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Observations of the 1996 Leonid meteor shower by radar, visual and video techniques

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ABSTRACT

The activity of the 1996 Leonid shower from two radars, global visual and single-station low-light-level TV (LLTV) observations is presented and summarized. Radar observations from Ondřejov in the Czech Republic indicate a peak rate of (>+1) Leonids near $\lambda_{\odot} = 235\overset{\circ}{.}2 \pm 0.1$ (Equinox 2000). As observed by this radar, this peak interval was characterized by a significant increase in the number of bright Leonids as demonstrated by a noticeable lowering of the mass index near the peak. From radar observations in Ontario, Canada (using the CLOVAR system), a raw peak flux of $1.3 \pm 0.3 \times 10^{-2}$ meteoroid km^{-2} h^{-1} brighter than radio magnitude +7.7 was reached at $\lambda_{\odot} = 235\overset{\circ}{.}3 \pm 0.1$, uncorrected for initial train radius effects. Single-station LLTV observations suggest a peak shower flux of $1.8 \pm 0.4 \times 10^{-2}$ meteoroid km^{-2} h^{-1} brighter than absolute magnitude $+5 \pm 0.5$ between $235\overset{\circ}{.}3$ and $235\overset{\circ}{.}39$. The position of the radiant on the night of maximum of the shower is found to be $\alpha = 152\overset{\circ}{.}9 \pm 1\overset{\circ}{.}0$ and $\delta = 22\overset{\circ}{.}1 \pm 1\overset{\circ}{.}0$ from CLOVAR observations and $\alpha = 153\overset{\circ}{.}3 \pm 1\overset{\circ}{.}7$ and $\delta = 22\overset{\circ}{.}1 \pm 1\overset{\circ}{.}7$ from LLTV observations. Visual observations of the shower yield a peak zenithal hourly rate (ZHR) of 86 ± 22 at $235\overset{\circ}{.}17 \pm 0\overset{\circ}{.}07$ or an equivalent flux of $1.2 \pm 0.4 \times 10^{-2}$ meteoroid km^{-2} h^{-1} brighter than absolute visual magnitude +6.5. The visual peak was short-lived (1.5 ± 0.5 h HWHM) and richer in fainter meteors than neighbouring intervals. Discrepancies in the estimated absolute Leonid flux found using differing methods are noted and possible reasons for the differences discussed. The stream in 1996 showed two distinct meteoroid populations: a population of recently ejected meteoroids rich in smaller particles near $235\overset{\circ}{.}17$ which is very narrow in nodal extent (HWHM $0\overset{\circ}{.}07 \pm 0\overset{\circ}{.}02$), and an older component (of order 10 revolutions in age) peaking near $235\overset{\circ}{.}4$ which is rich in larger stream meteoroids, of long duration (FWHM $1\overset{\circ}{.}2 \pm 0\overset{\circ}{.}4$), which contributed most to the total mass flux at Earth from the stream in 1996.

Key words: techniques: radar astronomy – comets: individual: 55P/Tempel–Tuttle – meteors, meteoroids.

1 INTRODUCTION

The recent recovery of 55P/Tempel–Tuttle (Hainaut et al. 1997) highlights the potential for enhanced activity to be observed from the Earth in coming years from Tempel–Tuttle's associated meteoroid stream, the Leonids. The possibility that in one or more of the years from 1998–2000 a 'meteor storm' will transpire cannot be ruled out, and the characterization of the stream before it reaches such a stage is imperative to putting any such storm into context. In particular, activity in the years leading up to any possible storms may reveal features which may be useful in predicting activity in subsequent years. Brown, Šimek & Jones (1997), for example, noted that a local maximum in radar rates occurred in 1965 at the precise location of the 1966 Leonid storm.

The Leonid return of 1996 marked the last year of good lunar conditions for observing the stream until 1998. Here we report on radar observations made with two different radar systems, global visual observations and single-station low-light-level television recordings of the stream in 1996.

2 RADAR OBSERVATIONS

2.1 Ondřejov

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 & Šimek (1960), Šimek (1965) and Hajduk (1965). Reductions of these Leonid observations from Ondřejov records were performed in the same manner as discussed in detail in Brown et al. (1997) for reductions of radar shower data for the years 1970–1995.

All echoes recorded on the film which had durations longer than 1 s (which corresponds to a visual-magnitude Leonid of +1) were counted. The diurnal variation in sporadic rates throughout the observation period each night is assumed to be similar to the long-term average for the same intervals of solar longitude. The echo rate is assumed to be entirely sporadic before $\lambda_\odot = 234\overset{\circ}{.}71$ and after $\lambda_\odot = 235\overset{\circ}{.}9$ (J2000). This sporadic activity is then subtracted from the total rate in the interval containing the main shower activity to derive raw hourly shower rates. The final corrected hourly shower rates are then computed after multiplication of the raw rates by the inverse of the radar response function. The final results are presented in Fig. 1.

From Fig. 1 it is apparent that a peak in activity occurred near $\lambda_\odot = 235\overset{\circ}{.}2 \pm 0.1$, when the shower echo rate was more than a factor of 2 above the sporadic background. The decline from maximum is also present, beginning immediately after $\lambda_\odot = 235\overset{\circ}{.}3$. The intervals during which the radiant is above 10° elevation as seen from Ondřejov are also shown in the diagram.

As in past years, a multiplier of best fit between the mean activity profile derived from all observations from 1970–1993 and the current profile was computed (see e.g. Brown et al. 1997). Physically, this represents the fluence of meteoroids from the Leonid shower over the entire period of observation capable of producing meteors of magnitude +1 (Šimek 1987) and brighter, relative to the long-term average from 1970–1993. In 1996 this multiplier was found to be 2.42. This is much higher than in any previous year (the highest from 1970–1995 being in 1994 when it reached 0.96). This clearly indicates that the Ondřejov radar recorded very large

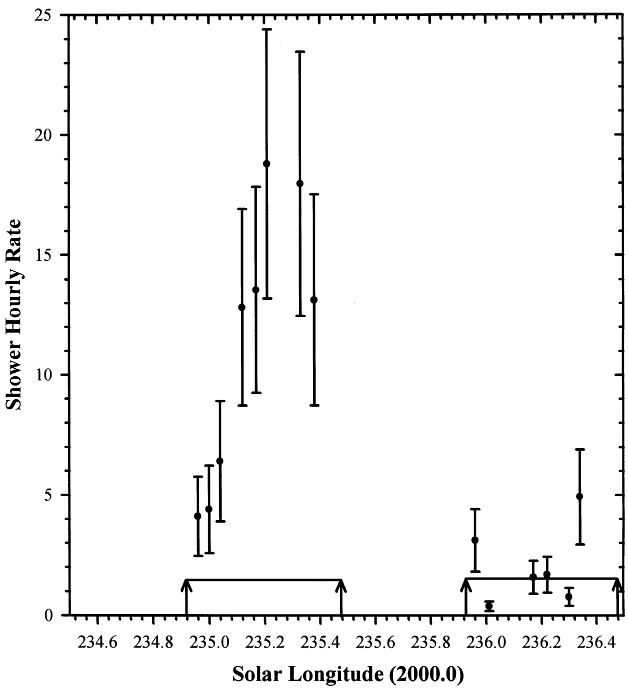


Figure 1. The Leonid hourly shower rate for echoes with duration 1 s and greater. These correspond to Leonids of radio magnitude +1 and brighter. The time intervals covered by the lines connecting the arrows are those in which the radiant is more than 10° above the horizon.

Table 1. Mass index computed from the distribution of overdense echo durations near the time of the peak of the Leonids in 1997 as observed with the Ondřejov radar. The background measurements refer to the mean values for s found from 1964–1995 in the same period. The s values are based on distributions of meteor echoes with durations longer than 10 s, which correspond to Leonids of radio magnitude −1 (Šimek 1987).

Solar Longitude (2000.0)	s_{shower}	$s_{\mathrm{background}}$
$234\overset{\circ}{.}94$– $235\overset{\circ}{.}04$	1.46±0.06	2.25±0.03
$235\overset{\circ}{.}11$– $235\overset{\circ}{.}2$	1.13±0.02	1.87±0.03
$235\overset{\circ}{.}29$– $235\overset{\circ}{.}38$	1.44±0.02	1.99±0.03

increases in the numbers of bright Leonids in 1996 compared with all recent years. This is due partly to good observing geometry for the outburst which occurred near $235\overset{\circ}{.}2$ and partly to the intrinsic increase in activity from bright meteors in 1996 compared with past years.

The distribution of the durations of shower echoes is expected to follow a power law of the form (cf. Kaiser and Closs 1952)

$$\log N = 0.75(1 - s)\log T,$$

where N is the cumulative number of overdense echoes having observed durations of T seconds or greater and s is the power-law exponent in the number–mass distribution. At longer durations, this relationship changes in such a way as to produce a 'knee' in the distribution, which causes a downturn in the number of very long-duration overdense echoes over that which would be expected on the basis of a linear extrapolation from the number of lower duration overdense echoes (see Kaiser and Closs 1952 for a detailed discussion). This 'knee' is caused by an increase in the rate of electron removal, probably due to reactions with ozone (Jones and Šimek 1995). Using the early linear part of this curve (for the Leonids this corresponds to $T > 10$ s), values for s were calculated in different intervals where sufficient numbers of echoes were present, as shown in Table 1. The values for s are low, reaching a minimum of 1.13 in the interval $\lambda_\odot = 235\overset{\circ}{.}1$–$235\overset{\circ}{.}25$. This s value is too low to be physically believable and the quantitative values for s should not be taken as true measures of the mass index. Rather, the values for s can be interpreted as indicating a relative decline in s in this interval. Also shown in Table 1 is the average background s from observations in the same interval of solar longitude averaged from 1964–1995. The variation in $s_{\mathrm{background}}$ with solar longitude is likely a result of Leonid contamination in some years. It is clear, however, that the value for s is much lower than has been previously observed in this region and thus the proportion of large meteoroids in the Leonid stream in this region was higher in 1996 than usual. It was not possible to compute absolute flux values for the Ondřejov system, as the echoes which were counted ($T > 1$ s duration) are probably not specular in many cases (cf. Brown et al. 1997) and thus it is not possible to compute an echo-collecting area, the underpinning of which is adherence to specular reflection.

2.2 CLOVAR

In addition to the Ondřejov radar data, Leonid activity was also recorded by the CLOVAR London, Ontario ST Radar. The CLOVAR ST radar, which operates at 40.68 MHz and has a peak power of 10 kW and an effective PRF of 90 Hz, is situated in London Ontario (43° N and 81° W). Details of the system, reduction techniques and the antenna system are given elsewhere [cf. Hocking

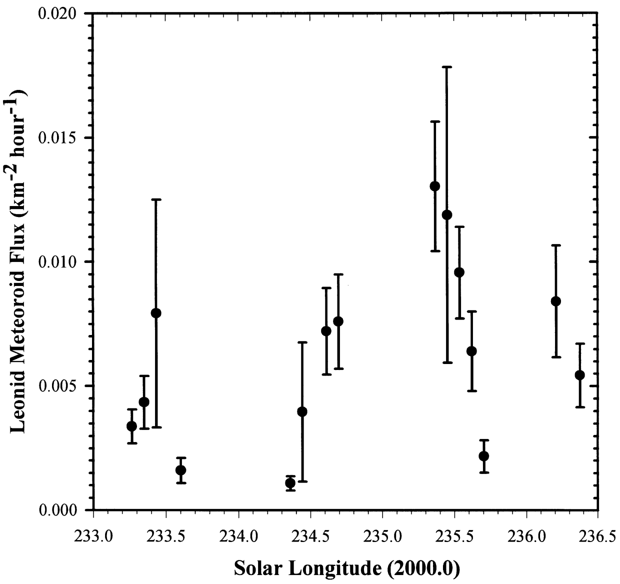


Figure 2. The flux for the 1996 Leonids as determined from CLOVAR radar observations. The limiting radio meteor magnitude sensitivity for the system is +7.7. Note that intervals near the rising or setting of the radiant have been removed in some cases. If recorded rates on a given day and time were lower than the echo rate recorded on the sporadic control day (November 19), no datum is shown.

(1997) and Hocking and Thyaparan (1997)]. The operation of the radar as a meteor radar is discussed in detail by Brown et al. (1998).

Unlike the Ondřejov system, CLOVAR has a fixed antenna system which is nearly all-sky. The five receiving antennae are arrayed as an interferometer such that the direction to the specular point on each meteor trail can be obtained to an accuracy of $\approx 2^\circ$. All echoes to the limiting sensitivity of the system (radio magnitude of +7.7) had information on their height, amplitude and duration recorded.

Using the directional information from all echoes, it is possible to calculate a radiant for the ensemble of observed echoes using the radiant imaging technique of Jones and Morton (1982). For the CLOVAR data on the night of November 17, the best-fitting radiant location was $\alpha = 152.9^\circ$ and $\delta = 22.1^\circ$ with a root-mean-square (rms) diameter of 0.4°. The error in the radiant location is approximately 1° in either coordinate.

Using the radiant location, all echoes which were within 5 degrees of 90° from the radiant were then selected. These echoes contained both Leonids and sporadics. We took the rates from the same hours on November 19, which met the same specular condition relative to the Leonid radiant, to be representative of the sporadic background and subtracted these from the echo rates near the maximum. The echo-collecting area for CLOVAR has been derived previously in detail (see Brown et al. 1998). The resulting shower rates were then binned into 2-h intervals and the integrated collecting areas computed. The resulting flux profile for the Leonids is shown in Fig. 2. The number of echoes is quite small in most bin intervals, but the decline from maximum between 235°.3 and 235°.7 is apparent. The observed peak flux from CLOVAR was found to be $1.3 \pm 0.3 \times 10^{-2}$ meteoroid km^{-2} h^{-1} to a limiting magnitude of +7.7. We note that this is a lower limit as no correction for initial train radius has been applied (see Discussion section).

3 LOW-LIGHT-LEVEL TELEVISION OBSERVATIONS

In addition to these RADAR data, a single ISIT (an image intensifier which is fibre-optically coupled to a silicon intensified target camera) was operated from near CLOVAR on the night of maximum (1996 November 17). This ISIT had a limiting sensitivity for stellar sources of approximately +8.5 and was sensitive to those Leonids near the radiant with lower angular velocities as faint as apparent magnitude $\approx +7.5$. The ISIT had a 50-mm *f*/0.7 lens and an effective field of view of $9^\circ \times 13^\circ$. Additional details of the ISIT used and performance characteristics are given in Sarma and Jones (1985) and Duffy, Hawkes & Jones (1987).

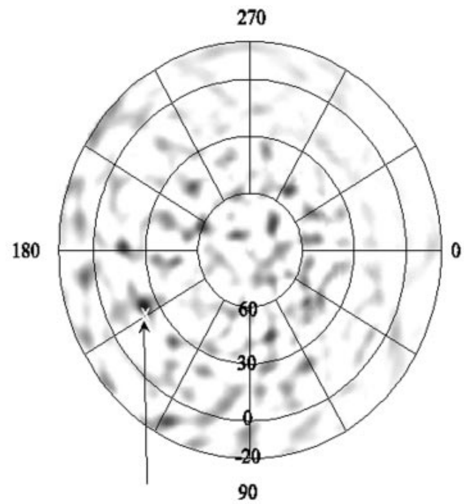
Recording with the ISIT took place from Elginfield, Ontario (43.200°N and 81.317°W) and ran from 4.00–11.33 UT, November 17 (7.33 h). Throughout this period there was occasional cloud and after 10.5 UT there was twilight interference. In all, some 69 meteors were recorded in this interval.

For each meteor, the start and end points of the apparent trajectory visible in the video field were measured based on the location of nearby stars after digitization of the appropriate video frames. The apparent peak magnitude was estimated by comparing the meteor luminosity with that of nearby stars. Note that we did not correct for the angular velocity for each meteor – this implies that the observed meteors are actually brighter than our estimate as the angular velocity decreases the integration time available to form the video image of each meteor. As well, ISITs tend to have non-linear response across the screen, with peak response in the centre of the screen, trailing off by as much as a full magnitude near the edges. The end result of these two effects is that our estimated magnitudes are fainter than the true magnitudes by 1.5 mag on average.

In an effort to partially compensate for the high angular velocity of the Leonids, for two full hours just before dawn the ISIT was pointed within 10° of the Leonid radiant. In this interval we believe we were able to detect Leonids with apparent magnitudes as faint as +7.5 at the centre of the field of view.

We applied the same radiant imaging technique as described for CLOVAR to the TV data, using the start and end points to define the plane of the trajectory. The resulting all-sky imaging plot is shown in Fig. 3, along with the same plot for CLOVAR for 1996 November 17 for comparison. Using the same iterative radiant location technique as employed to define the Leonid radiant from CLOVAR data, it was determined that the best-fitting radiant for the Leonids from the TV trajectories was α=153.3° ± 1.7° and δ=22.1° ± 1.7°. This radiant size is limited by the precision and number of measured TV meteor trails and does not represent a true physical size. In addition to this method of determination, at 08:22:51 UT a stationary meteor (i.e. one heading directly for the observer and hence out of the actual radiant location) was recorded at α=153.2° and δ=23.1°, the trail of which lasted for 2.3 s, providing a check on the above.

In total, it was determined that 39 of the 69 meteors had great-circle trails which intersected to within an angular distance less than the rms radius of the radiant. Using the apparent magnitudes of this 39-meteor subset, along with the mass–magnitude–velocity formulae for TV meteors determined for this same ISIT by Sarma & Jones (1985), we individually computed the masses for each potential Leonid. Using this distribution we then calculated the mass index, *s*, to be 1.64 ±0.17 for Leonids with absolute magnitude +5 and brighter. Note that we have made no attempt to compensate for partial trails – all meteors which either started or ended in the field of view were counted if their backward



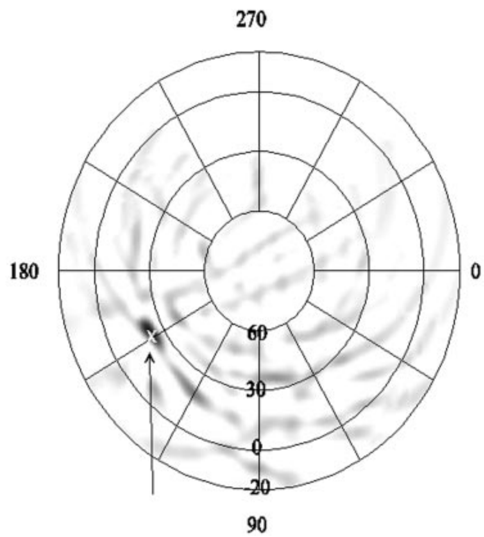


Figure 3. Radiant activity computed using the radiant imaging technique of Jones & Morton (1982). The top plot shows radiant structure from CLOVAR echoes recorded during November 17 while the bottom plot shows the radiant structure from the TV data using the same technique. The small arrow and white cross in each plot show the location of the expected Leonid radiant at α=153° and δ=22°. The azimuthal coordinate is right ascension and the polar angle is declination. Darker shading indicates higher radiant activity.

prolongated trails came within 3° of the Leonid radiant. The effect of not including corrections for partial trails would be to artificially increase the value for *s*; thus our determination is an upper limit. This value is subject to uncertainty larger than the formal error due to the very small number of Leonids used. It does, however, provide a rough estimate of the mean mass index for the Leonids determined from ISIT video observations on November 17 valid over the magnitude range from absolute magnitude +5 and brighter.

Using the 2-h interval (8–10 UT, November 17 or $\lambda_\odot = 235\overset{\circ}{.}30$–$\lambda_\odot = 235\overset{\circ}{.}39$) which was more than 90 per cent cloud-free, we can calculate the Leonid flux after first determining the integrated collecting area in the atmosphere. From the video field of view and its pointing direction throughout the 2-h interval, the area in the atmosphere actually covered by the TV at 100 km altitude is 875 km^2. Taking into account the diminution of this area due to radiant–TV pointing direction geometry yields an average collecting area of 850 km^2 over the full 2-h interval (i.e. 1700 km^2 h). From this measurement and the total number of Leonids recorded in this interval (27), we derive a TV flux to a limiting apparent magnitude of $\approx$ +7.5 of 1.8 $\pm$ 0.4 $\times$ 10^{-2} meteoroid km^{-2} h^{-1}. The limiting absolute magnitude is approximately 1 mag (to +6.5 and mass of 2 $\times$10^{-8}kg) brighter due to the average range ($\sim$ 150 km) of most of the observed Leonids and a further 1.5 mag brighter on average due to trailing effects. Thus the TV flux is 1.8 $\pm$ 0.4 $\times$ 10^{-2} meteoroid km^{-2} h^{-1} to a limiting absolute magnitude of +5$\pm$0.5, corresponding to a mass of $\sim$6$\pm$3$\times$10^{-8} kg.

4 VISUAL OBSERVATIONS

The zenithal hourly rate (ZHR), flux and particle distribution profiles for the 1996 Leonids have also been computed based on 434 individual observations made by 109 observers comprising 4449 Leonid meteors. The single-observer counting method for showers was employed throughout, with observers using the International Meteor Organization (IMO) standard observing method (cf. Rendtel, Arlt & McBeath 1995). Details of the reduction techniques and final computations of the ZHR, population index and flux can be found in Brown & Rendtel (1996).

Fig. 4 shows the ZHR profile for the 1996 shower for the one-day interval centred about $235\overset{\circ}{.}5$. A linear increase in the ZHR from $\approx$ $235\overset{\circ}{.}0$ to $235\overset{\circ}{.}17$ is apparent, at which time the peak of 86$\pm$22 is reached. Note that the higher than average sporadic rates in the early portion of this interval suggest that some of the early activity in the rising portions of the curve may be overstated. At the peak, however, the sporadic HR is very near the normal value for this time of the year (10–15). There was a large scatter in individual ZHR estimates during the peak period as manifested by the large error margins. The first peak has a ZHR half-width to half-maximum (HWHM) of $0\overset{\circ}{.}07\pm0\overset{\circ}{.}02$ (1.7 $\pm$ 0.3 h).

A second, weaker peak is also visible in the profile near $\lambda_\odot$=$235\overset{\circ}{.}4\pm0\overset{\circ}{.}1$. This peak is ill-defined within the error margins

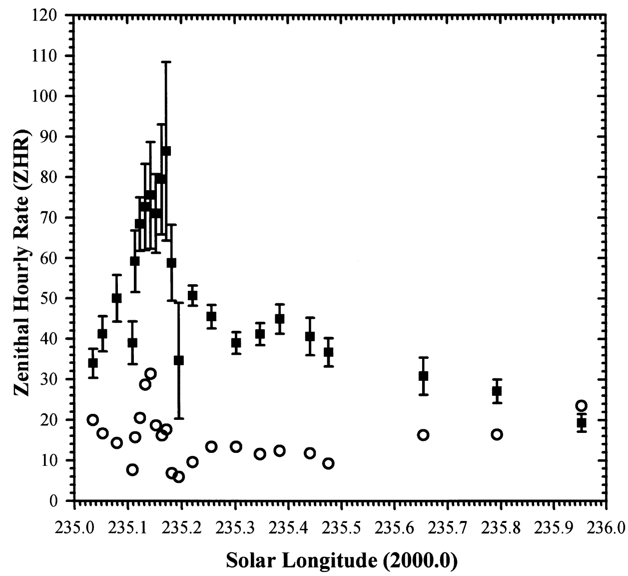


Figure 4. The ZHR versus solar longitude for the 1996 Leonid return. This profile was computed using $0\overset{\circ}{.}1$ smoothing intervals shifted by $0\overset{\circ}{.}05$ before $235\overset{\circ}{.}1$ and $0\overset{\circ}{.}02$ intervals shifted by $0\overset{\circ}{.}01$ from $235\overset{\circ}{.}1$–$235\overset{\circ}{.}2$. The remainder of the profile was found using $0\overset{\circ}{.}1$ increments shifted by $0\overset{\circ}{.}05$ from $235\overset{\circ}{.}2$–$235\overset{\circ}{.}5$ and $0\overset{\circ}{.}5$ increments shifted by $0\overset{\circ}{.}25$ thereafter. The solid squares are shower ZHRs while the open circles are the sporadic hourly rate (HR) in the corresponding intervals.

and is likely associated with the normal annual peak which has shown a maximum near 235°.5 in past years (Brown 1994). The 1995 ZHR profile showed a similar structure close to this location (Brown 1996). The peak ZHR associated with this maximum is 45 ± 4, which is more than four times the normal annual maximum and is 10 larger than the 1995 level. This peak is an order of magnitude broader than the early maximum, having a HWHM of 0°.6±0°.2. This measure of the HWHM applies to the broad profile and ignores the sharp early maximum. It is instructive to note from the visual sporadic and shower ZHR profiles that Leonid activity in 1996 climbed above the sporadic background only over the interval 234°.0– 236°.0.

From the visually recorded magnitude distributions compiled between 1988 and 1993, the mean population-index value (r) for the Leonid stream was found to be 2.0 (Brown 1994). The population index expresses the ratio of total meteors observed in magnitude class M_v to those seen in magnitude class $M_v + 1$ and is related to the mass-distribution index, s, via $s = 1 + 2.5\ \log(r)$ (McKinley 1961). Fig. 5 shows the r profile over the same interval of solar longitude as given in Fig. 4. The pre-maximum and extreme post-maximum intervals have measurements of r in the 2–2.2 range.

From Fig. 5, there is a statistically significant increase in r near the time of the early ZHR peak relative to the intervals immediately before and following. The extreme minimum in r is reached near 235°.31±0°.02 where it attains a value of 1.6±0.06. This low value for r remains constant near 1.7–1.8 until 237°.0, at which time r climbs to 2.6±0.5. This is very much lower than the $r = 2$ normally associated with the central portion of the stream and, if true, would indicate that for the visual magnitude range (>+5) an abundance of bright Leonids over the roughly day-long period centred about the traditional peak was observed, compared with normal Leonid activity. However, the abundance of bright meteors in this interval may also be due in part to fewer observers being active in this region and many European observations being interrupted by clouds. From the r profile and the ZHR activity it is possible to derive a flux profile for the 1996 Leonids and this is shown in Fig. 6. The peak flux at the early peak corresponds to $1.2\pm0.4\times\ 10^{-2}$ meteoroid km^{-2} h^{-1} to a limiting absolute magnitude brighter than 6.5. The later, broad peak is roughly four times lower than this value, in large part due to the very low values for r in that interval.

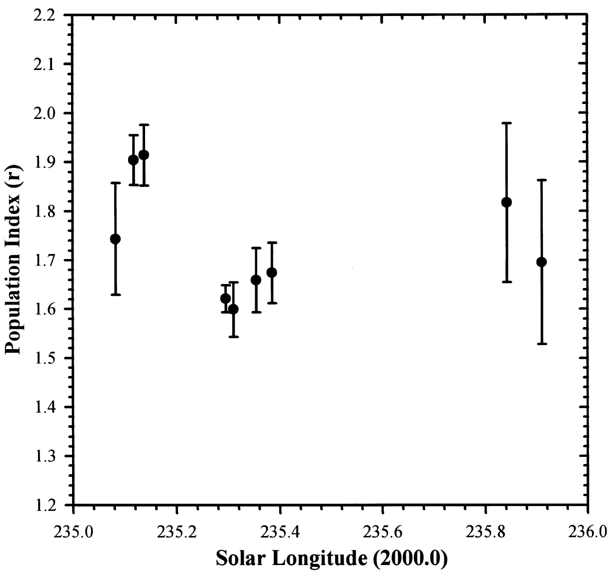


Figure 5. The change in the population index for the 1996 Leonids for the 1-d interval about the peak as obtained from magnitude data consisting of 3220 Leonid meteors. Each datum was derived from a group of between 25 and 688 visual Leonid magnitude estimates. The population-index has been calculated from magnitude distributions consisting of meteors in bins which are 1.5 mag above the limiting magnitude for any one observer, implying a limit near apparent meteor magnitude +4.5–+5.

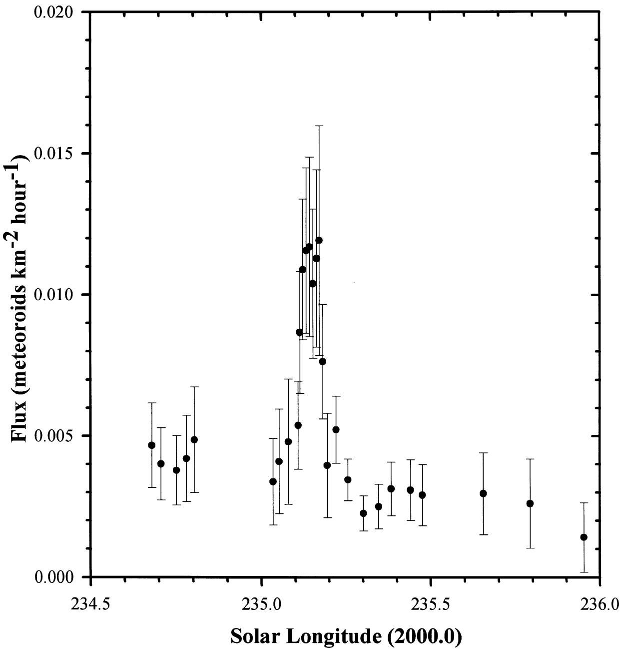


Figure 6. The visually determined flux for the 1996 Leonids. The flux corresponds to meteors brighter than absolute magnitude +6.5. This corresponds to a Leonid of mass 10^{-8} kg.

5 DISCUSSION

All of the above observations are consistent with a dominant peak in larger (visual-class) meteoroids in the region 235°.1–235°.2 in 1996. This peak is of relatively short duration judging from the visual and Ondřejov observations, having a HWHM of about 2 h. From the larger visual data set, the most probable time for the peak is 235°.17±0°.07. The Ondřejov data stop near the time of the second, weaker peak in the visual data, though this is precisely when the CLOVAR data shows its peak flux (235°.3).

The actual magnitude of the Leonid flux from visual, radar and TV observations, in the same intervals, is not mutually consistent within the formal error margins when allowances are made for the differing limiting sensitivities. The visual flux peaks before the onset of LLTV observations or the CLOVAR observations. However, the CLOVAR flux determinations are a minimum of five times higher than the flux measurements based on the visual data recorded in the same interval. The 1.2-mag difference between the limiting sensitivities for the two systems provides (at most) a factor of 2 change in flux, assuming that the s values found from the LLTV and visual observations at the time of the peak of the CLOVAR flux [$s = 1.5$ from visual observations, using $s = 1 + 2.5\ \log(r)$, and $s = 1.6$ from TV] hold down to the limiting sensitivity for CLOVAR.

One possibility is that the visually determined flux is biased toward brighter Leonids. Recall that the majority of visually detected meteors are recorded in magnitude categories of +4 and brighter. There are very few +5 and virtually no +6 magnitude

Leonids actually included in the visual sample. The correction to a final flux in the visual results is based on the assumption that the population-index remains constant to the reference magnitude limit of +6.5. In particular, the value for the flux is sensitive to the numbers of 'corrected' meteors in the final few counted categories (as is the case for any power-law distribution). This is because a large number of fainter Leonids will make the population index larger. If many of these fainter Leonids are missed, then r is artificially lowered as is the flux. Indeed, Langbroek (1996) comments on the large number of faint Leonids accompanying the early peak in the visual flux profile which was witnessed by European observers. While this may partially explain the discrepancies in the measured flux, it is improbable that such an effect alone can fully account for the factor of 4–5 difference in the radar/TV results recorded for the same time intervals.

An additional source of uncertainty lies with the CLOVAR radar measurements. Since the echo height ceiling at 40 MHz effectively excludes detection of meteors which ablate above 110 km, fainter Leonids will not be included. This limit is further reduced in practice for CLOVAR due to the effective PRF of 90 Hz, which limits detection of echoes that persist for less than approximately 0.01 s, corresponding to the underdense decay time expected for heights of 106 km and higher. According to Sarma & Jones (1985), the maximum brightness for TV meteors is reached at this height at Leonid speeds for meteors of absolute magnitude +7; hence some of the faintest Leonids are not detected. Only Leonids which can penetrate to such a depth and still have trails with an electron line density above the sensitivity limit have some chance of being detectable. This implies that the effective limiting magnitude for CLOVAR for Leonid meteors is somewhat less than the theoretical value of +7.7 found for other showers (cf. Brown et al. 1998). This will also change the value for the collecting area of the radar in a non-trivial manner. This effect, coupled with the poorly known correction for the echo height ceiling, implies that the quoted radar flux values are at best lower limits to the true flux values to a limiting magnitude somewhat greater than +7.7.

An additional complication is that the radio magnitude–visual magnitude–TV magnitude scale is poorly calibrated, particularly at fainter magnitudes. Cook et al. (1973) found that the error between the TV and radar magnitudes typically amounted to 2–3 mag (and often more) and that the deviation between the two scales worsened with velocity (the radar magnitudes tending to be systematically lower than those of the TV system). Until these differing scales are calibrated relative to each other in a more precise sense (particularly at high velocities such as 72 km s^{-1} for the Leonids) it is difficult to place high weight on comparisons between flux values determined with differing techniques.

Another possible source of error lies in the acceptance criteria for the TV Leonid meteors. Since the camera field of view (FOV) was always close to the radiant during the period in which the flux was determined (typically about 10° away), we assume that meteors with great circle paths lying within 3° of the radiant may have included sporadics. For FOVs close to a radiant of finite size, the 'acceptance' angle for a meteor trail becomes larger. While this undoubtedly has produced some sporadic pollution of our Leonid TV flux estimate, it is not likely that this could lead to an increase of almost 10 times over the actual Leonid flux, assuming the visually determined flux is correct.

Accepting the fluxes as measured at face value for the moment, and noting the limiting magnitudes for the visual, TV and radar measurements (6.5, 5.0, and 7.7), we see that the TV flux value of 0.018 meteoroid km^{-2} h^{-1} suggests that the TV flux at the radar limiting magnitude (using $s = 1.7$) should be 0.1 meteoroid km^{-2} h^{-1}. This would suggest that the fraction of Leonids actually detected is approximately 13 per cent. For comparison, at this velocity and for CLOVAR's wavelength (7.4 m), using the data given in Jones (1983), we expect that approximately 2 per cent of Leonids would be detectable, an effect entirely due to the echo-height ceiling. Other approaches to this problem (see e.g. Brown et al. 1997) suggest that this value should be higher, perhaps as much as 10 per cent for CLOVAR. This disparity is probably a consequence of the poorly known correction for the height ceiling at high velocities coupled with the poor intercalibration between the TV and radar magnitude systems. Radar observations of the Leonids by two identical systems operating at two widely spaced frequencies would significantly reduce this uncertainty.

Based on all observations, in 1996 the Leonid shower exhibited two principle morphologies: a short-lived, intense component which was enriched in smaller meteoroids near 235°.17, and a broader component of activity with a higher proportion of large meteoroids which peaked near 235°.4.

The high fluxes associated with the early outburst peak, combined with its short duration and increase in numbers of fainter meteors compared with the broader component, are consistent with the interpretation of the peak being composed of very young material (only a few revolutions old) and potentially associated with the storm-producing segment of the stream (the ortho-Leonids).

A similar short-duration peak was deduced from visual observations in 1995, but with far less confidence (Brown 1996). It is still not clear whether this was a genuine feature of the stream in 1995 or simply an artefact of poor observer coverage. The peak location for the possible outburst in 1995 was four hours earlier than in 1996, though the two just barely agree within the (large) errors for the location in 1995.

The position of the early peak in 1996 is almost precisely the same as the locations of the 1966 storm and an enhancement recorded by radar in 1965 (Brown et al. 1997). This might imply that the material we are currently encountering has suffered few planetary perturbations in the intervening years and thus has not significantly changed its nodal longitude. Kazimirčak-Polonskaja et al. (1968) and Guth (1968) were among the first to point out explicitly that the mean secular advance of the nodes of the stream (amounting to some 29 arc min per revolution) is actually achieved through a number of punctuated advances associated with perturbations from Jupiter, Saturn and Uranus. Thus the actual rate of change for any one Leonid meteoroid from one revolution to the next may be anywhere from nearly zero to several times the average rate. According to Kazimirčak-Polonskaja et al. (1968), the portions of the stream likely to be nearest to the Earth in 1999 show little change in nodal longitude between 1950 and 2000. In particular this section of the stream maintains similar nodal longitudes from 1966–2000. If this is in fact the case, then the activity we have first seen in 1996 presages the probable location of the shower peaks over the years 1997–2001. Similar results were also found by Brown & Jones (1996) on the basis of numerical modelling of the stream; they suggested that shower peaks during the current Leonid epoch would most probably be near 235°.16. Further detailed modelling needs to be carried out in light of the recovery of the parent comet, and a key observation during the 1997 Leonid return will be the presence or absence of a strong component of the shower, richer in faint meteors near these solar longitudes.

The broader activity, which peaks later, near the time of the normal maximum, is composed of larger meteoroids than either the outburst peak or the normal annual shower. The total duration of this section of the stream is 1.2±0.4 d – this is the FWHM of the stream. McIntosh (1973) noted that such a wide sheet of material has a nodal spread many times the size of the mean nodal perturbations on the stream as a whole over several revolutions, and hence must have suffered planetary perturbations over a much longer time period (at least several centuries). On this basis, we suggest that the low values for r and the long duration of this portion of the shower are indicative of meteoroids of the order of 10 revolutions old.

6 CONCLUSIONS

The 1996 Leonid shower produced an outburst in activity at $235\overset{\circ}{.}17\pm0\overset{\circ}{.}07$ with a peak visual ZHR of 86±22 and associated r value of 1.9 ($s = 1.65$). This translates into a peak flux of $1.2\pm0.4\times 10^{-2}$ meteoroid km^{-2} h^{-1} to a limiting absolute magnitude brighter than 6.5 (mass $\sim10^{-8}$ kg). Visual observations provide the primary quantitative details of the peak, with the corrected radar observations from Ondřejov supporting the basic outburst shape and location. LLTV observations over the interval from $235\overset{\circ}{.}3$–$235\overset{\circ}{.}39$ yield a flux of $1.8 \pm 0.4 \times 10^{-2}$ meteoroid km^{-2} h^{-1} to a limiting absolute TV magnitude of 5±0.5. As some sporadic contamination may have been present this should be taken as an upper limit, although we do not believe it is too high by more than a factor of 2. The CLOVAR radar flux peaks at $235\overset{\circ}{.}3$ at a value of $1.3\pm0.3\times10^{-2}$ meteoroid km^{-2} h^{-1} to a limiting radio magnitude of +7.7. Extrapolation from the TV results suggests that only 12 per cent of Leonids were detected at CLOVAR's operating frequency. From TV observations covering the interval $235\overset{\circ}{.}13$–$235\overset{\circ}{.}45$ an average mass index of $s = 1.64 \pm 0.17$ was found. In the same interval, the visual observations suggest $s = 1.5 \pm 0.06$ at somewhat brighter magnitudes, which is consistent with the TV mass indices being upper limits and with s being constant across the magnitude range +5–+6.5.

The TV and CLOVAR radar fluxes are inconsistent with, and higher than, the visual fluxes between $235\overset{\circ}{.}3$ and $235\overset{\circ}{.}3$. Differences in the fluxes measured in this interval with the different methods might be interpreted as being due to visual observers missing a continued increase in the outburst activity from the shower of fainter meteors from $235\overset{\circ}{.}3$ onward. It is also possible that some of these disparities result from the imprecise conversions between the radio, TV and visual magnitude systems as well as uncertainties associated with the radar observations of small, fast Leonids. The large differences in absolute flux measured with the three methods strongly suggest that great care in interpretation should be taken when flux measurements are made with only one method alone.

The sharp outburst activity associated with the shower has a HWHM of $0\overset{\circ}{.}07\pm0\overset{\circ}{.}02$. It shows a particle make-up which is richer in faint meteors than surrounding intervals based on visual observations. In addition to this feature, a broad plateau of visual activity was observed lasting 2 d with an indistinct peak at $235\overset{\circ}{.}4\pm0\overset{\circ}{.}1$ of ZHR magnitude 45±4 and flux 3×10^{-3} meteoroid km^{-2} h^{-1} brighter than absolute visual magnitude +6.5. The minimum in the population index also occurs at the peak of this broader activity.

The broad peak in activity is associated with older material (of the order of 10 revolutions), while the outburst peak likely represents fresh ejecta only a few revolutions old. The former activity component may also be associated with the storm-producing segment of the stream and presages the location of the storms in the years to come. Close scrutiny of Leonid activity near this location in 1997 (1997 November 17 11 UT) will help clarify its nature.

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REFERENCES

Brown P., 1994, WGN, 22, 190
Brown P., 1996, WGN, 24, 139
Brown P., Jones J., 1996, in Gustafson B. Å. S., Hanner M. S., eds, Physics, Chemistry and Dynamics of Interplanetary Dust. Astron. Soc. Pac., San Francisco, p. 105
Brown P., Rendtel J., 1996, Icarus, 124, 414
Brown P., Šimek M., Jones J., 1997, A&A, 322, 687
Brown P., Hocking W. K., Jones J., Rendtel J., 1998, MNRAS, 295, 847
Cook A. F., Forti G. F., McCrosky R. E., Posen A., Southworth R. B., Williams J. T., 1973, in Hemenway C. L., Millman P. M., Cook A. F., eds, Evolutionary and Physical Properties of Meteoroids, NASA SP-319. NASA, Washington DC, p. 23
Duffy A. G., Hawkes R. L., Jones J., 1987, MNRAS, 228, 55
Flemming D. E. B., Hawkes R. L., Jones J., 1993, in Stohl J., Williams I. P., eds, Meteoroids and their Parent Bodies. Astron. Inst. Slovak Acad. Sci., Bratislava, Slovakia, p. 261
Guth V., 1968, in Kresák L., Millman P. M., eds, Physics and Dynamics of Meteors. Reidel, Dordrecht, p. 476
Hainaut O. R., Meech K. J., Bauer J., West, R. M., 1997, Meteorit. Planet. Sci., 32, A53
Hajduk A., 1965, Bull. Astron. Inst. Czech., 16, 135
Hocking W. K., 1997, J. Geophys. Res. D, 102, 687
Hocking W. K., Thayaparan T., 1997, J. Geophys. Res. D, 102, 833
Jones J., 1983, MNRAS, 204, 765
Jones J., Morton J. D., 1982, MNRAS, 200, 281
Jones J., Šimek M., 1995, Earth, Moon, Planets, 68, 329
Kaiser T. R., Closs R. L., 1952, Phil. Mag., 43, 1
Kazimirčak-Polonskaja E. I., Belijaev N. A., Astapovic I. S. Terenteva A. K., 1968, in Kresák L., Millman P. M., eds, Physics and Dynamics of Meteors. Reidel, Dordrecht, p. 449
Koschack R., Arlt R., Rendtel, J., 1993, WGN, 21, 152
Langbroek M., 1996, WGN, 24, 207
McKinley D. W. R., 1961, Meteor Science and Engineering. McGraw-Hill, New York
McIntosh B. A., 1973, in Hemenway C. L., Millman P. M., Cook A. F., eds, Evolutionary and Physical Properties of Meteoroids NASA SP-319. NASA, Washington DC, p. 193
Plavcová Z., Šimek M., 1960, Bull. Astron. Inst. Czech., 11, 228
Rendtel J., Arlt R., McBeath A., 1995, Handbook for Visual Meteor Observers. IMO, Potsdam
Sarma T., Jones J., 1985, Bull. Astron. Inst. Czech., 36, 9
Šimek M., 1965, Bull. Astron. Inst. Czech., 16, 142
Šimek M., 1987, Bull. Astron. Inst. Czech., 38, 80

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