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The Leonid Meteor Shower: Historical Visual Observations

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The original visual accounts of the Leonids from 1799 to 1997 are examined and the times and magnitude of peak activity are established for 32 Leonid returns during this two-century interval. Previous secondary accounts of many of these returns are shown to differ from the information contained in the original accounts due to misinterpretations, typographical errors, and unsupported assumptions. The strongest Leonid storms are shown to follow a Gaussian activity profile and to occur after the perihelion passage and nodal longitude of 55P/Tempel–Tuttle. The relationship between the Gaussian width of the strongest returns and their peak activity is established, and the particle density/stream width relationship is found to compare favorably to that expected based on observations of IRAS cometary dust trails. Variations in the width of the 1966 storm as a function of meteoroid mass are shown to be consistent with that expected from classical gas-drag meteoroid ejection treatments. The five largest storms from 1799 to 1966 are found to peak at solar longitudes systematically larger than 55P/Tempel–Tuttle's nodal longitude at the same epochs, suggesting an asymmetry in the dust ejection perpendicular to the cometary orbital plane. The dust-distribution about 55P/Tempel–Tuttle is reevaluated with these new data and predictions are made for the 1999–2000 showers. © 1999 Academic Press

Key Words: **meteors; Leonids; visual observations.**

1. INTRODUCTION

Meteor Science in its modern form was born on the morning of November 13, 1833. It was the great Leonid return of that year which provoked widespread interest in the subject after being observed extensively in North America (Olmsted 1834). Due to its unique nature of producing strong showers every 33 years, the Leonid shower is probably the most extensively written-about meteor stream. This observational data base permits useful constraints to be placed on modern theories of the stream's evolution. Detailed histories of the shower can be found in Yeomans (1991), Mason (1995), Dick (1998), Burke (1986), and Littman (1998).

With the recent passage of Tempel–Tuttle through perihelion, activity from the shower is again on the rise as is interest in the stream in general. Our motivation is to reexamine as many original accounts of the shower which contain usable numerical information as possible and to determine the characteristics of past showers, independent of the many secondary accounts which appear in the literature, in an effort to better understand the stream's past activity, its formation, and as a way to predict what may happen in the years from 1999 onwards. In addition, this revised set of historical Leonid data provides a set of observations reduced in a common manner, which any model of the stream must be able to explain and to which others can easily examine and apply their own corrections.

In this work, we examine in detail available original records of the Leonids for modern returns of the shower (here defined to be post-1799). In doing so, we attempt to establish the characteristics near the peak activity of the stream borne out by the original records for years near the passage of 55P/Tempel–Tuttle. We utilize firsthand and original records of the shower for each year to construct activity curves for the shower. Using these data we then estimate the solar longitudes for each return for which significant activity occurred and the approximate time of peak activity. The method of reduction of these visual data and the methodology of their interpretation is given in Section 2. In Section 3 we present the results of application of these reduction techniques to available original visual observations of the shower from 1799 to 1997, along with discussions of the limitations and biases inherent in the reduced activity profiles for each Leonid return examined. Section 4 presents some discussion of the results in the context of the dust distribution about 55P/Tempel–Tuttle and implications for the Leonid shower in general based on the reinterpretation of these observations. A summary of the primary conclusions from this work is given in Section 5.

2. OBSERVATIONS OF THE LEONIDS

In what follows we present a detailed, though by no means complete, examination of the original accounts associated with the Leonids between 1799 and 1997. The original sources which were consulted to form the activity profile for each year are given in the figure captions. A brief discussion of each year's activity profile is given and mention made of previous errors found in secondary sources. Years which are not discussed are specifically omitted due to a lack of access to the original observational material.

Leonid activity reported in historical literature is based on visual observations of the shower. From the hundreds of

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original accounts examined it became obvious that any attempt to produce a precisely corrected activity curve of similar quality to those produced from modern amateur meteor observations would be entirely impossible and quite misleading. In an effort to quantify what hard data does exist in historical accounts, we performed only three main corrections to the raw reported numbers: a correction for the elevation of the radiant, a correction for the total effective observing time and (where needed) a correction for the number of observers reporting as a group. The aim of such a minimalist approach to the corrections is to provide a lower limit to the estimate of the zenithal hourly rate (ZHR) of the shower, as well as reducing the propensity for subjective interpretation of the historical shower record. In rare cases where it is explicitly stated, the fraction of the sky covered by clouds during observations is also included.

The ZHR is the number of meteors from the shower an average observer would see in one hour of net observing under unobstructed skies with the radiant overhead and the faintest visible star in the field of view equal to +6.5. Quantitatively, the ZHR is calculated as

$$\mathrm{ZHR} = \frac{C N r^{6.5-lm}}{\sin(\theta) T}, \tag{1}$$

where C is a correction for the perception of the observer relative to an average observer (where $C = 1$ for an average observer), N is the number of shower meteors recorded in T hours of observation, lm is the limiting stellar magnitude, and θ is the elevation of the shower radiant. The quantity r is the ratio of the number of meteors in magnitude category M to those in category M-1 and is called the population index. Detailed discussions of the ZHR and its derivation are given in Brown and Rendtel (1996) and Jenniskens (1994). The ZHR is not a direct measure of the flux from a shower. However, in those cases where the population index changes very little over the activity period of a shower, the variations in ZHR are a good measure of the relative changes in the flux to the effective limit of visual meteor observations (magnitude $\sim +3$ to $+4$).

None of the historical accounts provide quantitative estimates of the darkness of the sky (LM or limiting magnitude) and very few provide any distinction between sporadic and shower meteors. We are interested in determining the time of peak activity, an estimate of the ZHR at the peak, and some indication of intervals where no obvious observations have been made (and hence a storm might have gone unnoticed). As well, less precise information, such as the duration of the shower noticeably above the sporadic background and (for storms) the width of the storm producing segment of the stream are useful.

To this end we completely ignore the correction for sky brightness, noting that this is a sensitive function of r and that modern observations almost always produce sky brightness corrections greater than one; i.e., the LM is rarely better than 6.5 for most observations. Making this approximation will generally result in an estimate of the ZHR which is a lower bound to the true ZHR. In particular, in conditions where large numbers of shower meteors are present, we expect that our estimate for the activity will be a true lower limit, in part due to the omission of the sky brightness correction term and in part due to saturation effects (cf. Koschack *et al*. 1993). The presence of the moon will also further decrease the visibility of the shower and this is noted qualitatively in the description for each activity profile and developed more in the Discussion section.

For modest activity (ZHRs of ∼50–100), inclusion of sporadic meteors with the shower count offsets the effect of ignoring the sky brightness and a more realistic estimate of activity is made. At the bottom end of the activity, when the shower strength is comparable to or less than the sporadic background, inclusion of sporadic meteors clearly overestimates the actual shower activity. In these cases, the fact that the shower is swamped by the sporadic signal is obvious as the activity profile remains constant over many days, often showing the usual diurnal variation, particularly in cases where the majority of the observers are in a restricted longitude zone.

In addition to ignoring the sky brightness correction, we assume no significant perception corrections. From modern observations, observer perceptions may vary by as much as a factor of ∼3 but typically the deviations are smaller (cf. Koschack *et al*. 1993, Jenniskens 1994). Given no precise means to perform such corrections we leave $C = 1$ throughout.

As many older observations are reported as group observations, the correction factors reported by Millman and McKinley (1963) reducing group observations to that of a single observer are utilized.

By using either minimal or no assumptions in the corrections for historical observations (pre-1969) we are attempting to provide a picture of Leonid activity as unbiased as possible. Note that for more recent observations (1988 to present) detailed estimations of sky brightness by observers are available and these data are incorporated to produce a more accurate ZHR profile.

To further help in interpretation we divide the historical observations into three quality categories: poor, medium, and high quality. High-quality observations are single-observer reports with no cloud and with the radiant higher than 25° at the midpoint of the observation. For conditions where clouds are present but obscure less than 20% of the field of view, or radiant elevations between 25° and 20°, or for group observations the records are considered medium quality. If two of the foregoing conditions are met for one observation, or for observations with the radiant below 20°, or for group observations which sum all meteors (i.e., multiple count single meteor events) the quality is automatically given as poor. Observations made with extremely small sections of the sky visible (i.e., through windows) or with radiant elevations below 15° are generally rejected outright.

The end product of this process is activity curves which are necessarily noisy, but which contain the essential information to conclude what lower limits may be reasonably placed on reported activity from past Leonid returns. Peak ZHRs and their

TABLE I
Details of Leonid Showers from the 1799 Epoch to Present

Year	Time of Max (UT) (NOV)	$\lambda_{O\,max}$ (J2000.0)	Comet node-$\lambda_{O\,max}$	Peak ZHR	Activity width (σ) (degrees) $\times 10^{-2}$	Duration (hours)	Age of Moon (days)	Min Obs to Node (hours)
1799	12.35	232.8	0.23	—	—	~4	15	−2
1831	13.25?	232.5	0.67	~60?	—	—	8	>−11
1832	13.2	233.2	−0.03	2000	—	days?	20	0
1833	13.4	233.15	−0.02	60000	—	~5	1	0
1834	13.25?	232.7	0.47	~60?	—	~7	12	−5
1835	14.8?	234.0	−0.83	~100?	—	—	23	+20
1836	13.3?	233.3	−0.13	100−150	—	—	5	+2
1865	13.25?	232.8	0.49	~150	—	—	25	−6
1866	14.05	233.34	−0.05	$8 \pm 2 \times 10^3$	1.7 ± 0.2	4	5	0
1867	14.40	233.423	−0.13	$>12 \pm 3 \times 10^2$	2.2 ± 0.2	>5	17	+1.5
1868	14.40	234.2	−0.91	$4 \pm 2 \times 10^2$	—	>7	0	+18
1898	15.2	234.3	0.33	50−100	—	~day?	0	−1
1899	15.2	234.0	0.63	20−50	—-	~12?	12	+5
1901	15.5	233.828	0.80	250	9.5 ± 0.1	>7	3	0
1903	16.25	234.05	0.58	>200	7.0 ± 0.2	~7	26	−10
1930	17.4	235.3	−0.22	100−140	—	>4?	26	+5
1931	17.35	235.0	0.08	~150	—	~8	7	0
1932	16.25	234.6	0.48	>70	—	>12	18	0
1933	16.4?	234.5	0.58	~50	—	~day	0	−1
1934	17.33	235.2	−0.12	50–60	—	~day	10	+2
1961	—	—	—	~70	—	—	10	—
1963	17.4	234.8	0.33	30	—	>5?	1	+2
1964	17.4	235.6	−0.47	~50	—	24	12	−3
1965	16.6	234.55	0.58	>120	—	2 days	23	+1
1966	17.5	235.16	−0.03	$8\text{-}10 \times 10^4$	1.1 ± 0.1	12	5	0
1967	17.5	234.9	0.23	40	—	—	15	0
1968	17.5	235.65	−0.52	~110	—	3	26	+7
1969	17.4	235.28	−0.15	300	2.0 ± 0.3	3	8	0
1994	18.3	235.8	−0.54	~100	—	14	15	0
1995	18.3	235.5	−0.24	35	—	7	25	0
1996	17.2	235.17	0.09	90	—	2	8	0
1997	17.51	235.22	0.06	100	—	3	19	0
1998[a]	17.05	234.5	0.78	250	—	20	28	0
1999[b]	18.08	235.28						
2000[b]	17.34	235.28						

Note. The actual maximum is based on the best available accounts from those years and cannot be considered wholly authoritative; the real maxima may be several hours on either side of this time, particularly in cases where the closest observation to the nodal point (Min Obs to Node) is large. The Moon refers to the age of the Moon from the new phase. Values with ? after them are particularly uncertain.

[a] Data are preliminary from the International Meteor Organization. Note that the peak ZHR in 1998 was not at the same location as the peak flux of the shower due to the presence of a dominant population of large meteoroids. The peak flux occurred near the nodal crossing of 55P/Tempel–Tuttle, though visually the shower was most spectacular some 18 hr before the nodal crossing.

[b] Times of maxima are for the nodal crossing of 55P/Tempel–Tuttle. A storm, if it occurs in either of 1999 or 2000, is likely at this time or 1–2 hr thereafter based on the historic record. Note that these times differ slightly from the author's previous times of maximum estimates (cf. Brown and Jones 1993) as the latter are independently derived from an early numerical model of the stream.

locations (in terms of solar longitude - J2000.0 is used throughout) are given in Table I.

3. MODERN

Starting with the 1799 epoch, there are fairly detailed records which allow assessment of the characteristics of individual storms. The observing circumstances, comet–Earth geometry and details of the returns during each epoch from 1799 to 1997 are given in Table I. Where enough observations of sufficient quality are available we have attempted to construct an activity profile for the stream based on these observations; elsewhere, only estimates of the peak time and associated rate are given with appropriate references to the original material.

4. RESULTS

4.1. *The 1799 Epoch*

Our most comprehensive accounts for this time period come from the Journal of Alexander von Humboldt (1852) and the

Journal of Andrew Ellicott (1804). Both are original eyewitness accounts of the spectacular 1799 Leonid meteor storm as seen from South America and the Gulf of Mexico, respectively. Both accounts suggest that significant activity began near 12.3 Nov UT 1799 despite the fact that the nearly full moon was overhead. This is corroborated by reports from England, where observations of the display are reported for the last 2–3 hours before dawn (12.2–12.3 Nov UT 1799) (Monthly Magazine 1799), and Germany (Humboldt 1852), but evidently not witnessed earlier in the evening to a significant degree. Similarly, Humboldt and others he interviewed in settlements over northern South America in subsequent months suggested that the shower was in decline well before sunrise. This suggests an end near 12.4–12.5 Nov UT 1799. There are no accounts from Asia of the 1799 display, which also supports the notion that the display may have ended before 12.6 UT Nov 1799. The magnitude of the activity has been quoted by various authors as lying near 30,000/hr (Kazimirchak-Polonaskaya *et al*. 1968, Yeomans 1981), but the means by which the estimate was made are not given. There is little doubt that this was a truly spectacular display which contained many bright meteors; otherwise it would have been severely denuded by the presence of the full Moon, but the precise ZHR value is uncertain. The peak appears to have occurred in the interval 12.3–12.4 Nov 1799 (solar longitude of 232.8°).

Accounts of showers witnessed in China often linked with the Leonids in 1798 and 1800 are given by Tian-Shan (1977). Unfortunately, the date of peak listed for the shower in 1798 is inconsistent with an origin linked to the Leonids, while no specific date in November is given for the 1800 shower. Errors in the translation of the original document or in properly converting the date to a modern format may be the cause.

4.2. *The 1833 Epoch*

The 1833 return has been described in detail by Olmsted (1834) and Twining (1834), where reports from throughout the eastern and southern United States were collected together with reports from ships at sea. It is clear from the numerous accounts provided by Olmsted that the 1833 shower was quite broad, lasting for at least four and perhaps six hours. The time of maximum is stated by several independent observers to have occurred at approximately 13.4 Nov 1833. This time corresponds to more than an hour before Astronomical twilight began over most observing locales in the eastern United States and fully two hours before the onset of civil twilight. Considering that the radiant was still climbing in altitude at this time, it seems likely that this represents the true time of maximum. The only precise numerical value for the 1833 display given by Olmsted (1834) refers to one observer from Boston who observed near 13.45 UT Nov 1833 and recorded 650 meteors in 15 min in heavy twilight. The observer further reports that his field of view was confined to less than 10% of the full horizon and that he missed at least 1/3 of the meteors. This yields an interpretation of the ZHR as >38,000 centered about this interval; the maximum rate slightly earlier must have been several times this number under darker skies. Olmsted also notes that this value probably underrepresented the true maximum strength of the storm. Henry (1833) observed the shower from Princeton, New Jersey close to sunrise and noted that "When first seen by me they were so numerous that 20 might be counted almost at the same instant descending towards the horizon in vertical circles of every azimuth or point of the compass were visible in any one instant." While the exact meaning of "an instant" is not clear, it seems probable that this reflects a meteor rate close to 20 per second. He also notes that a student outside at 9.5 local (13.4 UT) recorded 1500 meteors "...in the space of a few minutes...." Taken at face value, and assuming a minimum of 2 minutes for the observation, this implies a maximum rate of $\sim$750/min or $\sim$13/sec in general accord with Henry's own observation. These observations (probably the best numerically available for the peak of the 1833 display) imply peak ZHRs in the range of 50,000–70,000. This is also consistent with interpretation of the observation reported by Olmsted (1834) from Boston almost an hour later of 38,000 as a lower limit to the peak activity.

The storm in 1833 was also seen much further West as demonstrated by the fact that at least six different tribes of Western and Plains Native Americans recorded the display (Mallery 1886). The eyewitness accounts mention instances of meteors being observed after sunrise and recount in detail the large number of bright fireballs accompanying the display (Olmsted 1834, Twining 1834). The first vestiges of the shower were recorded reliably near 13.3 Nov 1833, while the display continued into daylight over the eastern United States until at least 13.5 Nov 1833. The best estimate of maximum is 13.4 UT Nov 1833 with a peak rate of 60,000.

Other sources quote 50,000–150,000/h for the peak (Kazimirchak-Polonaskaya *et al*. 1968, Yeomans 1981, Kresak 1980) but the basis for these values is not discussed in these works.

In addition to the major storm of 1833, the two years preceding November 1833 also showed unusual Leonid activity. Activity of order a Leonid/minute was reported from Spain (Olmsted 1836b) and France (Quetelet 1839), between 13.2 and 13.3 Nov 1831 as well as the eastern United States (Olmsted 1835) on the morning of November 13, 1831.

The storm produced in 1832 lasted many hours on the night of November 12/13, 1832 from at least Nov 12.8–Nov 13.3 and was chronicled in South America (Olmsted 1837a), the Middle East (Rada and Stephenson 1992, Hasegawa 1997), Western Europe (Olmsted 1834) and eastern Europe/Russia as far as 60°E (Sviatsky 1930, Quetelet 1839), as well as North America (Arago 1857). This return is variously mentioned as rich in fireballs and may have been quite intense taking into account the Moon's position near the radiant on November 13, 1832. No Oriental records of this storm were made. Several of the accounts mention that unusual numbers of meteors were visible the night before (12 Nov 1832), suggesting a very broad activity maximum of bright meteors. Gautier (1832) reports average hourly rates near 2000 from Switzerland at approximately 13.2 UT November, 1832, the only numerical data available for the 1832 storm.

The years following 1833 also showed modest shower activity. The 1834 display was partially hampered by a waxing gibbous Moon. From many accounts collected throughout the eastern and midwestern United States (Bache 1835a,b) by casual observers, only weak activity was reported, while more experienced observers noted peak rates under dark skies in the early morning hours of approximately one Leonid/minute in the interval November 13.1–13.4, 1834 (Twining 1835, Olmsted 1835). Poor lunar conditions in 1835 hampered observations, but some observers in the eastern United States reported rates of more than 1 Leonid/minute near 14.8 Nov 1835 (Olmsted 1836b). The 1836 display was also active with ZHRs of 100–150 from the eastern United States near 13.3 Nov 1836 (Olmsted 1837a), and European rates nearer 50 at 13.2 (Quetelet 1839), while 1837 was hampered by moonlight with significantly lower rates reported (Olmsted 1837b). It seems possible that some of the higher rates reported in the years after 1833 were due, in part, to heightened interest.

4.3. *The 1866 Epoch*

The 1866 epoch was characterized by three strong Leonid returns, with storms occurring in at least 1866 and 1867. There are sufficient observations available from 1865 to permit reconstruction of a partial activity curve and this is shown in Fig. 1. Although 25 days old in 1865, the Moon was a significant source of disturbing light in the early morning hours. The observations

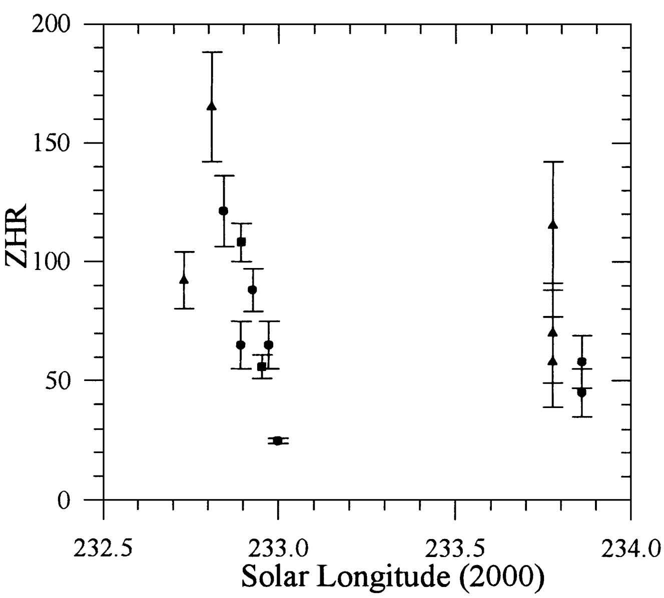

FIG. 1. ZHR profile for the 1865 Leonid return. Data are from Newton (1866), Wheeler (1866), and Glaisher (1865). Data quality for each point (as defined in Section 3.0) are shown by solid circle (high quality), solid square (medium quality), and solid triangle (poor quality) and this is used for all subsequent figures.

indicate a modest return with a peak ZHR in the neighborhood of ∼100–150 for the time intervals covered. However, the interval containing the solar longitude at which the 1866 storm occurred (233.34°) (19 UT 1865) has no observations for six hours on either side of it and occurred over the West Pacific. It further lacks Oriental records of any activity. Hence the possibility that a stronger shower occurred and was missed is plausible as the available observations are from eastern North America and the United Kingdom only. Previous sources have also reported modest activity for the 1865 return based on second-hand accounts from the United Kingdom (Mason 1995, Kazimirchak-Polonaskaya *et. al*. 1968).

The 1866 return was extensively described by observers in England (cf. Herschel 1867). Figures 2a and 2b show the complete activity curve for the 1866 return. The peak in activity occurred at 233.337° when the ZHR reached a maximum of 8000 ± 2000 as computed from numerous 10-min counts centered about this time interval from the United Kingdom. Note that the radiant from the United Kingdom was roughly 20° in elevation and hence the correction factors are large. However, this possible overcorrection is somewhat balanced by the loss due to saturation effects as the visible rates were near a meteor per second from the United Kingdom. Sufficient observations exist near the maximum to perform a running average of the best observations; this is shown in Fig. 2c. The curve fit is Gaussian of the form

$$\mathrm{ZHR} = A\left(\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{[\lambda_O - \lambda_{O\,\max}]^2}{2\sigma^2}}\right), \tag{2}$$

where A is a normalization constant, σ is the half-width of the distribution, λ_0 is the solar longitude (independent variable), and $\lambda_{O\,\max}$ is the location of the maximum. The curve is computed by performing a nonlinear regression fit to the original smoothed data (shown as black dots). The result for 1866 is $\sigma = 0.017° \pm 0.002°$ and $\lambda_{O\,\max} = 233.337° \pm 0.007°$ (J2000). This implies that to the Gaussian half-width points, the 1866 storm was 25 min in duration and peaked at $01{:}12 \pm 0{:}10$ UT on 14 Nov 1866. These results are comparable to those given by Kazimirchak-Polonaskaya *et al*. (1968) (maximum of 5000–7000 at 01 : 22 UT 14 Nov 1866) and somewhat lower than those found by Jenniskens (1995) (maximum of $17{,}000 \pm 5000$ at 01 : 00 UT 14 Nov 1866). Yeomans (1981) lists a peak ZHR of ∼2000 based on data from Kazimirchak-Polonaskaya *et al*. 1968 and Olivier (1925), but neither specifically lists hourly rates of 2000, with Olivier listing an hourly rate of only 2800 for two people.

The 1867 shower was hampered by the nearly full Moon. Nevertheless, large numbers of observations from eastern North America were made of the storm. The ZHR profile for the 1867 Leonid storm is shown in Fig 3a. The raw observations show a considerable spread nearest the time of maximum, a likely product of the lunar interference. In Fig. 3b, the Gaussian fit to the activity is shown which yields a maximum time of

233.423° ± 0.002° with a ZHR of 1200 ± 300 and a half-width of the storm of 0.022° ± 0.002° or 32 min. Note that the ZHR here is a strong lower limit given the lunar interference. From modern observations, a correction of ∼4 in the ZHR is typical under these full-moon skies, so the true ZHR is most probably in the 4000–5000 range.

Jenniskens (1995) finds a very similar time of maximum at 233.713° (B1950) and a compatible (fully corrected) peak ZHR of 6000 ± 2000. Kazimirchak-Polonaskaya *et al.* (1968) list the peak hourly rate as 2184, based on values given in Olivier (1925), which were derived from a report given in Twining (1868) of observations made in Chicago during the peak of the storm

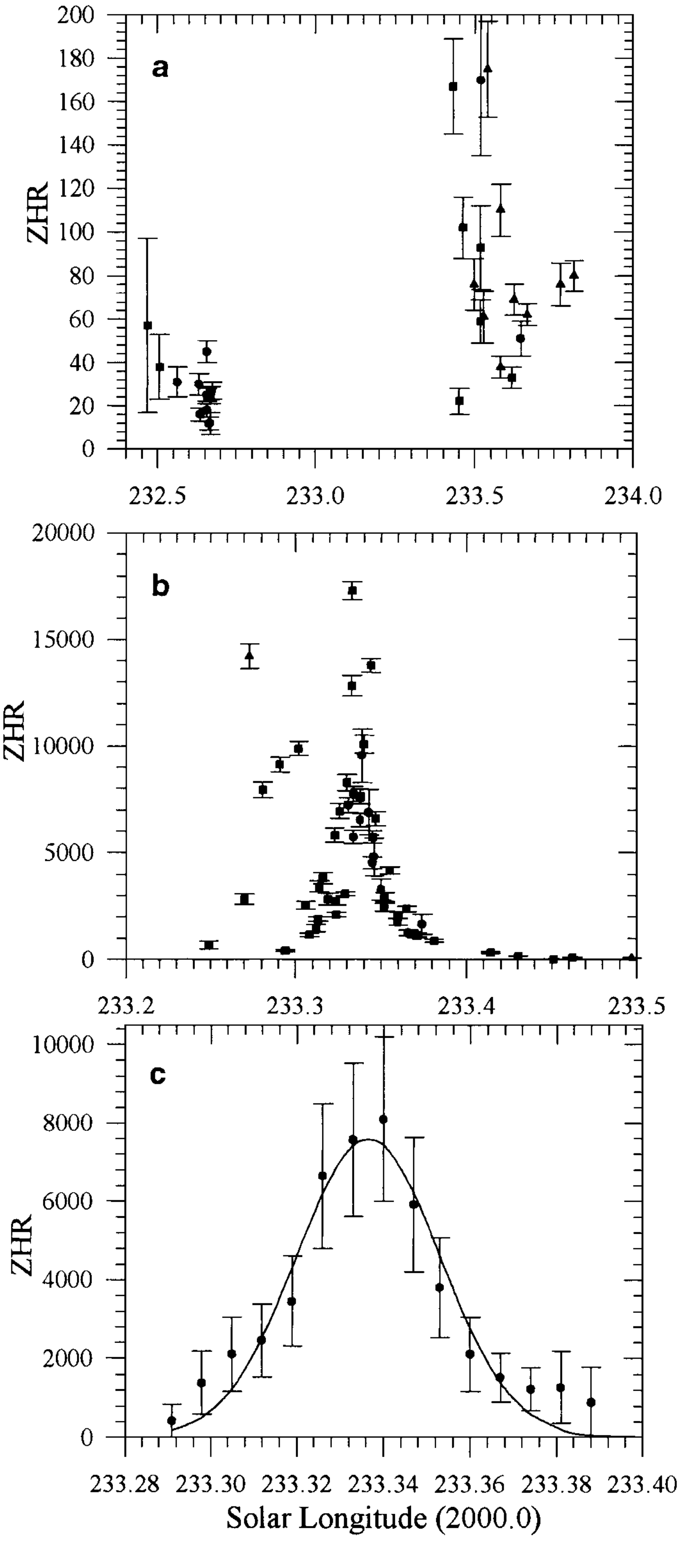

FIG. 2. ZHR profile for the 1866 Leonid return. Data are taken from accounts given in Malta (Galea 1994), Smyth (1867), Grant (1867), Main (1867), Newton (1867), De La Rue (1867), Dawes (1867), Hind (1867), and Cooke (1867). The top graph (a) shows the level of broader activity for a day on either side of the storm maximum (b) and (c) is a Gaussian fit (solid line) to the smoothed data in (b) using a smoothing window of 0.02° width shifted by 0.007° (10 min) in accordance with the shortest time counts.

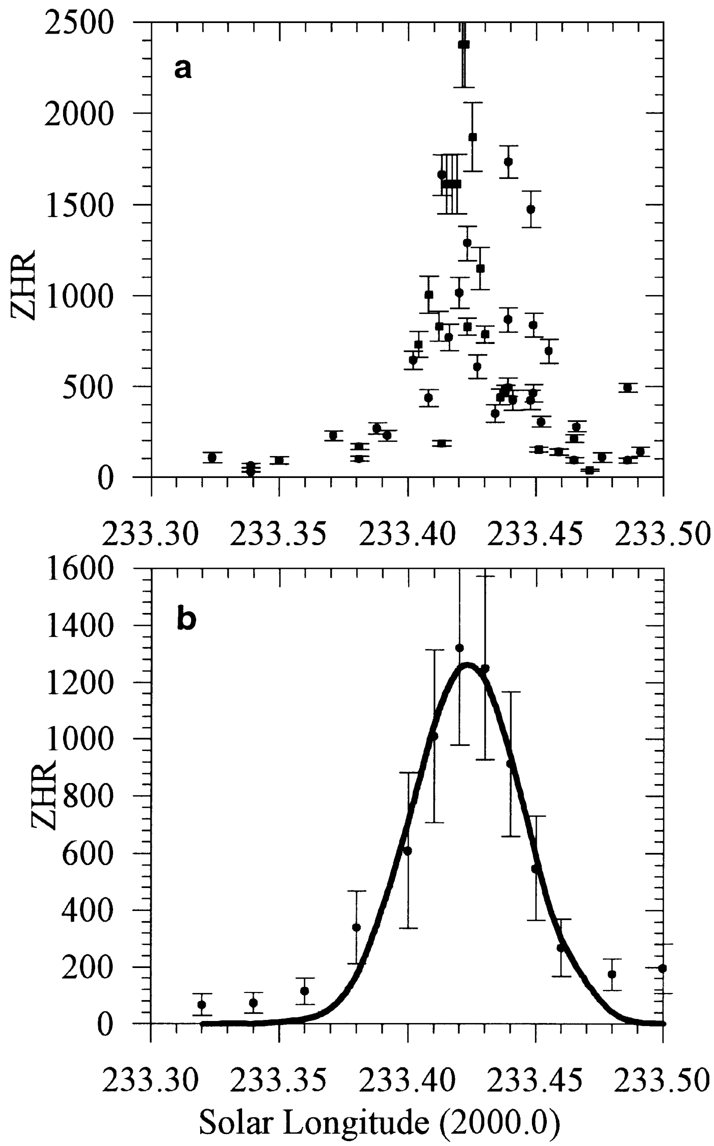

FIG. 3. ZHR profile for the 1867 Leonid return. Data are from *Annals of the Dudley Observatory* (1871), Twining (1868), Anon (1871), Leonard (1936), and Stuart (1868). (a) shows the activity for the 5-hr period centered about the storm maximum. (b) shows the Gaussian fit (solid line) to the smoothed data, which are binned in a window of 0.05° shifted by 0.02° before 233.38° and after 233.46° and by 0.02° shifted by 0.01° inside this interval.

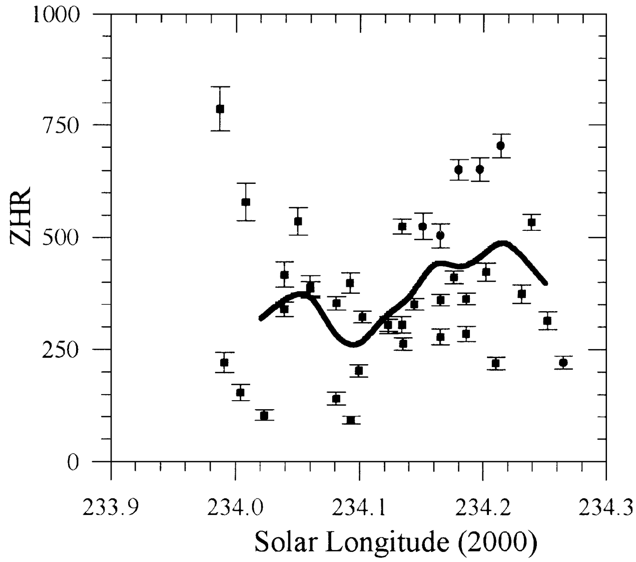

FIG. 4. ZHR profile for the 1868 Leonid shower. Data are derived from reports in Newton (1869) and Grant (1869). The solid line is a smoothed average of the available observations smoothed over a window of 0.05° shifted by 0.02° from 234° to 234.25°.

in 1867, where 1529 meteors were seen in 42 min. Olivier gives this number without further explanation and this value has subsequently been reported in other secondary sources (e.g., Roggemans 1989). However, the value refers to the number of meteors seen by 8–30 observers (Twining 1868), and is thus many times the single observer rate. Yeomans (1981) lists peak ZHRs as 5000 based on data given in Kresak (1980), where a peak time 10 hours earlier than listed here is given, but that source reports no reference as to how either the time or strength is found.

The 1868 return occurred under new Moon conditions and was widely reported from Europe and North America. Figure 4 shows the activity profile covering the night of November 13–14, 1868. This display is unusual in that no clear peak is evident and activity remains significant for many hours. The solid line in Fig. 4 shows the smoothed activity profile confirming little or no variation in the ZHR over a six-hour period. Though considerable spread exists in the observations, it is clear that a very strong shower occurred and lasted for many hours. If any short-lived storm occurred, however, it appears to have been missed; the location of the 1866 and 1867 storms would have taken place over the Pacific in 1868. The peak ZHR in 1868 is approximately 400 ± 200 near $234.2^\circ \pm 0.1^\circ$. Jenniskens (1995) finds a ZHR of 700 near 233.122° (B1950) but this is based on only two sets of observations, one from Maclear (1869) and one from Grant (1869). Maclear's observations were made under a dense haze from South Africa with a low radiant and are not used here. The hourly rates reported by Kazimirchak-Polonaskaya *et al.* (1968) of <1200, Lovell (1954) of 1000, and Yeomans (1981) of ~ 1000 are based on Olivier's (1925) report of Kirkwood observing 900 in 45 min in the early morning hours of November 14 from Indiana. In fact, Kirkwood's original report (Kirkwood 1869) states that the 900 meteors were seen by "...a committee of the senior class," clearly demonstrating that the 900 in 45 min was a group observation and that the single-observer ZHR number was much lower, consistent with the ZHR values presented here.

4.4. *The 1899 Epoch*

The 1898 return of the Leonids marked the first relatively strong return of the 1899 cycle. Part of the prominence of this display no doubt resulted from the heightened public interest in the shower due to the expected storm in 1899 and the lack of lunar interference. Figure 5 presents available observations. No clear maximum is visible and what few good observations exist suggest that activity over the period covered is of a ZHR 50–100 over 234.1°–234.6°. Note that the nodal longitude of 55P/Tempel–Tuttle in this period was 234.59° (Yeomans *et al.* 1996) and hence no strong activity occurred at or before this location in 1898 based on these data.

In 1899 lunar conditions were unfavourable but intensive watches by many groups worldwide yielded no definite indication of strong activity. Maximum activity occurred near 234° with a peak ZHR in the range 20–50, though the overall profile is quite flat (Fig. 6). Hasegawa (1993) quotes a translation from the Beijing observatory which lists an entry for November 14, 1899 at 17 UT (233.54°) suggesting a major shower/storm was witnessed. However, observations from India beginning only 3 hr later show little or no significant activity (Smith 1900). Given the nodal longitude of the comet in 1899 (234.59°) and the lack of available observations in the window from 234.25° to 234.8° it seems possible that the Beijing observation has been misinterpreted and might refer to the next day (Nov 15 17 UT—solar longitude 234.54°).

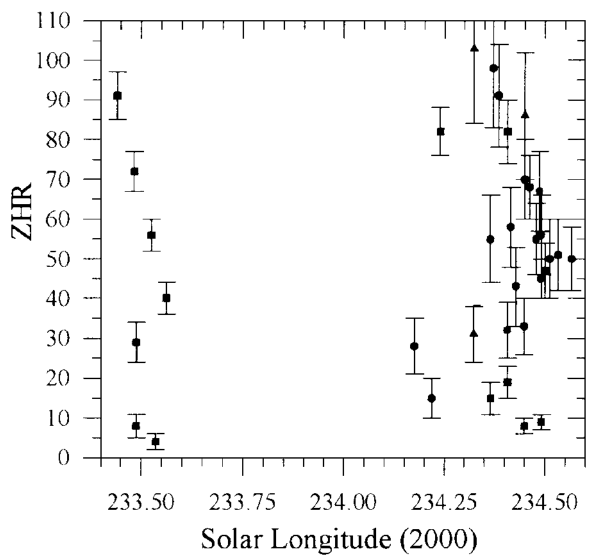

FIG. 5. ZHR profile for the 1898 Leonid shower. Data are taken from reports given in Wilson (1898), Elkin (1898), Keeler (1898), Weiss (1899), Weld (1899), Brackett (1899), Jenkins (1899), and Mills (1899).

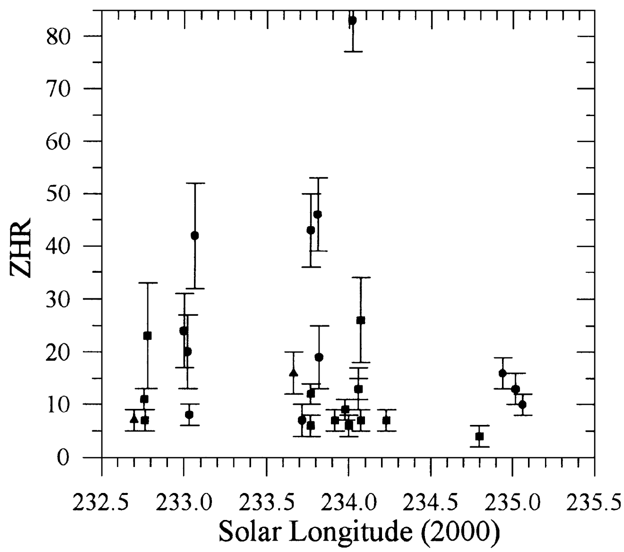

FIG. 6. ZHR profile for the 1899 Leonid shower. Data are from Denning (1899), Payne (1899), Turner (1900), Rambaut (1900), Smith (1900), Hinks (1900), Denning (1900), Moulton (1900), and Anon (1899).

Observations were sparse in 1900 due to less interest in the shower because of the disappointing 1899 return and strong interference from a last quarter Moon (cf. Besley 1900). One often-quoted report of storm-like conditions from Hudson Bay (Stupart 1901) is based on a single report from a meteorological observer. No other observations of any such large display in 1900 were made, despite the fact that observations under clear skies were carried out at the same time by observers further south in 1900 (cf. Rees 1901), leading to serious uncertainties in the veracity of the lone report.

The 1901 shower, however, was quite strong. Figure 7 shows the activity profile derived from European and North American observations of the shower in that year. A very clear, consistent rise in activity was reported by observers across western North America, culminating near dawn on the west coast when ZHRs approached 250. Accounting for sky conditions and saturation effects which certainly would have been significant at this level of activity, the peak ZHR in 1901 might well have approached 500 on the basis of these data. The solid line in Fig. 7 shows a Gaussian fit to the activity profile. Note that only the rise and (possibly) the peak were observed; the falling portion of the shower occurred unobserved over the Pacific. The location of the peak from available observations is $233.828^\circ \pm 0.014^\circ$ and the half-width of the Gaussian profile is $0.095^\circ \pm 0.01^\circ$. This implies that the full-width of the strong outburst in 1901 lasted 5–6 hr (only 3 hr of which were actually observed), but never achieved storm levels. Notations in the literature often cite the 1901 Leonid return as a "storm," though no observational evidence for this exists. Kazimirchak-Polonaskaya *et al*. (1968) list rates of 144,000 per hour in 1901 as seen in the United Kingdom, clearly a typographical error which has been further reproduced in Yeomans (1981) and Roggemans (1989). Kazimirchak-Polonaskaya *et al*. (1968) further note hourly rates of 800 from California in 1901, but this value is derived from observations in Claremont, California given second hand in Pickering (1902) and elsewhere, whereas the original report (Brackett 1902) lists 717 seen by 4 observers in the final hour of observation before twilight. The single-observer hourly rate is less than 1/3 of this number, consistent with our ZHR values of 250. Jenniskens (1995) lists the 1901 shower as a "storm" with a peak ZHR of 7000. There is no direct observational evidence for this and we further note that of the four observational sets used in his data, one has an improper time base, having been copied from Denning (1902), where the location for Echo Mountain observatory is mistakenly given as Virginia, when it is in fact in California. The value of 7000 is calculated assuming a power law fit to the data extrapolated to the ZHR value of 7000, whereas his individual measured values are no more than 500 as reported. His data are also not as complete as presented here and we suggest that the drop in rates occurring shortly after 233.84° is real. This suggestion is further supported by the reports in Taber (1902), which indicate that no unusual activity was seen in Hawaii, Guam, or by steamships in the Pacific on the night of maximum.

The Moon interfered with observations again in 1902 and this, coupled with very bad weather (cf. Herschel 1902) and lack of observer interest led to poor coverage as in 1900. No unusual activity was reported from the few clear locations where observations were made (Pickering 1903, Barnard 1903).

The next year, 1903, the Leonid shower returned in full force. The outburst witnessed that year peaked at or slightly after morning twilight from the United Kingdom on the morning of

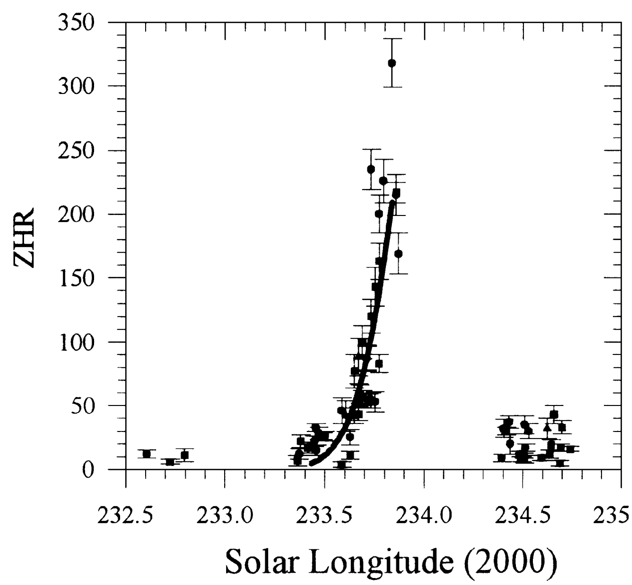

FIG. 7. ZHR profile for the 1901 Leonid shower. Data are from Payne (1901), King (1902), Upton (1902), Salloms (1902), Dole (1902), Brenke (1902), Leavenworth (1902), Brackett (1902), Denning (1902), and Besley (1902). The solid line represents the ascending portion of the Gaussian fit to the data.

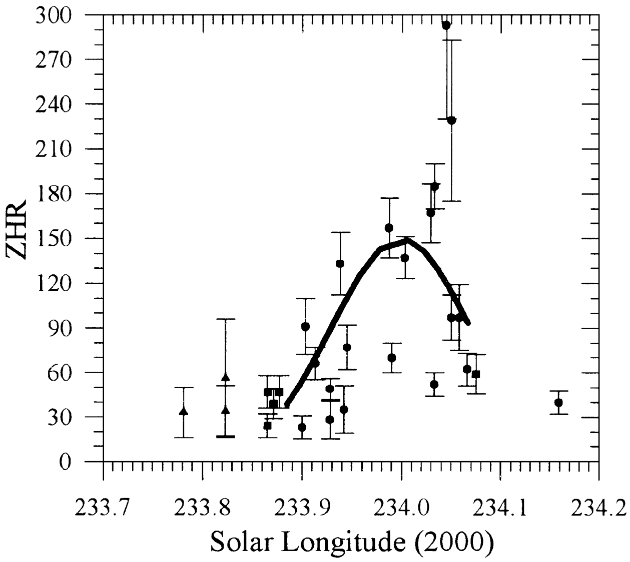

FIG. 8. ZHR profile for the 1903 Leonid shower. Data are taken from reports contained in Henry (1903), King (1903), Rolston (1903), Young (1904), Rodriques (1904), Denning (1903), (1904), and Besley (1904). The solid line represent the best fit Gaussian to the raw data.

November 16, where it was widely observed. Observations from North America several hours later show that the outburst had subsided and rates were at preoutburst levels. Nautical twilight in the United Kingdom began near 234.05° on 16 November, 1903 and this is precisely when rates appear to drop precipitously; clearly the shower ZHR was much higher than the 90–100 level calculated from the raw counts in this time period. However, the observations after 234.15° are from North America and represent only one observer (Olivier 1903). The half-maximum time for the ascending portion of the activity profile is approximately 2 hr, while the descending portion is indeterminate due to the heavy interference from twilight in the United Kingdom (Fig. 8). The maximum ZHR is 200–250 and given expected saturation effects and twilight conditions, this might well have been as high as 300–400. Jenniskens (1995) lists the maximum ZHR in 1903 as 1400 based solely on the observations from Denning (1904). His data are again extrapolated on the basis of an assumed power-law fit and no actual observational evidence for such high rates exists; to the contrary it appears very unlikely that ZHRs ever exceeded the level of 400 in 1903 and more probable that they were close to 200–300 at maximum.

4.5. *The 1933 Epoch*

Leonid activity waned after 1903. Clearly heightened activity next occurred in 1930. On November 17 of that year, observers across North America and the Caribbean reported Leonid rates close to 100/hr with only slight interference from a 26-day old Moon (Fig. 9). A preponderance of fireballs was noted by many observers was associated with this display (Olivier 1931a). Activity as seen from Europe only a few hours before the high rates reported over North America appears to have been normal according to Prentice (1930), although he does not provide usable rate data. The large scatter in observations nearest the time of peak activity at $\sim$235.3° $\pm$ 0.1° may be the result of an increasing proportion of observations occurring under light-polluted skies as compared to earlier epochs. While it is possible that there are large differences in perception among the reporting observers, the large number of observers included in the sample near the time of the peak (20) suggests this is an unlikely cause. Indeed, the highest rates in this interval are reported from strictly rural locations. The average ZHR at the peak is nearly 100, though the range in ZHRs is 20–140, with observations concentrated in "groups" at ZHR values of 130 and 50, possibly reflecting the urban–rural split in data.

The year 1931 produced another strong Leonid return. The Moon was not a factor in 1931, setting early in the evening at the first-quarter phase and thus providing a clear view of the shower from dark locations in the early morning hours of 17 November. The outburst in activity was observed from 234.9° to 235.2° (Fig. 10), though no observations are available from 235.2° to 235.7°, so it is quite possible activity persisted beyond this interval. The peak ZHR was similar to 1930, at 110 ± 50 based on the average of all counts over the outburst interval, where the counts show nearly constant levels of activity. Several reports in Olivier (1932a) suggest some observers noted as many as 3 Leonids/min near the maximum, so the value of 110 may be a lower limit, a truer value being closer to the upper limits of the given error margins near $\sim$150. Leonid rates on days before and after this maximum are near $\sim$20–30.

The next year, 1932, was widely anticipated as the most probable for the Leonids to produce a meteor storm during the 1933 cycle (Olivier 1929). The presence of the Moon only 4 days past

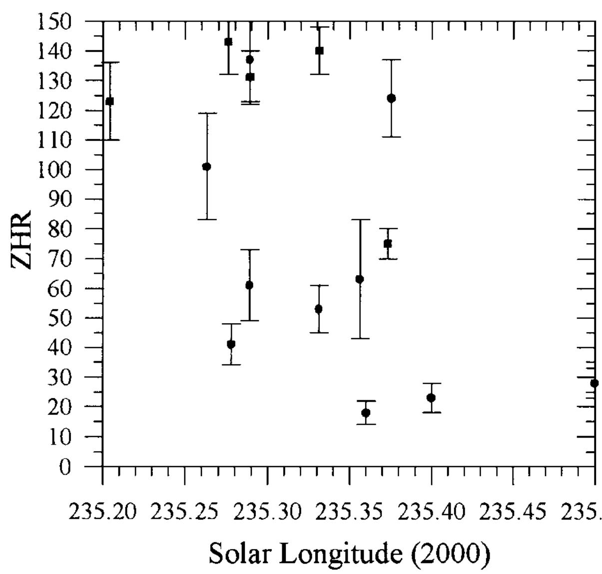

FIG. 9. ZHR profile for the 1930 Leonid shower. Data are from Olivier (1931a, 1931b), Wylie (1930), and Morgan (1930).

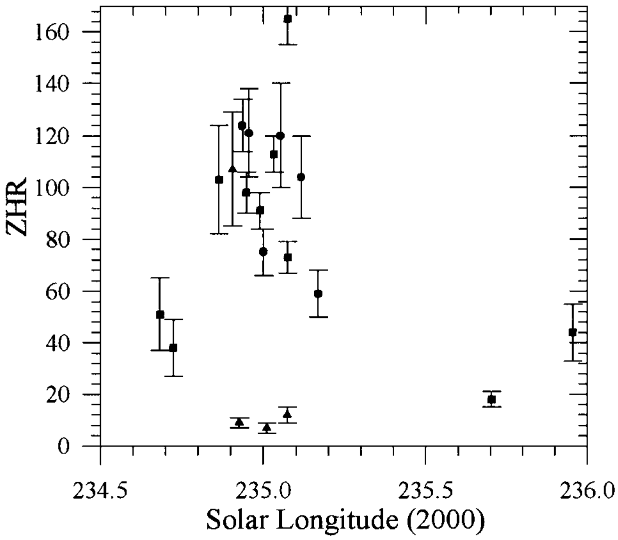

FIG. 10. ZHR profile for the 1931 Leonid shower. Data are from Olivier (1932), Nassau and McCuskey (1932), and King (1931).

full and less than 40° from the radiant, significantly denuded the display. Strong activity, however, was noted from Europe and North America on 16 November, 1932. The peak in activity occurred between 234.4° and 234.7° with an apparent ZHR of ∼70 falling to less than half this value on the day before and after the maximum (Fig. 11). The true ZHR is probably 3–4 times this value and given the typical corrections for lunar interference is suggestive of an actual peak ZHR in the range of 200–300 for 1932. Lovell (1954), Kazimirchak-Polonaskaya *et al.* (1968), and Yeomans (1981) list the 1932 return as having produced observed rates of 240/hr. This implies true ZHRs in the 500–1000 range when the effects of lunar interference are factored in and is the apparent reason 1932 is often listed as a "storm" or "near-storm" of the Leonids. This value is based on secondhand reports in Wylie (1933) of counts made in Dubuque, Iowa. The original report (Theobald 1933a) also notes that the peak rate observed was 240/hr. Further reading, however, shows this to be for six observers; the single observer raw rate was 50–70, comparable with the apparent ZHRs we have found. We note that within the 2.5-hr window centered about the nodal crossing of Tempel–Tuttle in 1932 (235.06°) only a single hour of observation (from New Zealand) is available at a relatively low radiant elevation. This does leave open the very real possibility that much higher activity took place in 1932 but was missed over the Pacific.

After the moderately strong display of Leonids under nearly full Moon conditions in 1932, much hope (and considerable observational effort) was placed on the 1933 Leonid return, which occurred with a new Moon. In general terms, however, this return was recorded as the weakest of the displays from 1931 to 1933, mimicking the disappointment of the nonappearance of the Leonid storm in 1899. In Fig. 12 it is apparent that Leonid activity was at best only a few times above that of the sporadic background during the times when observations were available. There are indications of extended activity lasting for several days, but the ZHRs are widely scattered and it is possible this merely reflects changes in diurnal sporadic rates. It seems unlikely that any Leonid activity with ZHR >∼50 occurred in 1933 and probable that the maximum was well below this level. As in 1932, only a single observation was reported within an hour on either side of the nodal crossing time of the comet and some

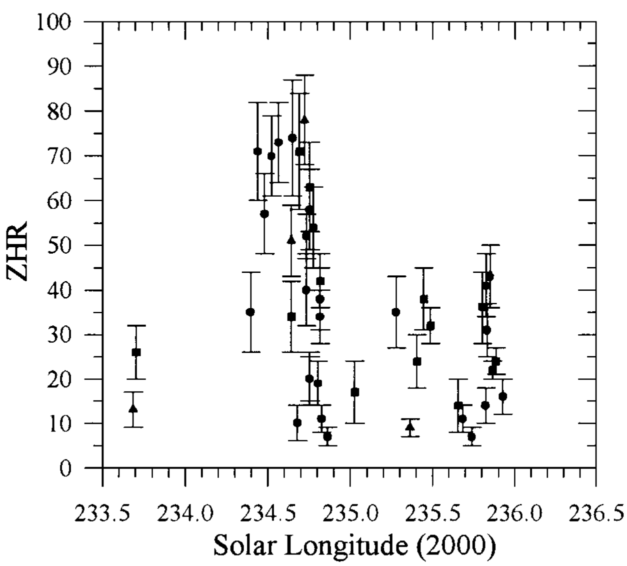

FIG. 11. ZHR profile for the 1932 Leonids. Data are derived from reports in Curry (1933), Pickering (1933), Theobald (1933a), King (1933), and Olivier (1933).

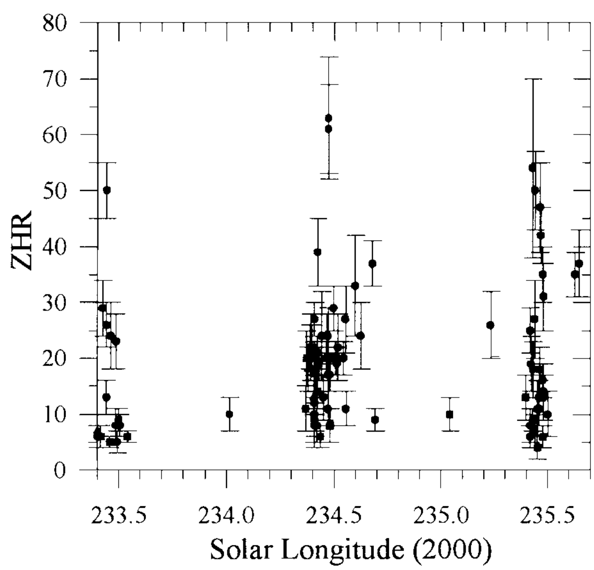

FIG. 12. ZHR profile for the 1933 Leonids. Data are from Theobald (1933b), Millman (1934), Hutcherson (1934), Olivier (1934a, 1934b), and King (1934).

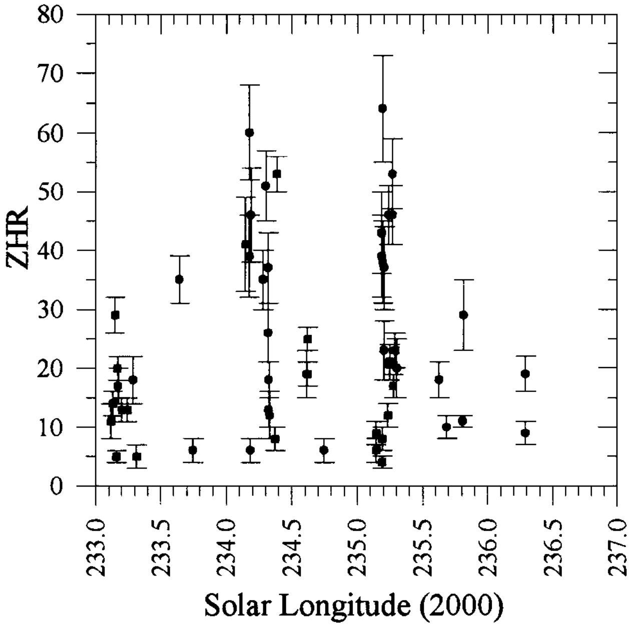

FIG. 13. ZHR profile for the 1934 Leonids. Data are reports taken from Millman (1935) and Olivier (1935).

higher activity over the Pacific or Asia could easily have gone unreported. No clear time of maximum is discernible, though the highest consistent counts are near 235.4°–235.5°.

The 1934 return of the Leonids was similar to 1933 in its weakness. The Moon did not interfere with observations in the early morning hours near the peak in 1934 and the low numbers of Leonids appear to have been truly indicative of a modest shower at best (Fig. 13). As in 1933, it appears maximum Leonid ZHR rates were on the order of 50–60 with a maximum occurring near 235.2°, though the activity is best characterized as dual-peaked at 234.3° and 235.3°, a likely reflection of diurnal sporadic variation and the large number of North American observations.

4.6. *The 1966 Epoch*

By the 1966 epoch a general consensus existed that Leonids were no longer able to produce storms. Indeed, McKinley (1961) states that "it is highly improbable that we shall ever again witness the full fury of the Leonid storm." Of course, this proved quite false as the 1966 Leonid storm became one of the strongest in recorded history.

The first inkling of the Leonid storm to come occurred in 1961. Observers in North America noted a strong display, rich in bright meteors (Robinson 1962). Few original observations from this year are available, however, and only a rough estimate from a small scattering of raw observations given by Robinson (1962) suggests ZHRs in the range of ∼70.

Strong interference from the Moon in 1962 precluded any large-scale observations, but the new Moon in 1963 encouraged many to observe the shower. Figure 14a shows the derived ZHRs from 1963 data, which are heavily biased toward North American longitudes. All observations suggest a modest shower at best, with a peak ZHR in the range of 30, or less. Clearly, many longitude ranges were not covered and visual activity may have been higher.

Modest lunar activity in 1964 interfered with the shower and, as in 1963, few observations outside North America were reported. Figure 14b shows activity which is suggestive of a peak ZHR near 50.

The year 1965 also suffered from poor lunar conditions, with the Moon very near the radiant. Nevertheless, many observers

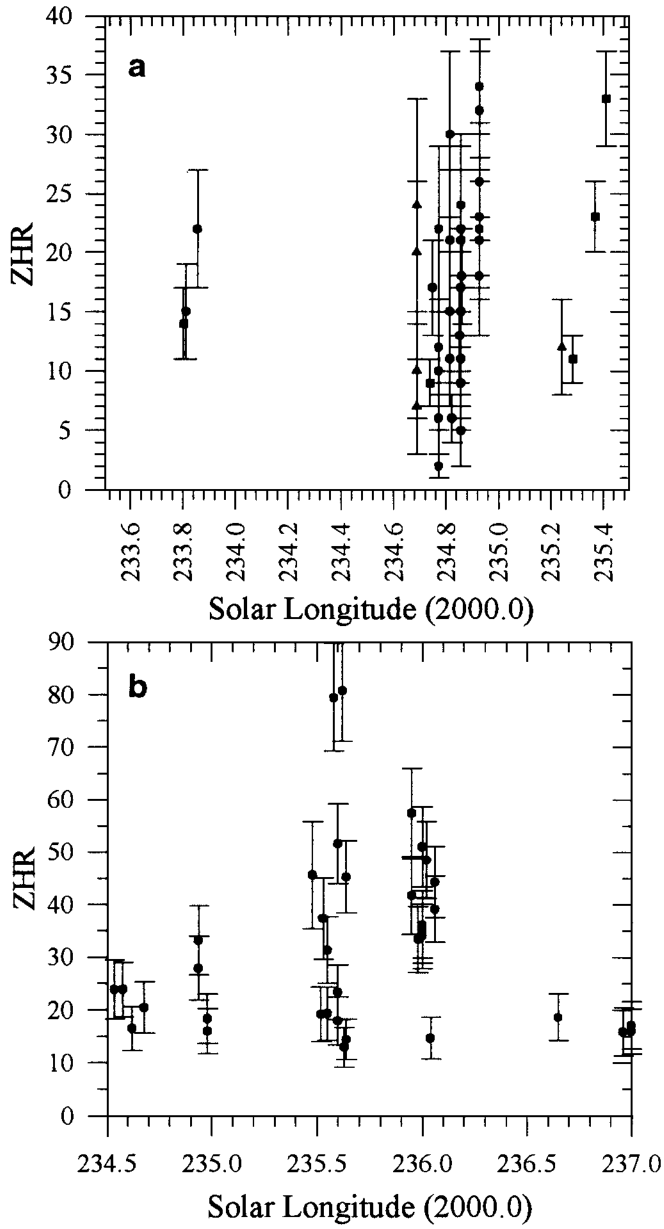

FIG. 14. (a) ZHR profiles for the 1963 Leonids. Data are reports taken from Robinson (1964), Rao *et al*. (1974), and Olivier (1972). (b) ZHR profile for the 1964 Leonids. Data are from Olivier (1972).

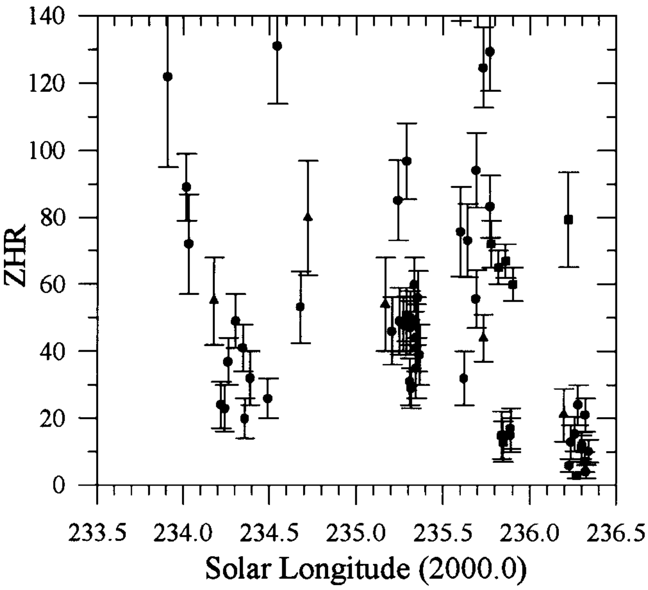

FIG. 15. ZHR profiles for the 1965 Leonids. Data are from Gingerich (1965), Rao *et al*. (1974), Astapovich and Terentjeva (1969), Robinson (1966a, 1966b), and Olivier (1972).

recorded the shower (Fig. 15). The initial indication that the shower was more active than in past years was given by Gingerich (1965) who reported bright Leonid meteors observed from Australia and Hawaii. These data suggest ZHRs as high as 130 under moonlight conditions, while observations from the former USSR (Astapovich and Terent'jeva 1969) hint at similar levels of activity more than 15 hr earlier. However, numerous observations between these two times in North America are indicative of levels perhaps 1/2 to 1/3 of these values. Certainly later observations on November 17 (from 235.17° onward) clearly show ZHRs in the 40–60 range. Again, large observation gaps occur and it is possible much stronger activity was missed. The large numbers of bright meteors reported by visual observers (Robinson 1966b, Gingerich 1965) are partly due to the lunar interference, but may also be truly reflective of the Leonid return in 1965. Radar observations from Canada and Czechoslovakia in 1965 (Brown *et al*. 1997a) show a large increase in the number of long-duration meteor echoes (i.e., large meteoroids). Peaks in the radar echoes (which correspond to the brightest visual Leonids only) are not well correlated with the visual data and suggest that these larger meteoroids were only moderate contributors to the overall shower numbers, though from the radar and visual data much more numerous than in the previous few years. Most interestingly, an apparent peak visible from both the Czech and Canadian radar data at 235.16° (i.e., the same solar longitude as the 1966 storm) is not visible at all in the visual data.

The highest ZHRs recorded in 1965, when examined with respect to the interfering Moon, support the contention that true ZHRs perhaps reached levels of 300–400; the lower ZHRs constituting the bulk of the available observations suggest more modest ZHRs in the 100–200 range for most of the activity interval. Certainly a broad level of activity from 234° to 235.5° is in evidence and in general accord with the radar results.

Numerous literature sources (cf. Mason 1995, Yeomans 1981, Brown *et al*. 1996) cite a meteor storm as having occurred in 1965, but this is not supported from either radar or visual observations. The source of these reports appears to be radar observations reported from Plavcova (1968) and a visual ZHR value of 5000 quoted by Kresak (1980). The former observations indicate a factor of ∼2 increase in the number of the shortest duration echoes measurable by the radar (corresponding to a visual magnitude of ∼ +5) on November 17 between 235° and 235.2° compared to other nearby days, which is certainly not consistent with a storm. The basis of the ZHR value of 5000 given by Kresak (1980) is not given either in this work or in subsequent work where it also appears (Kresak 1993). One possible source is a note by Martynenko (1965) which mentions 1000 meteors visually observed in 15 min on 17–18 November, 1965. However, this note also includes observations from the previous night where rates of 1120 in 1.5 hr are recorded and mentions that observations were carried out by a group from the Astronomical–Geodetical Society in Sudak, Crimea, without specifying the number of observers involved, whether duplicates were counted or any other details. Furthermore, observations from a similar longitude reported in Astapovich and Terent'jeva (1969) on the same night indicate visual ZHRs in the 10–20 range.

Another possible source for this information is the discussion given in McIntosh (1973), where it is stated that in 1965 as many large particles were encountered as in 1966 based on radar observations. It is explicitly noted that the nodal width observed for the shower in 1965 was approximately 30 times as large as in 1966 and assuming a similar initial meteoroid concentration (which as the author notes there is no *a priori* reason for supposing is true) this would imply the particle density in the orbit is 1/30 that of 1966. Indeed, the often quoted 150,000 ZHR figure for 1966 would naturally lead to a ZHR figure of 5000 taking this information at face value; in fact no such observations exist and the 5000 figure is entirely based on assumption. That a strong shower, rich in larger Leonids, occurred in 1965 seems probable, but no meteor storm is in evidence from available observations.

Lunar conditions in 1966 were ideal, with a new Moon on November 12. Observations from 12 to 3 hr before the peak of the great 1966 Leonid storm indicate ZHRs of 10–20 (see Fig. 16a). Similarly, the ZHR had returned to a level near 20 by 235.5°. The rise toward the storm peak began at approximately 235.02° and the ZHR rapidly ascended, surpassing the 100 level roughly 1 hr later at 235.07°. By the end of the next hour at 235.11° the ZHR was in excess of 500 and over the next 75 min climbed to a peak rate in the vicinity of 75,000–150,000 Leonids/hr (see Fig. 16b). The drop from this peak back to a level near 500 took another hour, at which time the final falling portion of the storm went unobserved over the Pacific ocean. It is interesting to note that the full extent of the storm was actually

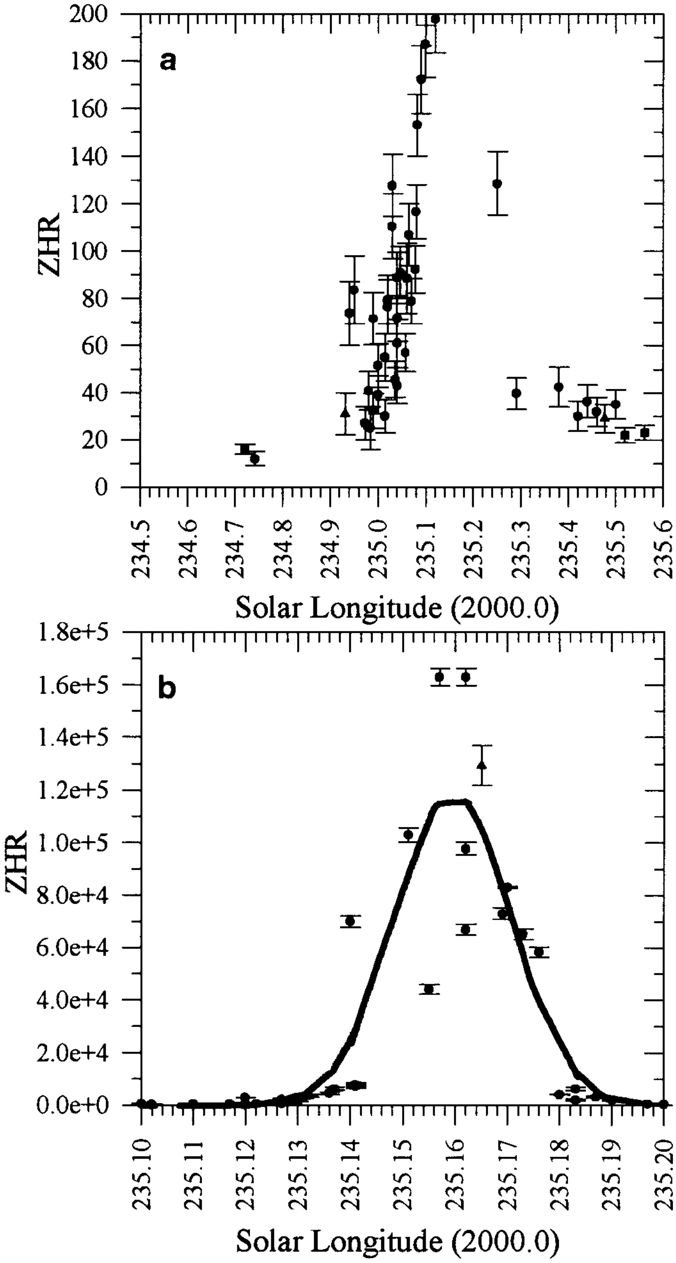

FIG. 16. ZHR profiles for the 1966 Leonids. Data are from Milon (1966), Milon (1967), Bailey (1966), Ashbrook (1967), Rao *et al.* (1974), Gingerich (1966), Khotinok (1967), Divinskii (1968), Olivier (1972), and Terentjeva (1967) for the 24 hr around the storm peak (a). ZHR profile for the 1966 Leonids near the time of the peak of the storm (b) with a Gaussian fit to the raw data.

only visible to a few observers in the central and western United States and the Soviet Arctic who saw the return under near ideal conditions. Observers further east in twilight saw a strong return, but only a fraction as intense as those watching under dark skies. This highlights the high probability that many Leonid storms of the past were undocumented due to poor weather, twilight, the Moon, and sparse concentrations of observers.

Applying Eq. (2) to the full observation set from 235.1° to 235.2° produces a Gaussian fit (shown in Fig. 16b) with a maximum at $235.160° \pm 0.002°$, a peak ZHR of ∼115,000 and a FWHM of $\sigma = 0.011° \pm 0.001°$, corresponding to a total duration of 30 min. For comparison, Brown *et al.* (1997a) found from Canadian radar observations of the storm (to a limiting magnitude of +6.8) a total duration using a Gaussian fit of 46 min. The longer duration of the shower from the radar data is consistent with the expectation that the storm is wider for smaller Leonid meteoroids which are expected to have a larger nodal spread purely on the basis of higher ejection velocities (cf. Jones 1995).

The highest rates were reported by Milon (1967) from a group of observers under ideal skies at Kitt Peak in the United States. Other observers in less ideal conditions reported rates 2 to 4 times lower (Ashbrook 1967). However, given the large numbers of Leonids visible, the very subjective methods of determining the rates at the peak, the wide variation in reported ZHRs (from 45000 to 160,000) at the peak and the uncertain range of observing conditions from the few observers who reported usable information, it seems worth stressing that the actual peak magnitude of the 1966 storm purely from visual data is uncertain to at least a factor of 2; a best guess from all available visual observations would place the peak ZHR of the storm between 75,000 and 100,000. It is instructive to note that the lower limit for the peak flux deduced from radar observations in 1966 by Brown *et al.* (1997a) is equivalent to a minimum peak ZHR of 80,000. There are no visual observations from the peak which support the conclusion of Jenniskens (1995) that actual peak ZHRs never exceeded 15,000 during the storm. The widely quoted peak value of 144,000 (cf. Yeomans 1981, Kazimirchak-Polonaskaya 1968) is based largely on the account from Milon (1967) which, within error, is not unrealistic, although it is certainly the highest count made by any group of observers.

The nearly full Moon quashed observations in 1967; the few reports (cf. Robinson 1968, Terentjeva 1967, Astapovich 1967) do not indicate any unusually high activity (ZHRs of ∼30–40 at most) in accordance with similar low activity observed by radar (Brown *et al.* 1997a).

Much better lunar conditions prevailed in 1968 and the shower was well covered from North America. A peak in activity was reported from the west coast (see Fig. 17), but is based on only two separate observers. Taken at face value, this west coast peak suggests peak ZHRs near 110 in 1968, while earlier and later observations are more consistent with peak activity closer to half this value. The solar longitude corresponding to the 1966 peak was not covered by observations in 1968.

The last great shower of the 1966 epoch occurred in 1969 under good lunar conditions. North American observers reported a distinct, sharp peak in activity near 235.27°, with individual ZHRs as high as 300 (Fig. 18a). The Gaussian shape of the outburst is apparent when the data are smoothed as in Fig. 18b. The Gaussian shape permits a fit using Eq. (2) with a peak at $235.277° \pm 0.003°$, a maximum ZHR of 210, and a Gaussian

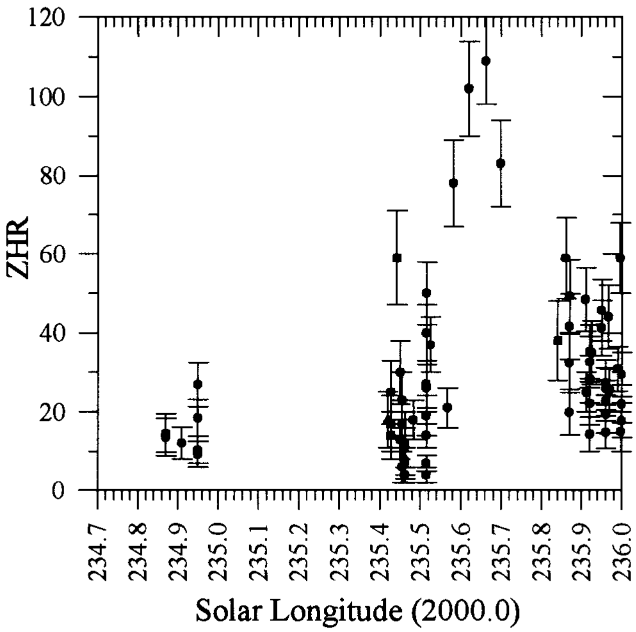

FIG. 17. ZHR profiles for the 1968 Leonids. Data are from Robsinson (1969), Olivier (1972), and Astapovich (1969).

width of $0.020° \pm 0.003°$, corresponding to approximately 1 hr FWHM, about twice as long as the 1966 storm. That the peak occurred so far from the location of the 1966 storm (at which time no enhanced activity was recorded) and the node of the comet suggests an entirely different origin for the 1969 outburst. This enhanced activity is similar in many respects to what was witnessed in 1901 and 1903.

4.7. *Recent*

From 1969 to the present, numerous visual observations of the shower have been made. Unfortunately, most of these have been made using markedly different techniques and reduced in incompatible ways by various scattered amateur groups worldwide. Between 1988 and 1993 a compatible set of visual observations of the shower was obtained on a global scale using the same standard techniques and reduced in an homogeneous manner in part as a result of the International Leonid Watch (Brown 1991). As no single year produced more than a few hundred observed Leonids, and no indications of heightened activity were present in any one year, an average profile of the quiet (or clino-Leonids) part of the stream was generated based on 6 years of visual observations. The data from all years between 1988 and 1993 were amalgamated to produce the ZHR curve given in Fig. 19. A total of 182 observers contributed 2697 usable Leonid meteors in 1102 observing hours in this period to produce the ZHR curve. Note that for this curve and for subsequent yearly curves given in Section 4.7, a fully corrected ZHR is given, i.e., one that corrects for the limiting stellar magnitude reported by observers (see Eq. (1)) and uses either a mean population index (r) or r profile for computation of ZHRs. This differs from all previously presented ZHRs (as explained in Section 3) and implies that the ZHRs given in this section are the more accurate.

As the statistical weight of the sample is still relatively low, we comment only on the apparent time of the maxima which is at $235.5° \pm 0.3°$ (2000.0) with an apparent peak ZHR of $\sim$10. Note that this value is sensitive to the value of r used, which in the present case is 2.0 (cf. Brown 1994). We also note that the background sporadic activity is at a level of about 10–15/hr in this figure; hence the annual Leonids only reach the level of

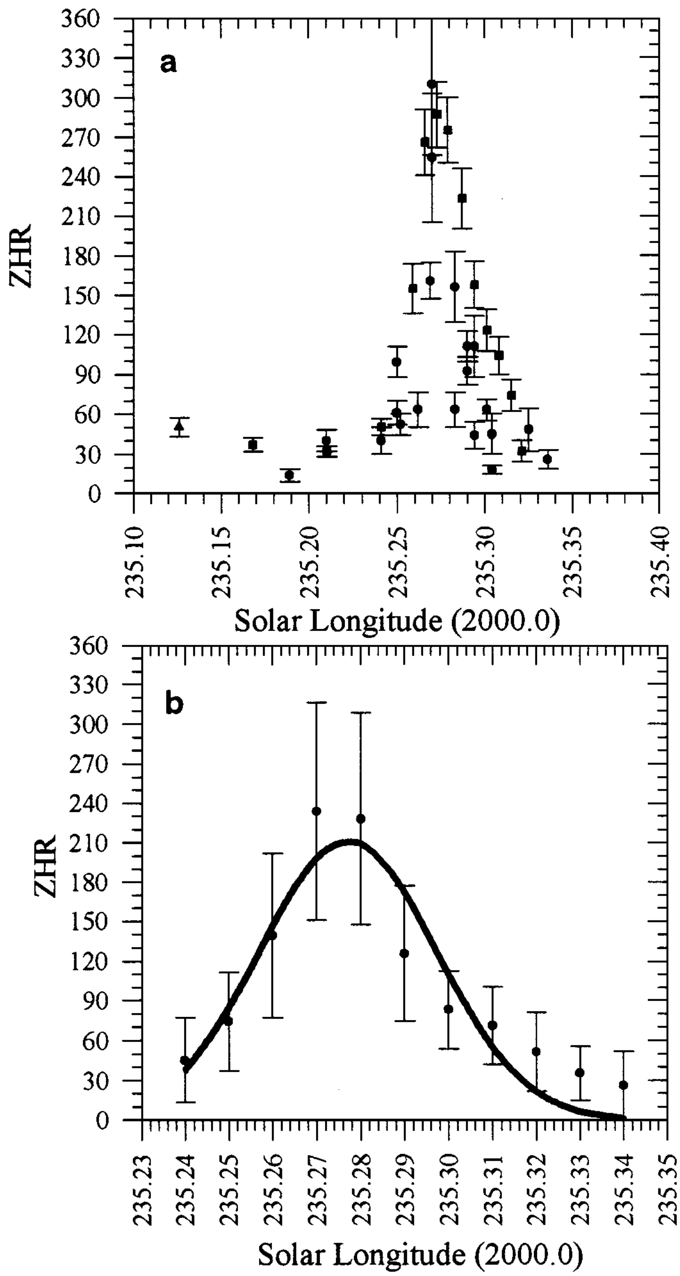

FIG. 18. (a) ZHR profile for the 1969 Leonids. Data are from Robinson (1970), Olivier (1972), and Millman (1970). In (b) a Gaussian fit to the original data binned in 0.02° bins shifted by 0.01° is shown.

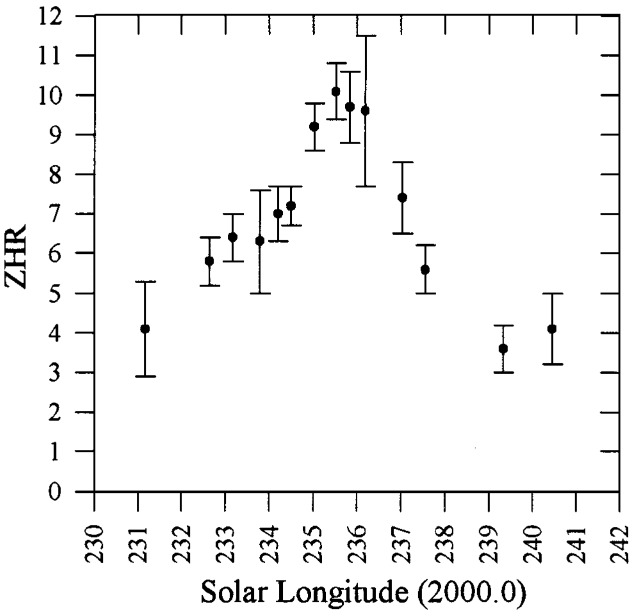

FIG. 19. Mean ZHR profile for the annual Leonids averaged from 1988 to 1994. Data are derived from Brown (1994).

the sporadic background for a few hours near the time of maximum.

The first enhanced activity of the current Leonid cycle took place in 1994 (Jenniskens 1996). The full Moon resulted in severe noisiness in the individually corrected ZHRs (cf. Brown 1995 for the original results), but a smoothing of the individual ZHR determinations was used to produce Fig. 20. A total of only 398 Leonids from 25 observers was available for analysis and this paucity of data coupled with the presence of the full Moon makes the final curve suspect. The peak in 1994 occurred near 235.8° but the overall profile is quite wide having a full duration to half maximum in ZHR of more than one day. The peak ZHR is uncertain near 100.

The 1995 Leonid return was hampered only moderately by the presence of the last quarter Moon. The interest resulting from the 1994 outburst produced the largest single year observer coverage of the shower to date, with 137 observers recording 3117 Leonids in 404 hr of observing time. This large data set also permitted determination of the population index profile over the period of activity of the shower. It was found that the particle makeup was relatively uniform throughout, with a near constant r value of 1.8 (Brown 1996). The large number of observations lend themselves well to a smoothed ZHR curve, which is shown in Fig. 21. There are two clear peaks in these data; a strong one near 235.0° and a smaller local maximum near 235.5°. The earlier maximum is outburst in character, but is composed of observations from only two observers with uncertain perceptions, making its significance doubtful. The later maximum occurs at the location of the "quiet"-time Leonid maximum from observations over 1988–1993 at 235.5° and is almost certainly associated with it.

In 1996 ideal lunar conditions and heightened observer awareness combined for another record number of visual Leonid observations. Figure 22 shows the smoothed ZHR profile centered about the day of maximum (November 17, 1996). Sufficient magnitude distributions were also recorded in 1996 to allow a high fidelity population index profile to be formed; this is shown in Fig. 23. The activity features of note are the clear outburst maximum at $235.17° \pm 0.05°$ and a smaller local maximum at $235.4° \pm 0.1°$. The former had a peak ZHR near 90 ± 25 and the

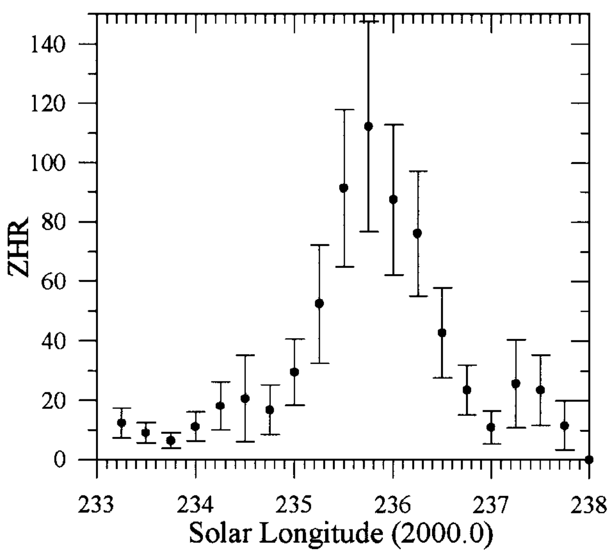

FIG. 20. ZHR profile for the 1994 Leonids. Data are taken from Brown (1995). Data have been smoothed in 0.25° bins shifted by 0.25°.

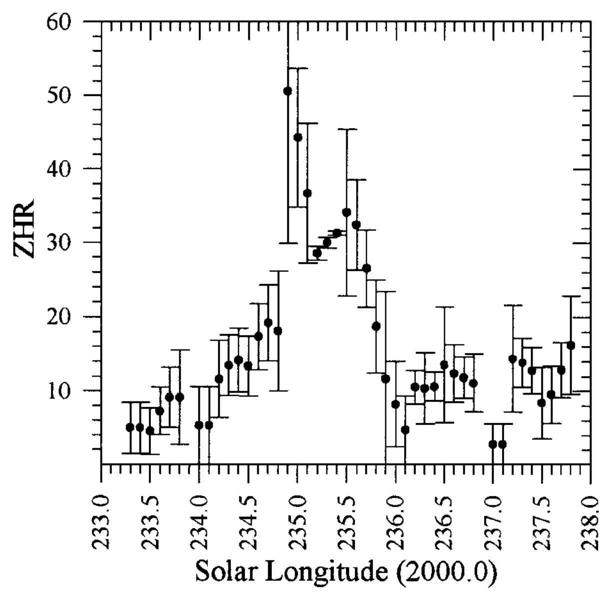

FIG. 21. ZHR profile for the 1995 Leonids. Derived from Brown (1996). Data have been smoothed in 0.2° bins shifted by 0.1°.

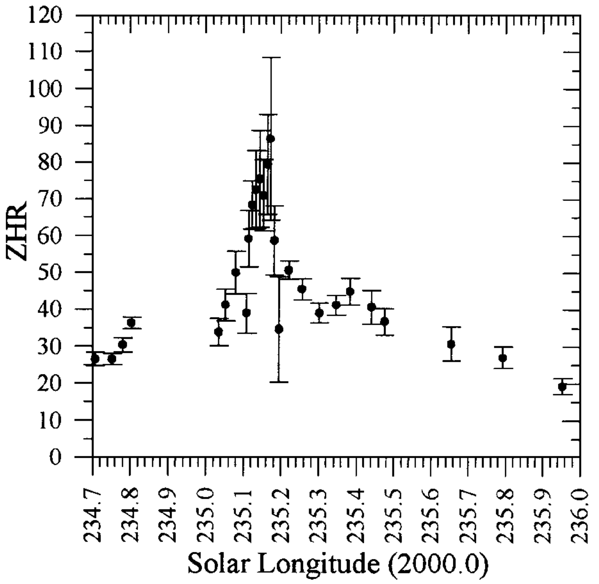

FIG. 22. ZHR profile for the 1996 Leonids. Derived from Brown and Arlt (1997). Data were smoothed in windows of 0.1° shifted by 0.05° before 235.1° and from 235.2° to 235.5° while bins of 0.02° shifted by 0.01° were used from 235.1° to 235.2°. The region beyond 235.5° was smoothed in 0.5° intervals shifted by 0.25°.

latter a value of 45 ± 5. The early outburst maximum was primarily witnessed by a few European observers, but the coverage was sufficient to establish this as a genuine feature (Brown and Arlt 1997). The outburst is also associated with an increase in the value of r to 1.9 from premaximum levels of 1.6–1.7, attesting to a proportional increase in the number of faint Leonids.

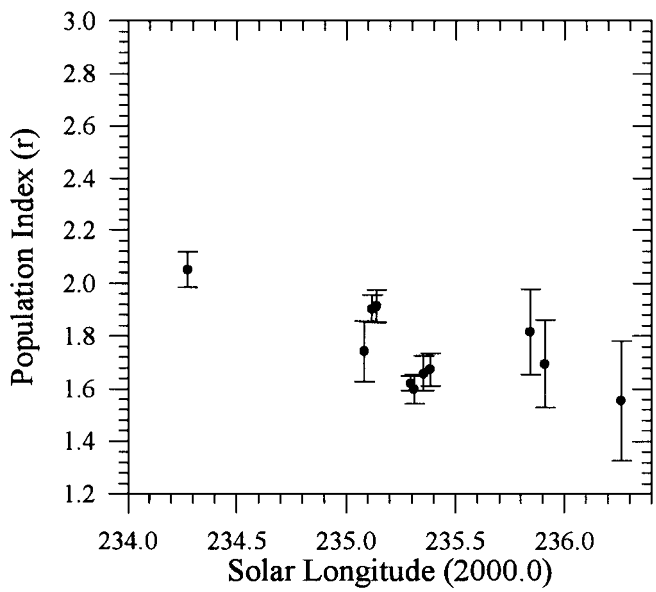

FIG. 23. Population Index (r) profile for the 1996 Leonids (from Brown and Arlt 1997).

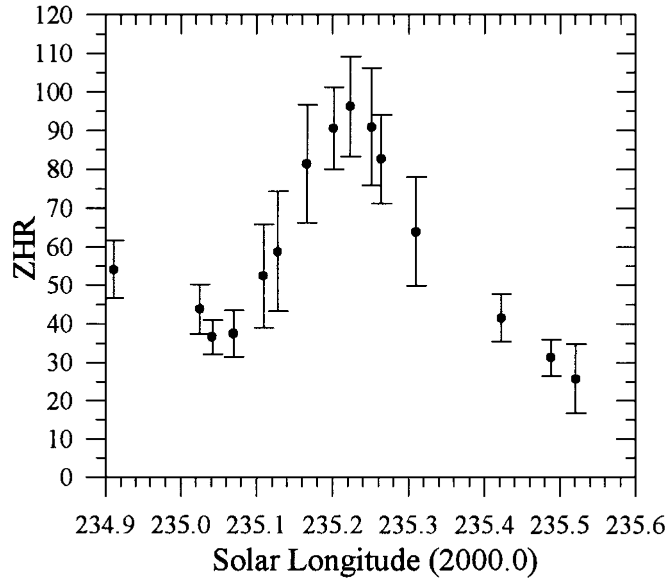

FIG. 24. ZHR profile for the 1997 Leonids. Derived from Brown and Arlt (1998).

In addition, the outburst was witnessed in radar observations of the shower (Brown *et al.* 1998) and to a lesser extent by TV observations. The peak flux from the visual observations corresponds to 0.012 ± 0.004 meteoroids km^{-2} hr^{-1} for Leonids of absolute magnitude +6.5 and brighter. The display showed heightened activity relative to the quiet-time profile for several days on either side of the maximum.

The 1997 Leonid return was significantly denuded by the presence of a nearly full Moon. Nevertheless, sufficient observations under heavy moonlight conditions were made to permit an approximate ZHR curve to be constructed and this is shown in Fig. 24. A peak at $235.22° \pm 0.04°$ is present, although the number of observations contributing to this is relatively small. The ZHR for the outburst maximum in 1997 was near 100 ± 10 while the "regular" maximum was near 30 ± 10. Both values are uncertain due to the lunar interference. The activity in 1997 was higher than normal for at least 12 hr on either side of these times and characterized by a number of bright fireballs (Brown *et al.* 1997b). It appears probable that the strong, narrow features observed near 235.16° in both 1996 and 1997 represent younger material in the stream than the broader activity present in both years as well as 1994–1995, but whether this is associated with a storm producing segment of the stream remains to be seen. It is intriguing to note that this is the same location as the 1966 storm maximum, which is located some 0.12° before the comet's present nodal longitude.

5. DISCUSSION

While the results given in Table I and discussed in detail in Section 4 have been computed without resorting to corrections for lunar biases, further examination of the data set in order to

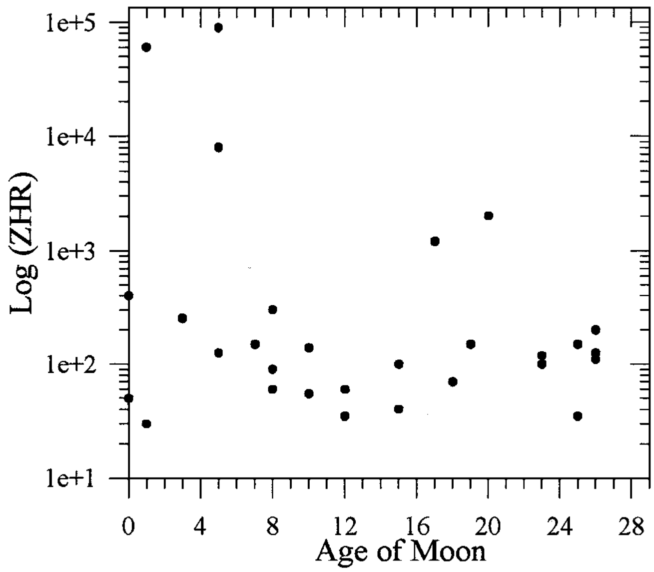

FIG. 25. Effect of the Moon on activity of the Leonids (from Table I).

elicit some useful information about the stream requires that some correction be adopted for this strong bias. That the Moon significantly affects the observed strength of the stream is obvious from Fig. 25, where the Log (Peak ZHR) given in Table I is plotted vs the age of the Moon at the time of the peak of the shower. It is clear that from about 9 to 24 days the trend is toward lower ZHRs, with the strongest displays for which numerical data exist all having been witnessed within a week of the new Moon.

From modern visual meteor observations, the difference between the apparent ZHR without sky brightness correction (as utilized here for historical accounts pre-1969) to actual ZHRs, taking into account lunar interference, amount to approximately a factor of 2 for lunar ages of 9,10, and 24 days after the new Moon, a factor of 3 for lunar ages of 11–12 and 22–23 days after new Moon and a factor of 4 for lunar ages at the time of a Leonid maximum from 13 to 21 days after new Moon. In what follows, we have adopted these sets of corrections for pre-1969 observations to generate the most probable maximum ZHR (ZHR_{mp}), independent of the Moon.

Of the returns listed in Table I, six had sufficient observations to fit a smoothed profile with Eq. (2). This allowed an estimation of the Gaussian width of the profile. This value is plotted against ZHR_{mp} in Fig. 26. The trend is toward wider profiles for lower ZHR_{mp}, a reflection of the expected older age of more widely dispersed material (McIntosh 1973). We note that the fit for five of these six returns is very good; the lack of consistency for the sixth point arises from the 1969 shower which was well observed visually and had a similar profile from radar records (Porubcan and Stohl 1992) and hence we must conclude that the relationship is only approximate for Leonid returns.

Using the five remaining points, however, a good least-squares fit is obtained such that the Gaussian width of the storm component of the stream and the peak ZHR are related via

$$\log(\sigma) = -0.29 - 0.35 \log(ZHR_{pm}), \tag{3}$$

where σ is given in units of degrees of solar longitude. As this dispersion relating to peak activity is likely only associated with the storm component of the stream, the relationship undoubtedly breaks down once ZHR_{pm} is below $\sim$100 when the broader component of activity is dominant.

To determine if this is a reasonable result for the Leonids, we compare these results with those of the IRAS cometary dust trails (Sykes and Walker 1992). Kresak (1993) has shown that such dust trails are precisely the same phenomenon that produces meteor storms at Earth and hence the width of the two should be similar. If we assume an average mass distribution of $s = 2$ within the central portion of the Leonid storms (cf. Brown *et al.* 1997a for a discussion of this point in connection with the 1966 Leonid storm), and use the relation between ZHR and flux given in Brown and Rendtel (1996), we can translate (3) into a relation between width along the Earth's orbit (σ in km) and spatial density (meteoroids per km^3) of Leonids (larger than mass m in kg) as

$$S = \frac{6.604\,\sigma^{-2.85}}{m}, \tag{4}$$

where S is the number of meteoroids per km^3 and σ is in km. We assume that the width of the dust trail for 55P/Tempel–Tuttle

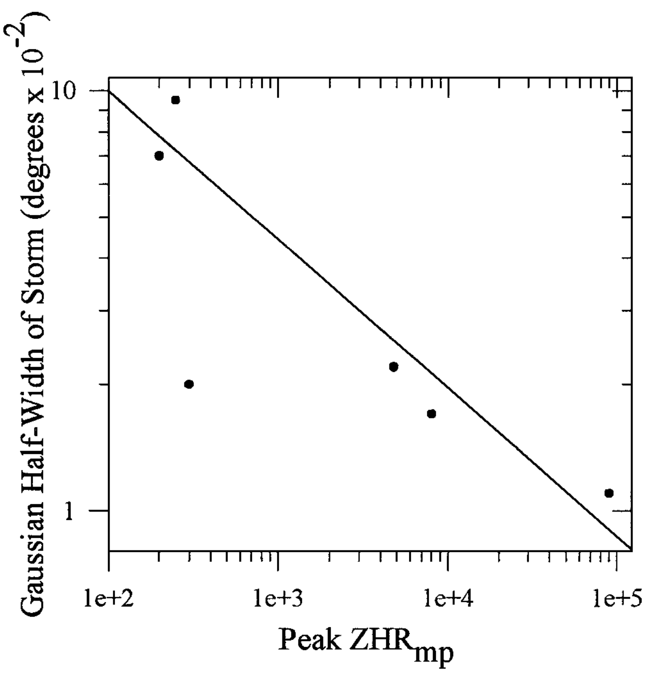

FIG. 26. Gaussian width of Leonid storms versus most probable ZHR (ZHR_{mp}). Plotted data are from the Leonid returns of 1866, 1867, 1901, 1903, 1966, and 1969.

should be comparable to the average of the short-period comet trails observed by IRAS (found to be 30,000 km at 1 AU from the Sun (Kresak 1993)), and that the trail is composed primarily of meteoroids 1 mm and larger (10^{-6} kg Leonids) (Sykes *et al*. 1990). As noted by Kresak (1993), the strongest of the Leonid displays (ZHRs = 100,000) had spatial densities one order of magnitude below the IRAS detection limit. Assuming $s = 2$ holds throughout, a Leonid ZHR of 10^6 (which would just be detectable as a trail in the IRAS survey) corresponds to spatial densities of $S = 10^{-5}$ meteoroids (>1 mm) per km^3. This corresponds to a σ of 1.5×10^4 km (using Eq. (4)) which is within a factor of two of the mean value found from the IRAS comet trail survey normalized to $r = 1$ AU. Thus it appears Eqs. (3) and (4) are representative of the general relationship between the width and meteoroid spatial density within the dust trail of 55P/Tempel–Tuttle at 1 AU and are consistent with the IRAS dust trail findings from similar short-period comets.

Similarly, the difference in the widths of the 1966 storm between radar and visual Leonids is a direct measure of the relative spread in ejection velocities for two different mass regimes within the stream. Using the Jacchia *et al*. (1967) mass–magnitude–velocity relationship, the limiting magnitude of the radar observations (+6.8) corresponds to Leonids with masses near 10^{-8} kg. The visual observations of the storm were effectively representative of Leonids with magnitudes between +3 and +4; these have masses of 10^{-7} kg. The storm width (in degrees of solar longitude) from radar (Brown *et al*. 1997a) was $0.0156^\circ \pm 0.0008^\circ$ for a Gaussian fit, while a similar procedure applied to the visual observations presented here yields a value of $0.011^\circ \pm 0.001^\circ$. From the standard theoretical treatment of meteoroid ejection from comets through gas-drag (cf. Jones 1995), the final ejection velocity is expected to vary with particle mass as $v \propto m^{-1/6}$. Thus, the average relative difference in the normal components of the ejection velocity for a decade difference in mass is expected to be 68%. Given that the visually determined width of the 1966 storm is 70% ± 10%, the radar determined value is consistent with the standard gas-drag ejection treatments and provides further evidence that the strongest Leonid storms are very young and have durations controlled by initial ejection velocities. That the locations of ejection of the responsible storm meteoroids along 55P/Tempel–Tuttle's orbit are unknown (if any single ejection location on the cometary orbit is actually entirely responsible for the 1966 storm) implies that this information alone is insufficient for a unique solution to the normal component of the ejection velocity question to be addressed.

Yeomans (1981) was the first to explicitly assume that the strongest shower peaks should occur close to the nodal longitude of the comet. As the closest distance between the comet and Earth increases, it would be expected that orbits of the dust encountered would be the most different from that of the parent comet and hence most likely to have a peak at a different longitude than the comet's nodal longitude.

In Fig. 27 we investigate this assertion by plotting the peak ZHR against the difference between the time of nodal passage and the observed maximum. There is nearly an even split with as many maxima occurring before the nodal passage as after.

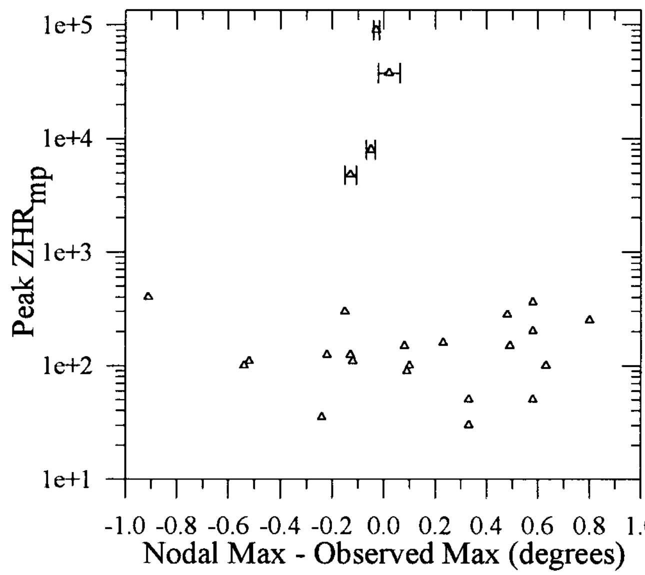

FIG. 27. Peak ZHR$_{mp}$ compared to observed maximum distance from nodal plane of 55P/Tempel–Tuttle (in solar longitude degrees). Error margins are given for the strongest storms using the Gaussian widths of the activity. For 1833 the error margin for time of the peak is estimated to be one hour based on reports (see text).

It can be seen that as the peak ZHR$_{mp}$ increases, there is a strong tendency for the shower maxima to occur closer to the nodal longitude of the comet. Intriguingly, all five of the strongest showers peak 0.5–2 hr after the nodal point of Tempel–Tuttle. While this may be a simple statistical fluctuation due to the small number of points involved, it is worth noting that these five storms have among the best determined locations of peak activity. For returns where the Peak ZHR was at a substorm level (<500), there is no clear pattern. This suggests that the major storms are of distinct (probably very young) origin relative to all other Leonid returns. The observed negative lag for the major storms (i.e., peak activity reached after the nodal longitude of the comet) may indicate an asymmetry in dust ejection normal to the cometary orbital plane. In particular, the larger nodal longitudes for the storms could indicate positive dust ejection normal to the cometary orbital plane of order a few tens of meters per second before perihelion to 20° true anomaly or in a direction opposite to the positive normal of the cometary orbital plane after this point.

In an effort to determine the approximate relative distribution of dust about 55P/Tempel–Tuttle, the 30 independent ZHR determinations given in Table I have been combined with the orbital encounter geometry for each return in Fig. 28. Here log (ZHR) is given in contour form. Note that these data include observations up to 1997. While this contour plot changes somewhat depending on the precise contouring technique applied, the overall shape of the distribution remains constant. As has been

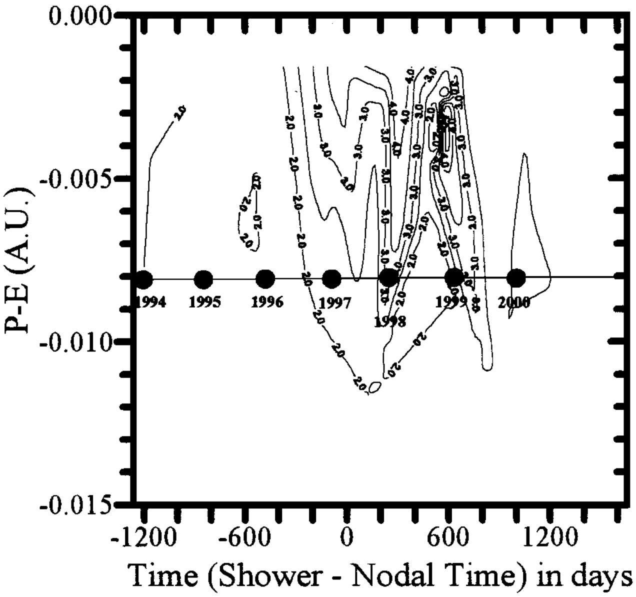

FIG. 28. Contour distribution of dust density about 55P/Tempel–Tuttle. Contours are in units of log (ZHR_{mp}). P–E (AU) is the closest distance between the cometary orbit (determined at perihelion for a given Leonid epoch) and the Earth's orbit in AU. Time on *x* axis is a measure of the observed time of the shower (in days) relative to the comets nodal passage.

noted previously by numerous authors (cf. Yeomans 1981, Wu and Williams 1992), our results are consistent with the greatest dust concentration being outside the comet's orbit spatially and behind it temporally. Note that in the data used here (post-1799) the Earth has only sampled dust outside the comet's orbit, so from this alone we can say nothing about the concentration inside the comet's orbit (cf. Yeomans 1981 or Mason 1995 for a complete discussion of the dust distribution with reference to older showers which were encountered inside the comets orbit).

Using these results to forecast activity over the next few years, it appears most probable that a Leonid storm of modest strength can be expected in either of the years 1998 or 1999. Peak ZHRs of order 1000 in 1998 and perhaps somewhat lower in 1999 are suggested by examination of the overall distributions, but the paucity of data points in the region nearest these years suggests these values be viewed with caution and no simple estimate of the probable range of expected peak ZHRs on this basis is practicable.

6. CONCLUSIONS

An examination of the original accounts of past Leonid storms has led to a revised list of the times and strengths of past Leonid showers for the post-1799 era as summarized in Table I.

From the detailed yearly results analyzed in Section 4, it is apparent that the activity of the shower in numerous years as quoted in many secondary sources is in error. The strongest of the Leonid storms show activity near maximum which is well represented as Gaussian in shape.

The profiles of the various Leonid returns suggests three distinct components to the Leonid shower, some or all of which may be visible in any one year. A broad annual component which lasts for 3 to 4 days and barely reaches sporadic levels (cf. Fig. 19) is almost certainly present every year and is the oldest section of the Leonid shower. In addition to this a more moderate level of activity, often accompanied by brighter Leonids (an extended component) is visible in some (but not all) of the years near the maximum in activity for any one epoch. This extended component may last up to 1–2 days (i.e., 1965) and may produce ZHRs as high as several hundred (i.e., 1868) for many hours. The extended component has been witnessed in every Leonid return from 1994 to the present. These two distinct components have been previously merged together and termed clino-Leonids.

The last component is the storm component or ortho-Leonids. This part of the stream, undoubtedly the youngest, is characterized by short, intense activity (cf. Fig. 26 for the relationship between the peak ZHR and duration) and is generally present most often in the one or two years immediately following the passage of the comet.

Using the best available data for the duration and strength of five of the ortho-Leonid storms, a relationship between the width of the storm component and the peak spatial density is derived which is broadly consistent with the findings from the IRAS cometary trail survey of comparable short-period comets.

Differences in the duration of the 1966 storm at two different limiting masses reveals the duration of the storms to be consistent with that expected based on initial ejection velocities which follow standard gas-drag treatments.

A possible systematic trend in the location of the peaks of storms after the nodal longitudes of the parent comet may represent an asymmetry in dust production normal to the cometary orbital plane.

Interpolation of the dust density about 55P/Tempel–Tuttle for the years 1998–2000 suggests that a strong 1966-class storm is unlikely, but that ZHRs on the order of 1000 may be reached in either or both of 1998/1999.

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