the peak of the shower, the flux to a limiting magnitude of +6.8 exceeded $\approx 39 \pm 2$ km^{-2} hour^{-1} using our best estimate for s (2.0) and a correction factor for initial train radius of 20%. From visual counts, the observed ZHR has been estimated to have peaked near 150 000. Using s=2.0 (corresponding to an equivalent population index, r, of 2.5) and the method outlined in Brown and Rendtel (1996), this peak observed ZHR and population index is found to correspond to a flux (for meteors of absolute magnitude +6.5 and brighter) of ≈ 75 km^{-2} hour^{-1}. These values are in agreement with each other (bearing in mind the still uncertain initial train radius corrections and the lack of correction for saturation effects in the radar record) but are difficult to reconcile with the findings of Jenniskens (1995) who determined a peak ZHR of 15 000 for the 1966 storm from visual observations, nearly one order of magnitude lower than previously reported in the literature and found here.

Jenniskens' result would be nearly equal to the measured radar rate if no initial train radius correction were performed. For meteoroids as fast as the Leonids, it is clear from the foregoing that the bias introduced by the initial train radius cannot be ignored at Springhill frequencies. The lower ZHR favoured by Jenniskens is based on the fact that the visual observations near the peak were uncertain due to the extremely high rates and that the Leonid rate curve does not follow the twin exponential model purported to hold for the ZHR profiles of other streams in Jenniskens (1995) near the Leonid peak in 1966. However, the actual observations do indicate rates approaching (and exceeding) 100 000 per hour, the lower 15 000 figure being adopted to match the rising portions of the profile without need for a 'bend' in the Jenniskens model profile to agree with the reported visual observations. In Fig. 8 we have performed a non-linear regression fit to the s=2.0 corrected radar data to a Gaussian and find that the rising portions of the profiles for the central portion of the Leonid activity in 1966 is best represented by a Gaussian profile. This difference between the assumed power-law behavior adopted by Jenniskens (1996) for the 1966 storm and the observed profile in Fig. 8 may be the source of this apparent discrepancy.

4. Summary

The response function derived using the iterative shower profile modelling technique of Šimek (1985) for echo classes $\tau > 1s$ corresponds simply to the geometric correction, $\frac{1}{sin(\theta)}$, due to the elevation of the radiant for the Ondřejov radar.

Analysis of the corrected shower profiles for the Leonids from 1964–1967 show that significant activity from larger meteoroids was present as early as 1964. The 1965 return was particularly rich in large Leonids (brighter than magnitude +1)from at least 234$.\!^\circ$0– 236$.\!^\circ$0. The corrected rates in these years from both Springhill and Ondřejov show similar locations for at least

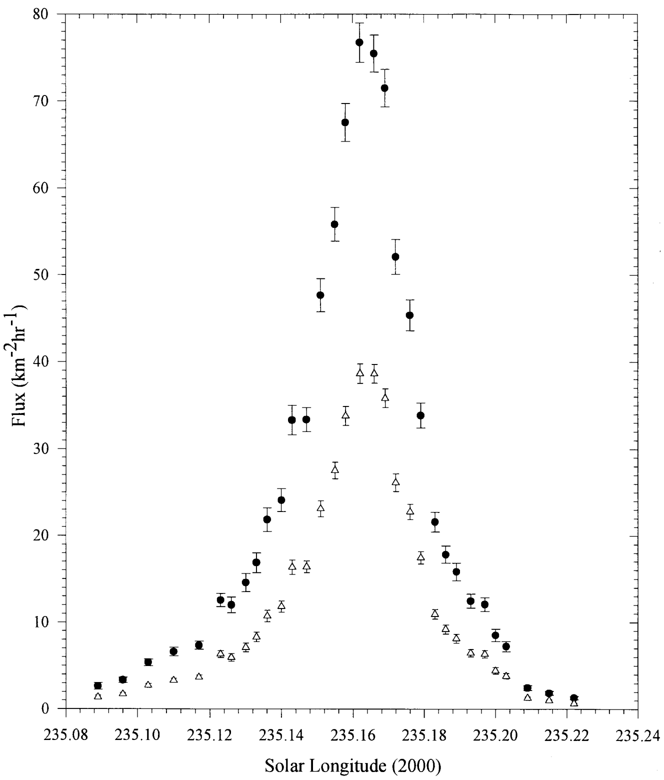

Fig. 7. The flux of the Leonids near the peak of the 1966 Leonid meteor storm from Springhill patrol radar data. The values shown are to a limiting radio magnitude of +6.8. The upper curve (•) uses s=2.2, while the lower curve (△) is for s=2.0. The error bars are Poissonian and represent $n^{-1/2}$ of the total count, where n is the number of echoes in each bin.

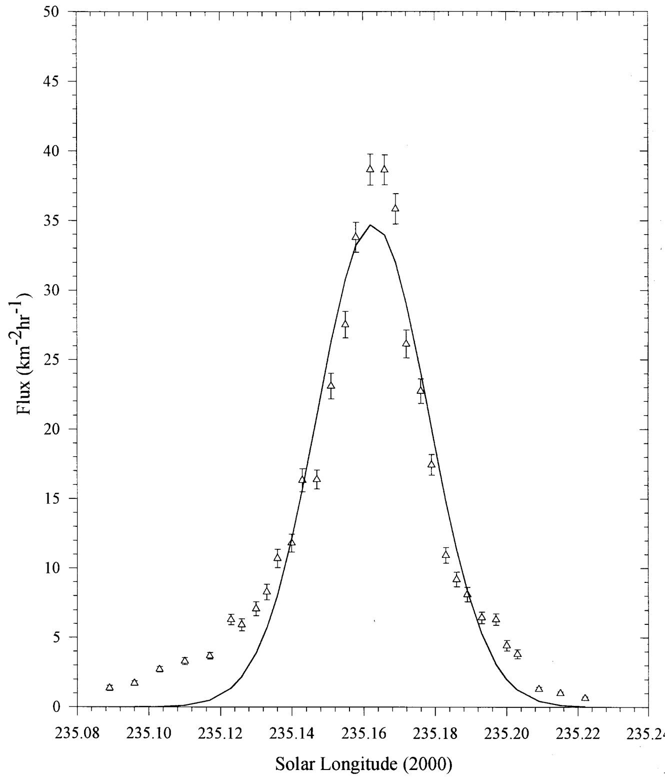

Fig. 8. The flux of the Leonids near the peak of the 1966 Leonid meteor storm from Springhill patrol radar data using s=2.0 and not correcting for saturation effects. The solid curve is a Gaussian fit to the flux curve. The Gaussian fit has a has a width of 0 $.\!\!^\circ$0156±0 $.\!\!^\circ$0008.

two mutually observed local maxima at (234 $.\!\!^\circ$2, 235 $.\!\!^\circ$15) while Springhill data also reveal at least three additional maxima not covered by Ondřejov (234 $.\!\!^\circ$4, 234 $.\!\!^\circ$6, and 235 $.\!\!^\circ$35). The 1966 shower is dominated by the feature at 235 $.\!\!^\circ$15 associated with the Leonid storm of that year; lesser activity from the shower is visible for several days on either side of this time. The 1967 shower shows no unusually strong activity in the population of larger meteoroids (brighter than magnitude +1) during the intervals covered. Most noteworthy is the apparent lack of any activity at 235 $.\!\!^\circ$15 in 1967 despite coverage of this interval by Springhill data.

The Leonid shower during 1970–1993 was characterized primarily by activity at or below the sporadic background. The iteration process failed to reveal a smooth profile for the stream due to the high sporadic contamination, though some indications of a short-lived feature near 235 $.\!\!^\circ$15 was detected.

In 1994 and 1995 the Leonids returned to activity levels well above the sporadic background with the radar profile in these years showing that the shower was most active after 235 $.\!\!^\circ$0 with enhanced activity continuing to the end of observations at 236 $.\!\!^\circ$0. The radar results in these years are in agreement with the general trend in activity for the shower noted by visual observers.

A re-analysis of the 1966 Leonid storm from Springhill patrol radar records, correcting for the effective collecting area of the radar and initial train radius biases permits a lower limit to be placed on the flux profile of the storm. The peak shower flux to a limiting magnitude of +6.8 assuming s=2.0 is found to be 39 ± 2 km^{-2} hour^{-1}. This is in agreement with visual observations of the 1966 storm, but contradicts the recent analysis of the 1966 Leonid peak ZHR value obtained by Jenniskens (1995). The 1966 storm profile has a Gaussian shape in its central core with a full-width to half maximum of 0 $.\!\!^\circ$0156±0 $.\!\!^\circ$0008 corresponding to a FWHM time of 23 minutes. Better absolute determination of the flux is not possible without precise information concerning the mass index at the peak of the 1966 storm for Leonids in the magnitude range +6–+7.

The quantitative and qualitative observational results presented here need to be explained by any complete model of the stream and as such provide the needed input to any such modelling effort.

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