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Meteor stream activity. III. Measurement of the first in a new series of Leonid outburst

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Abstract–In 1994 November, a shower of bright Leonid meteors signaled what is likely the first meteor outburst of Leonids associated with the upcoming return of comet P/Tempel-Tuttle to perihelion. Measurements of meteor activity and the meteor brightness distribution are presented. By comparing the present observation with those of past Leonid returns, a forecast is made of the time, the duration, the intensity, and the mean meteor brightness of Leonid outbursts that may occur if previously observed patterns are repeated in the forthcoming years.

INTRODUCTION

In 1994 November, a meteor outburst of Leonids was observed that may signal a series of such events in the coming years. A meteor outburst is defined as a significant enhancement of rates over normal annual activity and is thought to be caused by relatively recent cometary ejecta, providing information on the ejection process of large grains and the orbital evolution towards a meteor stream. Dedicated observations of meteor outbursts have been rare, however, due to their irregular nature. Hence, a new series of Leonid outbursts carries a promise of opportunity.

Among all historic outbursts, the Leonids are of special interest. It was the Leonid meteor storms of 1799, 1833, and 1866 that marked the beginning of meteor astronomy (Lovell, 1954; Hughes, 1982). The discovery of the radiant in the constellation Leo, and a conspicuous 33.25-year recurrence, made it clear that meteors are of extraterrestrial origin and composed of cometary debris.

The Leonids are also special because the orbit of parent comet P/Tempel-Tuttle is relatively stable, and the stream has produced intense meteor outbursts at nearly every return to perihelion, at least back to 902 A.D. This allowed Yeomans (1981) to uniquely map the distribution of dust near the parent comet, showing that most matter is found behind the comet and outward from the cometary orbit. At present, the Leonids are the stream with highest maximum meteor rates, quoted to be as high as 150 000 meteors per hour during the meteor storm in 1966 (Milon, 1967). Although that estimate may be off by a factor of 10 (Jenniskens, 1995), the Leonids at their maximum still offer the best, and perhaps only, opportunity for a dedicated study of a meteor storm.

Previous papers defined normal annual activity (Jenniskens, 1994a) and summarized available observations of meteor outbursts (Jenniskens, 1995). This paper revisits normal off-season Leonid activity and presents observations of the new 1994 outburst. The result is compared to the outbursts reported during the previous return in 1965.

THE OFF-SEASON ACTIVITY

In the off-season (*i.e.*, between the return of the comet), the normal annual Leonid activity has remained fairly constant from year to year. Apart from a few poorly documented exceptions, the reported rates (*e.g.*, Roggemans, 1987) varied by no more than a factor of two since 1969 when the last-well documented Leonid outburst was observed. This is consistent with the rates reported between 1935 and 1960 (Kazimircak-Polonskaja *et al.*, 1968).

There has been no report of a gradual increase of annual activity while the comet approached perihelion in the past few years, in agreement with the behavior of the Perseids prior to and during the return of P/Swift-Tuttle in 1992. This confirms the relevance of distinguishing between normal annual activity and meteor outbursts.

Figure 1 is an average annual Leonid activity curve for the period 1949 to 1992. The x-axis gives the position of the Earth in its path in units of degrees of solar longitude. The y-axis gives the meteor rate in units of Zenith Hourly Rate (ZHR), which is proportional to the meteoroid influx. The diagram is composed of data by Koseki (1993), Jenniskens (1994a), and Brown (1994), obtained from observations in the years 1949–1970, 1981–1991, and 1987–1992, respectively. The agreement in profile shape is excellent.

This zenith hourly rate profile can be described with a small number of parameters, which allows a comparison with other activity profiles. The profiles of the major annual meteor streams are usually well represented by one or two components of the exponential form (Jenniskens, 1994a):

$$ZHR = ZHR_{max} 10^{-B|\lambda_{\odot} - \lambda_{\odot}^{max}|} \qquad \text{Eq. (1)}$$

where ZHR_{max}, B, and $\lambda_{\odot}^{max}$ are free parameters. The Leonids need a two-component fit with a narrow main peak and a broad

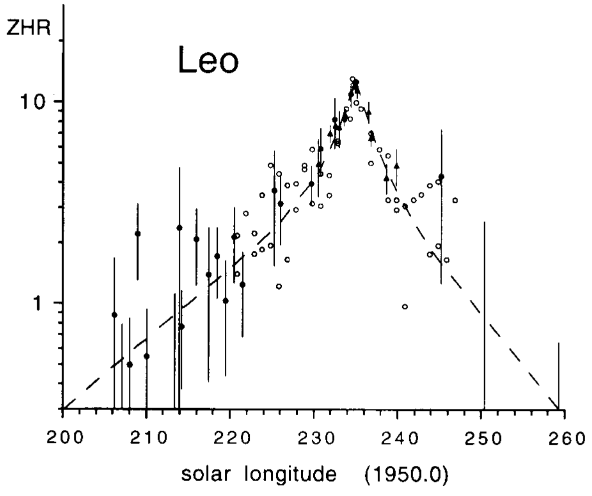

FIG. 1. Profile of annual Leonid activity. This is a compilation of data from Koseki (1993 = ○), Jenniskens (1994a = ●), and Brown (1994 = ▲). The ZHR values calculated by Koseki and Brown are scaled to those of Jenniskens by a factor of 0.37 and 1.22, respectively, and deviate in absolute level because of different definitions of the standard observer, the standard sky limiting magnitude, and a different correction for radiant altitude dilution.

background. Values for each parameter are listed in Table 1. These values are an improvement on those given in Jenniskens (1994a). This fit to the annual activity curve will be used as a baseline to which anomalous Leonid activity is compared.

A NEW LEONID OUTBURST

The author was fortunate to be among observers that witnessed an outburst of Leonids on 1994 November 18 (Jenniskens 1994b). Several bright meteors made the event most impressive. Unfortunately, no attempt was made to obtain multistation photographic data after a failed attempt due to bad weather the night before. However, visual and radio meteor-scatter observations have become available from other parts of the world that confirm the occurrence of an outburst. These data have now been analyzed, and results are presented below.

The Observations

The visual observations are not abundant because of interference by a nearly full moon. In 25 hours of effective observing time, 219 Leonids and 82 sporadic meteors were recorded by seven observers located in Rumania, Spain, and the USA (Table 2). Raw data are from Josep Trigo, Daniel Verde, Francisco Reyes Andres, Robert Lunsford and the author, which were kindly made available for further analysis, while additional data of David Swann and Valentin Grigore come from Brown (1994) and Grigore (1995). There is no individual series of counts that cover a significant part of the activity profile such as the data discussed in Jenniskens (1995). Therefore, the analysis of the observations depends on the fact that these were experienced observers with a well-established observing history.

The visual observations are complemented by results from two radio forward meteor scatter observers in Europe. I. Yrjölä in Kuusankoski, Finland (26E,+60N), kindly provided counts of radio reflections for further analysis. Similar data by M. De Meyere, Deurle, Belgium (5E,+50N), are given in Steyaert (1994).

TABLE 1. Summary of Leonid activity curve parameters.†

#	Component	Year	λ_o^{max} (B1950)	ZHR_{max}	B degree^{-1}	χ
1*	Outburst narrow - main peak	1966	234.468	15 000	30 ± 2	3.0
		1969	234.567	250	30 ± 2	3.0
		1866	232.627	17 000	30 ± 3	~2.5
		1867	232.713	6000	30 ± 6	–
2*	Outburst narrow - background	1966	(234.468)	~150	~6	–
		1866	232.625	1000	6 ± 0.5	–
		1867	232.713	350	6 ± 0.5	–
		1898	(233.46)	1100	4.1 ± 1.0	–
		1901	(233.46)	7000	3.5 ± 0.6	3.1
		1903	(233.46)	1400	3.5 ± 0.4	~2.5
3	Outburst broad	1994 visual	235.18 ± 0.10	75 ± 15	1.15 ± 0.30	2.1 ± 0.3
		1994 radar	235.22 ± 0.03	–	1.0 ± 0.1	–
		1961	234.4 ± 0.1	~200	–	2.3
		1965	234.6 ± 0.2	~300	~1.1	1.7
4	Annual-main peak	1949–92	234.9 ± 0.1	8 ± 2	0.20 ± 0.04	3.0 ± 0.4
5	Annual-background	1949–92	(234.9)	5 ± 1	B^+ 0.035 ± 0.006	–
					B^- 0.05 ± 0.03	

† For each Leonid activity curve component detected at a given date, this Table gives the solar longitude of peak activity (λ_o^{max}) in equinox B1950, which equals J2000 – 0.698°, the peak rate ZHR_{max}, the slope $B = d \log(ZHR) / d\lambda_o$, and the magnitude distribution index χ.

* Results from the narrow outburst component are from Jenniskens (1995).

Radiant and Mean Brightness

The visible meteors radiated from a point in the head of Leo at $\alpha = 150.6 \pm 1.8$, $\delta = +21.3 \pm 1.2$ (B1950). This median value was derived from a small number of 14 meteors seen <30° from the radiant and plotted on star charts by the author in the night of November 17/18 and 18/19. Depending on how well the meteor could be placed on the star background, each entry was given a weight factor. The error margin reflects the 1σ plotting accuracy and not the intrinsic scatter of the radiant. The position is perhaps slightly off from that of the Leonid storm in 1966, when the radiant was $\alpha = 152.5$, $\delta = +21.3$, at a moment earlier in time by 1.3° solar longitude.

A relatively large number of bright Leonids were seen. The observed magnitude distribution N(m) of several observers are given in Table 3. This distribution is affected by moonlight and observer perception. The true meteor distribution n(m) is equal to N(m) divided by some detection probability function P(m). The physically relevant parameter is the magnitude distribution index χ, defined as (Kresáková, 1966):

$$\chi = \frac{n(m+1)}{n(m)} \qquad \text{Eq. (2)}$$

which relates to the mass distribution index $s \sim 2.5 \log(\chi) + 1$, and which can be derived from the observed magnitude distribution N(m), because:

$$N(m) = n(0) \,.\, P(m) \,.\, \chi^m \qquad \text{Eq. (3)}$$

I have analyzed various combinations of data in time intervals and in units of similar sky conditions in order to find the value of χ from the sparse observations. I have used the probability function P(m) of Kresáková (1966) as a mean for all observers, allowing for a shift of the function proportional to the observed decrease of sky limiting magnitude. Alternatively, I have used P(m) derived from my distance of center of vision estimates (Jenniskens, 1994a) to correct my own observations. In addition, χ was derived from the distribution of bright meteors, where P(m) is close to 1, and by comparing the rate of observed Leonids and sporadic meteors as a function of magnitude, where P(m) is assumed to cancel out.

I find that χ of the Leonids is in the range 1.7–2.1, while the sporadic value is in the range 2.5–3.0. No significant variation with time could be determined, because of a lack of observations prior to and after the outburst. On a scale of $\chi = 3.4$ for sporadic meteors as in Kresáková (1966), the result is $\chi = 2.1 \pm 0.3$ for the Leonids. Hence, the Leonids were brighter on average than the annual Leonids, for which $\chi = 3.0 \pm 0.4$ in off-season years (Kresáková, 1966).

Support for the conclusion that the Leonids were brighter than usual comes from the radio forward meteor-scatter data. Automatic counts by Yrjölä show the mean meteor reflection duration, defined as the time that the recorded intensity is above a threshold value, to be longer during the Leonid outburst (0.81 ± 0.08 s) than for any of the annual streams observed with the same equipment (0.28–0.46 s). A similar excess of long duration echoes was detected by Bus *et al.* (1994). From the mean duration of reflections, in comparison to those of other streams, I surmise that the typical radio reflection during the outburst was from a +2 to +4 magnitude Leonid, while the detected sporadic meteors are typically of order +5 to +7 (McKinley 1961). Hence, the radio system monitors nearly the same mass range of meteoroids as seen visually.

Leonid Rates from Visual Data

The visual meteor counts (N_{Leo}/T_{eff}) listed in Table 2 are corrected for radiant altitude dilution, observer perception, and sky limiting magnitude resulting in a zenith hourly rate (Jenniskens, 1994a):

$$ZHR = \frac{N_{Leo}}{T_{eff}} \chi^{Lm-6.5} C_p^{-1} \sin(h_r)^{-\gamma} \qquad \text{Eq. (4)}$$

I adopt $\gamma = 1.4$ as in Jenniskens (1994a), $\chi = 2.1$ during maximum, and $\chi = 2.4$–2.8 on the nights before and after maximum. For the observations of Josep Trigo and Daniel Verde, I allow for a correction for the fraction of cloud cover (f_{cl}): $ZHR_c = ZHR / (1 - f_{cl})$. The total correction from an observed rate to the zenith hourly rate amounts to a factor 3–5. Error bars show the statistical uncertainty only (*i.e.*, $\sigma ZHR = ZHR/\sqrt{N}$, with N being the total number of observed Leonids).

Mean ZHR values per observer per night are shown in Fig. 2. A dashed line gives the level of annual activity from Fig. 1. It follows that the rates were significantly higher than this for three consecutive days. By assuming a symmetric curve as Eq. 1 for the excess outburst component, I find that the outburst component peaked on 1994 November 18 at 9.3 ± 2.5 hours UT, and the effective ($2\times e^{-1}$) duration of the event was 18 ± 5 hours (Table 1). Systematic uncertainties due to observer perception (Cp) and limiting magnitude correction (Lm) may amount to a factor of up to +1.7 in ZHR_{max} and a factor of +1.1 in B. The systematic errors are due to uncertainties in observer perception (Cp) and limiting magnitude (Lm) correction. The Cp is based on previous work of the observers in 1993 and 1994 and has an uncertainty of ~20%. The uncertainty in χ introduces an uncertainty of <50%. The uncertainty in the limiting magnitude correction depends on the correctness of an evaluation of the sky limiting magnitude estimates, which are somewhat observer dependent and could introduce errors of up to a factor of four. Hence, the result is most sensitive to the evaluation of the limiting magnitude estimates. Francisco Reyes Andres has systematically lower limiting magnitude estimates than the author by 0.6 magnitudes. Josep Trigo usually reports similar limiting magnitude estimates as the author, but now he reports very low values in the night of the outburst, in spite of an otherwise clear sky (between clouds) while there was no haze. Hence, his Lm values are increased so as to correspond to a clear sky with some moon and city light. The relatively large number of sporadic meteors reported by Valentin Grigore similarly suggests a higher limiting magnitude than given. David Swann, however, has previously reported high values of Lm during full moon conditions, and his lower than usual limiting magnitude estimate is taken at face value. The author observed from downtown Mountain View, California, on November 17/18. Considerable effort was made to make a good estimate of the limiting magnitude during the observations, and the result was compared to that at a darker site outside town on the next night.

Leonid Rates From Radio MS Data

The rate of radio reflections recorded by Yrjölä and De Meyere during the Leonid outburst are in good agreement, in spite of a different frequency and observing geometry.

TABLE 2 . Summary of visual observations.*

1994 Nov.	UT (hr)	λ_o long B1950	T_{eff} (hr)	f_{cl} %	hr o	moon o	Lm magn.	N_{leo}	N_{spo}	C_p	Observer†	ZHR (hr^{-1})
16	04.17	232.949	0.75	0	60	5	5.6 [6.2]	2	3	0.7	FR	6 ± 5
16	05.31	232.987	0.75	0	70	–8	5.7 [6.3]	1	4	0.7	FR	3 ± 3
17	09.50	234.181	1.25	0	31	44	5.2 [5.5]	6	6	1.2	BL	25 ± 10
17	11.00	234.244	1.00	0	50	30	5.4 [5.7]	1	6	1.2	BL	3 ± 3
17	12.00	234.286	1.00	0	62	18	5.4 [5.7]	5	4	1.2	BL	10 ± 5
17	13.00	234.328	1.00	0	73	6	5.3 [5.6]	14	9	1.2	BL	27 ± 7
18	01.00	234.832	1.11	0	41	40	4.0 [5.4]	14	4	1.1	VG	47 ± 13
18	02.20	234.883	1.06	0	53	28	5.0 [5.7]	17	4	1.1	VG	36 ± 9
18	03.42	234.934	1.02	0	63	16	5.0 [5.7]	35	2	1.1	VG	67 ± 11
18	03.50	234.938	0.31	0.12	51	33	4.0 [5.1]	8	0	1.3	JT	79 ± 28
18	04.09	234.962	0.32	0.22	58	27	3.3 [5.1]	5	0	1.3	JT	43 ± 19
18	04.42	234.975	0.32	0.22	61	23	3.8 [5.2]	6	0	1.3	JT	46 ± 19
18	04.88	234.997	0.56	0.06	66	17	4.0 [5.3]	4	1	1.3	JT	15 ± 8
18	05.77	235.033	0.43	0.70	69	18	5.9	5	1	1.0	DV	67 ± 30
18	06.30	235.055	0.52	0.50	76	11	5.9	10	1	1.0	DV	62 ± 20
18	10.77	235.243	1.00	0	63	26	4.5	13	0	1.1	DS	62 ± 17
18	11.77	235.285	1.00	0	74	14	4.5	15	4	1.1	DS	64 ± 17
18	12.75	235.320	0.30	0	64	24	5.1	5	0	1.0	PJ	55 ± 25
18	13.15	235.343	0.25	0	68	19	5.1	5	0	1.0	PJ	63 ± 28
18	13.51	235.358	0.27	0	71	15	5.2	5	1	1.0	PJ	49 ± 22
18	13.84	235.372	0.28	0	73	12	5.3	9	2	1.0	PJ	83 ± 28
19	03.75	235.957	0.97	0	54	40	5.1 [5.7]	6	3	1.3	JT	15 ± 6
19	04.22	235.976	0.30	0	61	34	5.1 [5.7]	3	1	0.7	FR	32 ± 19
19	04.73	235.998	0.40	0	66	28	5.1 [5.7]	1	1	0.7	FR	8 ± 8
19	05.12	236.014	0.40	0	69	24	5.1 [5.7]	1	1	0.7	FR	7 ± 7
19	05.73	236.040	0.30	0	73	17	5.3 [5.9]	4	0	0.7	FR	32 ± 16
19	09.70	236.207	0.40	0	30	66	5.6	1	2	1.0	PJ	13 ± 13
19	10.50	236.240	0.97	0	39	89	5.6	2	4	1.0	PJ	8 ± 5
19	11.50	236.283	0.97	0	51	48	5.7	6	3	1.0	PJ	16 ± 7
19	12.38	236.320	0.75	0	61	38	5.8	2	0	1.0	PJ	5 ± 4
20	05.00	237.018	0.85	0	68	35	4.7 [5.3]	3	0	0.7	FR	19 ± 11
20	05.75	237.050	0.50	0	73	26	4.7 [5.3]	0	0	0.7	FR	0 ± 11
20	10.67	237.257	0.97	0	41	65	5.5	2	3	1.0	PJ	11 ± 7
20	11.77	237.303	1.10	0	54	54	5.6	3	3	1.0	PJ	9 ± 5
22	10.95	239.289	0.95	0	44	71	5.9	0	5	1.0	PJ	0 ± 3
22	11.78	239.323	0.62	0	54	68	5.9	0	4	1.0	PJ	0 ± 4
Total:			24.95					219	82		6	

* The columns list date and time, solar longitude (B1950), effective observing time, percentage cloud cover, radiant altitude, altitude of the Moon, sky limiting magnitude, number of observed Leonids and Sporadics, the observer perception, the observer code and the calculated Zenith Hourly Rate.

† The visual observers are(in alphabetical order): Valentin Grigore (VG), at Targoviste, Rumania (+25.5E,45.0N), Peter Jenniskens (PJ), Mountain View, California (–122.0W,+37.2N), Robert Lunsford (BL), San Diego, California (–116.7W,32.8N), Francisco Reyes Andres (FR), Murcia, Spain (+01.1E,+38.0N), David Swann (DS), Carrollton, Texas (–96.9W,+33.0N), Josep Trigo (JT), Grau de Cautello, Spain (+00.0E,+39.0N), and Daniel Verde (DV), Gran Canaria, Spain (–5.6W,+27.7N).

Belkovich *et al.* (1995) checked for increased Leonid rates prior to 1994 from visual observations and found that the combined Leonid activity in 1992 and 1993 may have peaked already 2.5× higher than annual. However, those observers that reported high Leonid rates in 1993 November (Konsul and Shahin, 1994; Garrailov and Chakarov, 1994) also reported high sporadic rates (when given), while other observers saw normal annual rates at the same interval of solar longitude (Langbroek, 1994). Hence, the visual data do not conclusively prove enhanced rates in 1993.

Radio meteor scatter data exist for 1993, although these are contaminated by Auroral propagation (Fig. 3). After removing the narrow Auroral spikes, there is no sign of a similar broad outburst as in 1994 with peak rate higher than ZHR_{max} = 10, in agreement with the visual data.

The Encounter Geometry of the 1998 Return

The large number of documented historic Leonid outbursts allowed Yeomans (1981) to construct a map of the dust distribution near the comet, a version of which is reproduced in Fig. 4. The figure's vertical axis is the minimum distance to the comet orbit during an encounter (in astronomical units), while the horizontal axis is the time (in days) between the moment that Earth and comet pass this point. Dark dots mark those historic encounters that suggest a short duration event by giving a reference to a particular time in the night or to large numbers of faint meteors (Imoto and Hasegawa, 1958; Tian-shan, 1977; Hasegawa, 1993). Open circles in Fig. 4 show the encounter geometry for other possible outbursts after 1994 during the forthcoming return of the comet, the 34th since 902 A.D. The comet is due at perihelion on 1998 February 28.

Comparison with the 1965 Return

The 1994 outburst occurred 3.3 years before perihelion passage, at a point close to the location where in 1961 the first meteor outburst was detected (Fig. 4), but this time, the Earth passed 7 ×

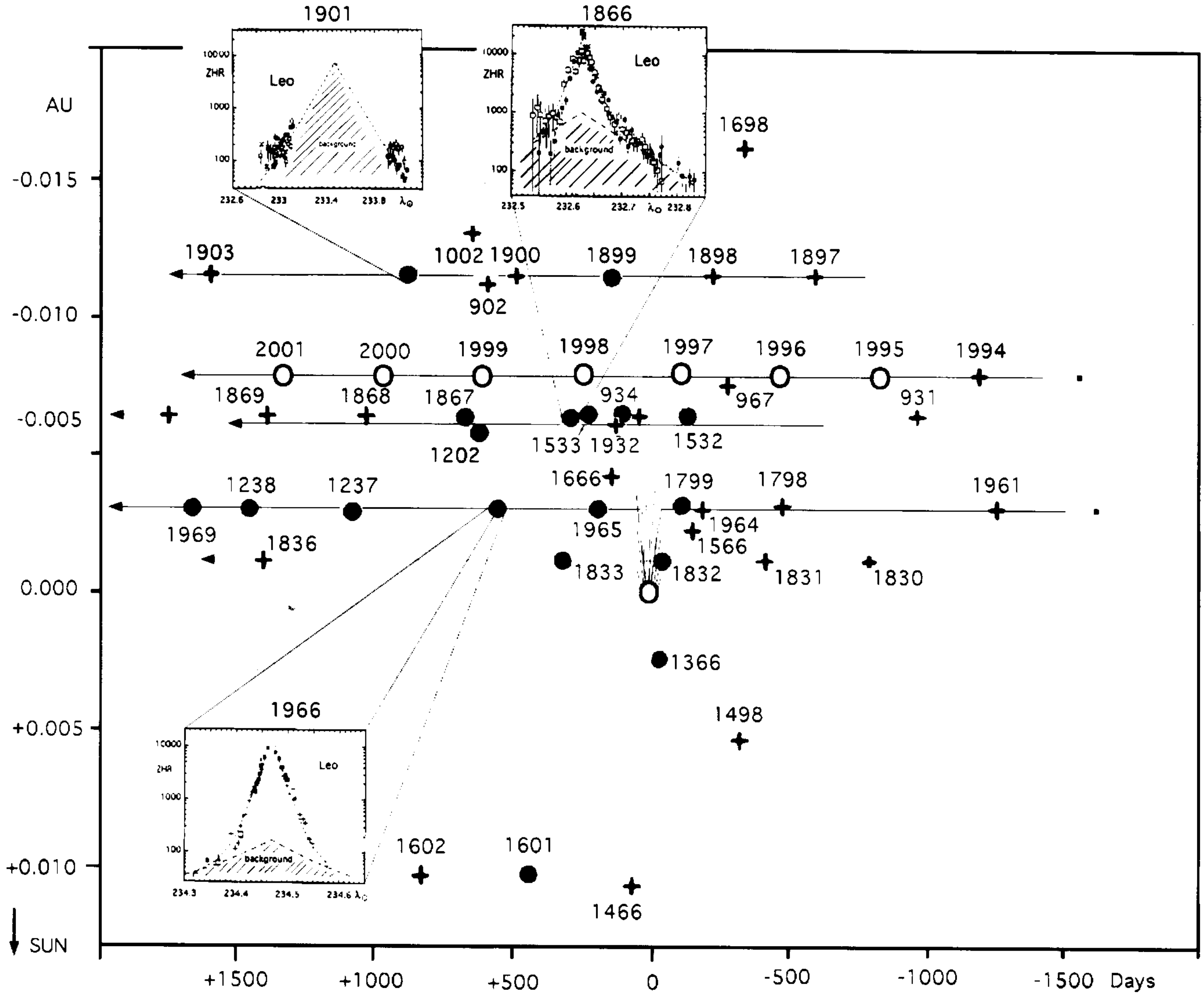

FIG. 4. Encounter conditions of the Earth with the Leonid stream. The time difference between the moment that the Earth and comet cross the descending node is plotted *vs.* the minimum distance to the comet orbit. The figure is adapted from Yeomans (1981). Crosses show when an outburst was observed, while black dots indicate the possible presence of a narrow component of faint meteors. The inset shows ZHR curves for the outbursts of 1966, 1866 and 1901 (Jenniskens, 1995), which are cross sections perpendicular to the plane of the page.

10^5 km further outward from the comet orbit. From the duration of that outburst, it follows that the extent along the Earth's path was some 2×10^6 km. If that dust is spread out at least as widely perpendicular to the Earth's path, which is likely, then the dust component encountered in 1994 is the same as that responsible for the outburst in 1961.

The 1961 outburst and others during the previous return are described in McIntosh and Millman (1970). Radar and visual data are reproduced in Fig. 5. By taking into consideration that the Canadian observations cover only part of the full range of solar longitude, we can only be certain that enhanced meteor rates occurred at solar longitude 233–235 in 1961, at solar longitude 233.8–236 in 1964, at solar longitude 233–235 in 1965, at 234.2–234.7 in 1966 (the meteor storm), between 234.7 and 236 in 1968, and possibly between solar longitude 234 and 235.5 in 1967. Visual rates at solar longitude 234.1 may have been too high in 1963. The visual rates, however, are uncertain because no limiting magnitude correction was applied, and the data are a very heterogeneous sample.

Most of these high rates seem to refer to a broad outburst, extending over a period of two days. Assuming that the reported radar rates are proportional to meteor influx, the increasing slope of the 1965 profile suggests B ~ 1.1, which is similar to the slope found in 1994. The radar data still contain an instrumental azimuthal or time-of-day dependence, suggested by the curved shape of most daily variation of rates. This effect was taken out by deriving an approximate response function from the radar detections in the off-season years 1958–1960, assuming that the rates did not vary much during the day in those years. The result after correction is plotted on a logarithmic scale, as before, in Fig. 6 and can be compared to the raw data in Fig. 5. Dashed curves give the possible position of broad outbursts. These events are found to peak at 233.9 ± 0.2 (1961), 234.4 ± 0.1 (1964), 234.0 ± 0.1 (1965), 234.6 ± 0.2 (1967) and 235.2 ± 0.1 (1968). If I assume that the duration of these meteor outbursts was always the same as in 1961, 1965, and 1994, and the activity curve followed Eq. 1, then the peak rates based on the visual activity from 1961 onward are $ZHR_{max} \sim 200$, 0, 20, 120, 300, 0, 100, and 100 meteors per hour in excess of annual rates, respectively. There is information on χ from radar data for two of these outbursts, both suggesting an abundance of relatively bright meteors: $\chi = 2.3$ in 1961 and 1.7 in 1965 (McIntosh and Millman, 1970). Hence, these events were similar to the outburst in 1994, both in duration and mean brightness. Although the 1967 and 1968 data suggest a broad dust component, it is not certain that these consisted of similar bright meteors.

The 1966 meteor storm was exceptional in that it was more narrow (B ~ 30; Jenniskens, 1995) and consisted of relatively faint meteors with $\chi = 3.0$ (McIntosh and Millman, 1970). Another narrow outburst of faint meteors was observed in 1969 with a sharp maximum between 234.5 and 234.62, which is not shown here (Millman, 1970; Porubcan, 1974). There is also a narrow component of faint meteors in the profile of 1965 at solar longitude 234.7. McIntosh and Millman interpreted this feature as due to a gradually changing χ over the profile but did notice a marked irregularity in rates. In view of the previous results, the more likely

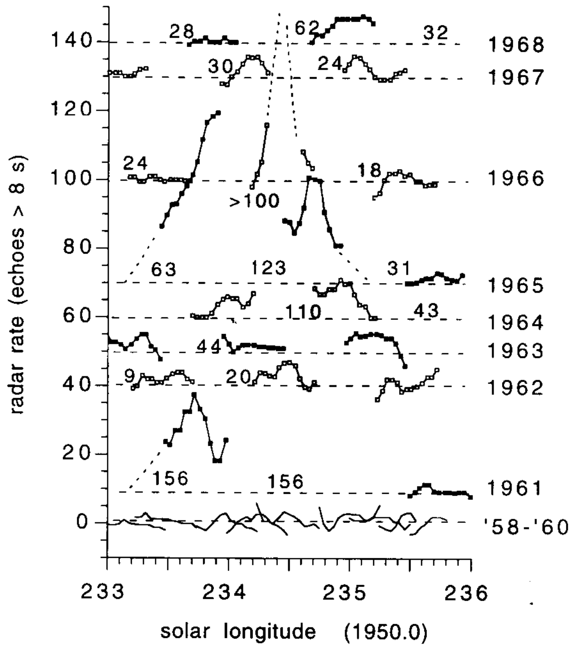

FIG. 5. Radar and visual Leonid rates during the 1961–1968 return. Data by McIntosh and Millman (1970). Leonid shower rates for echo durations longer than 8 s were determined by subtracting an average, non-shower, background count from the total count and correcting for radiant elevation using a simple sine function and are normalized to a radiant elevation angle of 30°. Numbers indicate the corresponding mean visual rate of six observers between 0 and 6 h LMT at Springhill Observatory. These values are ~2–3× the ZHR, given that the observed mean annual Leonid rate is 10–30.

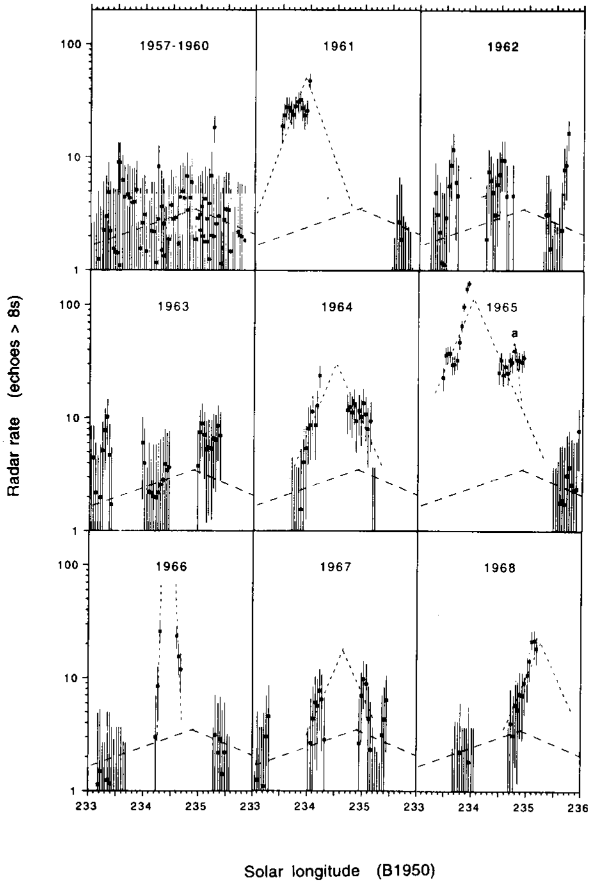

FIG. 6. Radar rates of Fig. 5 corrected for instrumental azimuth dependence and plotted on a logarithmic scale. Dashed lines guide the eye for the possible annual background and the occurrence of meteor outbursts.

interpretation is that of a composite of two unrelated dust components. The narrow component of faint meteors is at $\Delta\lambda_o$ = +0.47° after passage of the comet node, while the broad component of bright meteors peaks at $\Delta\lambda_o$ = −0.32° ± 0.08° before the node, causing a double peaked activity profile. Other such narrow outbursts may have occurred, but the Springhill radar did not cover the relevant interval of solar longitude in 1967 and 1968. The extent of this component, what seems to be a dust sheet, is mapped in Fig. 4.

These two dust components, one narrow and intense with many small meteoroids, the other broad and less intense with mainly bright meteors may represent different stages in meteor stream evolution or different formation processes.

A FORECAST FOR THE COMING YEARS

How will these different dust components behave in near-future returns when the parent comet P/Tempel-Tuttle passes perihelion? Let us assume that the previously observed patterns will be repeated. Such may well be the case, because planetary perturbations were mild in the past few returns (Kazimircak-Polonskaja *et al.*, 1968). The 1994 event is an assurance that the assumption is to some extent valid. The resulting forecast is given in Table 4, based on the following arguments.

Let us first consider the broad dust component of bright meteors. These dominated the events before, and perhaps also after, perihelion passage in 1965 November. There were significant variations of the time of maximum and the peak activity, which may be the result of planetary perturbations. The effect of such perturbations on the distribution of meteor orbits was recently demonstrated in a model of the Perseid stream by Wu and Williams (1993). The main planetary cause of gravitational perturbation is Jupiter, and its 12-year orbital period causes a systematic shift of the pattern of intersection points of individual orbits with the ecliptic on this time scale. However, the predicted motion of the time of maximum, which is a gradual progression to a later time, does not agree with observations. Instead, the observational record of past meteor outbursts often shows a progressive shift of the time of maximum towards the comet's node before perihelion passage and a progressive shift back after that (Jenniskens, 1995). The 1963–1968 outbursts are consistent with this, as may be the 1994 outburst. The 1961 outburst, however, is not consistent with this. Therefore, while I surmise that the peak of activity (at λ_o = 235.22 in 1994) will shift towards the position of the comet's node at λ_o = 234.58 while approaching 1998 and will shift back in later years, it can also be that there is a considerable scatter from year to year. The level of activity in each encounter remains even more uncertain. In general, the dust density is expected to increase closer to the comet, thus enhancing the chance of encountering a richer stream. The 1994 return suggests that the peak activity will be of the same order of magnitude as that in the previous series of events.

The Leonid storms are caused by a different dust component, probably relatively recent ejecta, containing weaker meteors with χ = 3.0. From the distribution of dark points in Fig. 4, it is suggested that this component will be met again in 1998 and 1999. I assume that highest rates will be in 1998 because the encounter conditions in 1998 are close to those in 1866. However, either year could give highest rates. The time of maximum is expected to fall shortly after the Earth's passage of the comet's orbital plane (at 234.578) and being progressively later in the years further away from the return of the comet in 1998 (Jenniskens, 1995). A more accurate time of maximum for the meteor storm may be obtained if this dust component announces its coming by a smaller event the year before the big storm, as in 1965. This could happen in either 1997 or 1998.

In Jenniskens (1995), I found that the narrow component of faint meteors has a background to its activity curve with B ~ 6. Little is known about the cause of this background, and its role can only be speculative. However, this background is present in varying relative strength, and it seems to become more important further away from the comet orbit. This is shown by the three activity curves shown as an inset in Fig. 4. This component did not play a significant role during the previous return, except perhaps in 1965. However, because the Earth will be further away from the comet orbit in 1998 than in 1966, rates may be high for a longer period of time than during the 1966 storm. Alternatively, the background may reflect recent planetary perturbations, in which case the background will remain weak instead.

It is clear that the forecast in Table 4 should be interpreted with caution when planning future observations. These predictions are not the result of modeling activity but rather assuming the Leonids will do what they did in the past. That is a reasonable assumption because of the absence of strong planetary perturbations since the previous return. The present forecast could be given more confidence with a theoretical underpinning provided by a dynamical model. Table 5 summarizes predictions that were made before based on such numerical simulations. There is considerable disagreement among the authors. The theoretical models are hampered by the unknown (time dependent) absolute dust production of P/Tempel-Tuttle, by unknown ejection mechanisms, and from limitations to the number of particles that can be modeled. However, because of the continuous increase of computing capacity, and supported by new observations, such theoretical models may prove valuable in making more reliable predictions in the near future.

TABLE 4. Prospects for near future Leonid outbursts.†

Year	λ_o^{max} (1950.0)	ZHR_{peak}	χ	Duration (hours)	Date	Time (hours UT)	Location	Moon %	Moon age
1994	235.22 ± 0.04	85 ± 15	2.1	20	Nov. 18	10 ± 1	E. USA	1.0	14
1995	235.2 ± 0.1	~30	2.0	20	Nov. 18	16 ± 3	Pacific	0.2	26
1996	235.1 ± 0.1	~100	1.9	20	Nov. 17	20 ± 3	Japan	0.5	7
1997	234.9 ± 0.2	~200	1.8 (3.0)	20 (0.7)	Nov. 17	21 ± 6	Japan	0.9	18
1998	234.64 ± 0.05	~10 000	3.0 (1.9)	0.7 (20)	Nov. 17	21 ± 1	Japan	0.0	28
1999	234.75 ± 0.15	~5000	3.0 (2.0)	0.7 (20)	Nov. 18	06 ± 4	E. USA	0.7	9
2000	235.0 ± 0.3	~100	2.1 (3.0)	20 (0.7)	Nov. 17	18 ± 8		0.6	21
2001	235.2 ± 0.5	~100	2.1 (3.0)	20 (0.7)	Nov. 18	~05		0.1	3

† This forecast is based on the assumption that previously observed patterns will be repeated. This table lists the solar longitude of peak activity (λ_o^{max}) in equinox B1950, which equals J2000 - 0.698°, the peak rate (annual + outburst combined), the duration, as well as the most favorable time and place to observe the event. The last column gives the fraction of the Moon that is illuminated (%) and the age of the Moon in days at the peak of the stream.

SUMMARY AND CONCLUSIONS

During the off-season, the Leonids are a moderately active annual stream with reported

TABLE 5. Forecast based on theoretical model calculations.

Reference:*	[1]		[2]		[3]	
Year	λ_o^{max}		λ_o^{max}		λ_o^{max}	ZHR_{max}
1997	234.869		–		234.11	1000
1998	234.897	rich	–		234.10	10 000
1999	234.925	rich	234.59	weak	234.10	100 000
2000	234.955	may be rich	235.57	moderate	234.09	1000
2001	–		235.77	very intense	–	
2002	–		236.19	very intense	–	

* Data by [1] Terentjeva (1991), [2] Kondratjeva and Reznikov (1985), and [3] Kresák (1993), while Brown and Jones (1993) predict a maximum each year at $\lambda_o = 234.50$.
All values of solar longitude are in equinox B1950.

peak activity varying by less than a factor of two in most years. The activity profile consists of a narrow main peak and a broader background, the shape of which has now been determined more accurately.

No significant increase of rates was reported until 1994 November when an outburst of bright meteors was observed by visual and radio meteor-scatter techniques. The encounter geometry was similar to 1961, when the first outburst associated with the previous return occurred. However, the time of maximum was $\Delta\lambda_o = 0.62°$ after passage of the comet node, while in 1961 it was $\Delta\lambda_o = 0.5°$ before. The event confirms the existence of a broad component in the P/Tempel-Tuttle dust distribution rich in large grains prior to perihelion passage. This dust component may have been responsible for a similar outbursts in 1965. There is some evidence that other such outbursts occurred in the years 1963 and 1964 and perhaps also post-perihelion in 1967 and 1968.

The Leonid storms are caused by a different, more narrow ($B \sim 30$), dust component rich in faint meteors ($\chi = 3.0$). This component was present in 1965, 1966, and 1969, with no data for 1967 and 1968. In 1965, both the broad and narrow component were detected. The activity curve of the narrow component contains a background of varying relative strength, with $B \sim 6$ and $\chi = 3.0$.

These features of Leonid activity curves may return in the forthcoming years, because recent planetary perturbations have been mild. A forecast in terms of the possible reappearance of each of these dust components is given in Table 4. All values in this Table include some speculation as to unknown properties of the dust distribution and unknown effects of planetary perturbations, which warrant further theoretical and observational studies. It is hoped that the 1994 event will mark the start of an international Leonid watch, an all-out effort to learn more about these impressive natural phenomena.

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Note added in proof: The Leonid meteor shower did return much as expected in November of 1995. Early reports suggest that a broad shower of bright meteors occurred centered at an early solar longitude $\lambda_o = 234.65 \pm 0.10$ (1950.0) with a peak rate of $ZHR_{peak} = 32 \pm 5$ meteors per hour.

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