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Leonid outburst activity 1996: A broad structure and a first occurrence of a narrow peak of fainter meteors

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Abstract–In 1996, a broad outburst structure of bright Leonid meteors similar to the 1995 and the 1994 displays (Jenniskens, 1996; Langbroek, 1996b) was observed. In addition, a second narrow outburst structure of fainter meteors, which will be reported and discussed in this paper, has with certainty been observed. This observation marks the first detection of such a narrow structure in the new series of Leonid outbursts. It has a similar exponential activity behaviour and similar emphasis on fainter meteors as shown by the 1866 and 1966 Leonid storm structures. Similar narrow peaks have been observed in 1965 and 1969 (Jenniskens, 1995, 1996).

The broad 1996 structure of bright meteors peaked at November 17.31 ± 0.04 (λ 235°.28 ± 0.04 (2000.0)). The additional narrow structure peaked at November 17.20 ± 0.01 (λ 235°.172 ± 0.007). The occurrence of the narrow peak can best be explained as a first modest sign of presence of the meteoroid structure that should be responsible for the expected meteor storm activity of the Leonids in 1998–1999. The appearance 0.°085 before the node of 55P/Tempel-Tuttle suggests that the expected 1998–1999 Leonid storms might peak just before passage through the node of the comet.

INTRODUCTION

The Leonid meteor stream, active each year near November 17, is known for producing conspicuous "outbursts" of meteors in 33 year intervals (outbursts are defined as temporary enhancements of stream activity well over the normal annual stream rates, due to an encounter with concentrations of fresh cometary ejecta that have not yet spread along the full cometary orbit (Jenniskens, 1995)). The meteoroids in the Leonid meteor stream originate from comet 55P/Tempel-Tuttle, which has a period near 33 years, and the meteor outbursts occur near the moment that the comet reaches its perihelion and is relatively close to the Earth (Yeomans, 1981; Hughes, 1982; Jenniskens, 1995; Yeomans *et al.*, 1996).

Connected to the recent perihelion passage of 55P/Tempel-Tuttle at 1998 February 28 (Yeomans *et al.*, 1996), the Leonid stream started a new cycle of outbursts in 1994 (Jenniskens, 1996). The zenith of this new cycle will probably be reached in 1998–1999, with prospects for a short spectacular meteor storm in one or both of these years (Kresák, 1993; Yeomans *et al.*, 1996; Jenniskens, 1996).

In 1994, a broad outburst structure rich in bright meteors with an effective 2x1/*e* duration of 0.77 days and a peak Zenith Hourly Rate (ZHR, see below) of 85 ± 15 on November 18.42 UT was observed (see Jenniskens, 1996, for details). A similar broad outburst structure, with a duration of 0.8 days and again relatively rich in bright meteors, reappeared in 1995 but peaked with a lower maximum ZHR of 30 ± 10 near November 18.0 UT (Langbroek, 1996b; Brown, 1996; Porubcan *et al.*, 1998).

The stream continued the new series of outbursts by producing strong activity in 1996, with a fine display lasting many hours, peaking over Europe and the USA. The high number of fireballs during the outburst activity caused excitement among observers (*e.g.*, Anonymous, 1997; Miskotte *et al.*, 1997). The 1996 appearance has become most notable, however, because it displayed two separate activity structures. Like the previous two years, 1996 saw the appearance of a broad activity structure of bright meteors. But in addition, this year also saw the occurrence of a second, shortlived narrow and strong activity peak of fainter meteors that was observed from Europe. A very preliminary report on the occurrence of this peak based on observations by members of the Dutch Meteor Society (DMS) observing from France was published by Langbroek (1996a) and confirmation came from Brown and Arlt (1997), who found a similar peak using observational data gathered by the International Meteor Organization (IMO) as part of the International Leonid Watch effort.

Here, I report on the activity behaviour of this narrow peak based on data gathered by Koen Miskotte, Jos Nijland, Marc de Lignie, and the author of the Dutch Meteor Society (DMS) and German observer Sirko Molau from the Arbeits Kreis Meteore (AKM). The activity analysis is enlarged with American data by observers George Zay, Bob Lunsford (IMO), and Norman McLeod III (American Meteor Society), obtained during the hours after the narrow peak ceased activity and covering part of the broader activity structure of bright meteors.

DATA AND REDUCTION PROCEDURE

The analytical method followed is that described by Jenniskens (1994, 1995, 1996). Raw data are normalized by transferring them into ZHRs, the hourly rates that a "standard" observer would see when observing with a naked eye, limiting magnitude of +6.5, and the radiant of the stream in the zenith (cf.,, Jenniskens, 1994, 1996). For this purpose, the data are corrected for deviations in the limiting magnitude (*Lm* = the brightness of the faintest stars visible with the naked eye), for radiant altitude dilution, and for observers perception (*Cp*). Only observations with radiant altitudes >20° have been included. All observers involved have a well-established observational history allowing calibration of their perception (see below) and reducing the risk of incorporating data of uncertain quality.

The observed meteor numbers are corrected for deviations in *Lm* by the equation:

$$r^{6.5-Lm} \quad (1)$$

The parameter *r* is the meteor brightness distribution index, which determines how the observed number of meteors is influenced by the limiting magnitude. This *r* value is determined from the meteor brightness estimates as discussed later in this paper.

The correction for radiant altitude dilution is obtained by the equation:

$$(\sin(h))^{-1.4} \qquad (2)$$

In this equation, h is the radiant altitude above the horizon, in degrees. The equation corrects for the fact that observed rates are lower with the stream radiant lower in the sky (cf., Jenniskens, 1994).

In addition, a correction factor Cp is employed. This is a correction factor for perception differences between observers (see Jenniskens, 1994). It is derived by using the rates of sporadic meteors (meteors that do not belong to a recognizable meteor stream and make for a continuous low-background activity of meteors during each night) observed by the observers in 1996 to calibrate them against a standard observer ($Cp = 1.0$) defined as an observer that observes an average of 10 sporadic meteors/h near 0 h local time in mid-August with a limiting magnitude at +6.5. The Cp values obtained for the observers are listed in Table 1a. A Cp below 1.0 signifies an observer that sees slightly less meteors than the "standard" observer under similar conditions; a Cp above 1.0 signifies an observer that sees slightly more meteors than the "standard" observer under similar conditions. Note that such differences do not necessarily have to do with observer's experience and data "quality" (cf., Jenniskens, 1994) but can be related to, for example, differences in eye sensitivity due to age. These differences introduce scatter in the obtained results if not corrected for.

Combined, the full equation used for ZHR calculation is (Jenniskens 1994, 1995):

$$\mathrm{ZHR} = (1/T_{effective}) \times N_{leo} \times r^{6.5-Lm} \times (\sin(h))^{-1.4} \times Cp^{-1} \qquad (3)$$

In which $T_{effective}$ is the effective observing time during each reductional interval (in hours); r is the corrected meteor brightness distribution index; N_{leo} is the number of Leonid meteors observed; Lm is the limiting magnitude during observations; h is the radiant altitude; and Cp is the observer's perception.

TABLE 1a. Summary of 1996 visual observations included in the analysis.*

November	h°	Lm	T_{eff}	N_{leo}	Observer	Cp	ZHR	±
17.065	33	6.20	0.38	7	MOLSI	0.9	58	22
17.128	43	6.40	0.52	14	LIGMA	1.0	62	17
17.133	43	5.70	0.50	18	NIJJO	2.0	56	13
17.149	47	6.30	0.18	8	LANMA	1.4	57	20
17.152	48	6.30	0.35	15	MISKO	1.2	63	16
17.162	50	6.50	0.23	19	LANMA	1.4	86	23
17.164	50	6.50	0.13	7	MISKO	1.2	65	25
17.173	52	6.60	0.28	24	MISKO	1.2	91	19
17.174	53	6.00	0.50	11	MOLSI	0.9	53	16
17.174	52	6.50	0.32	24	LANMA	1.4	75	15
17.187	54	6.45	0.38	30	MISKO	1.2	93	17
17.188	54	6.45	0.25	20	LANMA	1.4	80	18
17.190	55	6.00	0.25	11	MOLSI	0.9	101	30
17.200	56	6.30	0.28	36	LANMA	1.4	143	24
17.201	57	6.30	0.28	31	MISKO	1.2	142	26
17.205	56	5.78	0.44	23	MOLSI	0.9	149	31
17.241	61	5.60	0.20	6	MISKO	1.2	59	24
17.241	61	6.20	0.15	10	LANMA	1.4	72	23
17.289	23	7.30	1.00	20	MCLNO	0.4	112	25
17.331	37	7.30	1.00	23	MCLNO	0.4	70	25
17.372	50	7.30	1.00	28	MCLNO	0.4	61	11
17.375	22	6.40	1.00	19	LUNRO	1.0	80	18
17.408	32	5.74	1.00	15	ZAYGE	0.8	74	19
17.417	34	5.99	1.00	17	LUNRO	1.0	53	13
17.420	65	7.30	1.32	46	MCLNO	0.4	60	9
17.451	45	6.02	1.00	13	ZAYGE	0.8	36	10
17.458	47	6.13	1.00	16	LUNRO	1.0	31	8
17.496	58	5.95	1.00	28	ZAYGE	0.8	63	12
17.500	59	6.33	1.00	30	LUNRO	1.0	44	8
17.535	69	5.78	0.78	17	ZAYGE	0.8	48	12
17.542	71	5.77	1.00	35	LUNRO	1.0	60	10
TOTAL			18.72	603	Eight observers			

*The columns list date (UT), radiant altitude, limiting magnitude, effective observing time (hours), number of Leonids observed, observers code, the observers perception, and the calculated ZHR. Radiant altitude was calculated using the radiant position obtained during the 1995 outburst (Betlem *et al.*, 1997). Observer codes: LANMA = Marco Langbroek (Somme Valley, France); MISKO = Koen Miskotte (Somme Valley, France); LIGMA = Marc de Lignie (Somme Valley, France); NIJJO = Jos Nijland (Somme Valley, France); MOLSI = Sirko Molau (Sleswig-Holstein, Germany); MCLNO = Norman McLeod (Florida, USA); LUNRO = Robert Lunsford (California, USA); ZAYGE = George Zay (California, USA).

For more details and background on elements of the equation, I refer to Jenniskens (1994).

The calibration of the data to a well-defined "standard" observer as explained above is important. As a result of the chosen reduction method, the activity curve obtained is directly comparable with earlier results on annual and outburst Leonid activity published by Jenniskens (1995, 1996).

The raw data were gathered from five different observing localities. Dutch observers Marco Langbroek, Koen Miskotte, Jos Nijland, and Marc de Lignie observed from two localities just south of the Somme Valley, France, separated by some 50 km; German observer Sirko Molau observed from Sleswig-Holstein, Germany, separated some 800 km from the observers in France; American observer Norman McLeod observed from Fort Myers, Florida, on the east coast of the USA; American observers Bob Lunsford and George Zay observed from Descanso, California, on the west coast of the USA. Raw observational data and site coordinates for observers Marco Langbroek, Koen Miskotte, Jos Nijland, and Marc de Lignie have been published in (Langbroek, 1996a) and (Arlt, 1997) and are stored in the IMO and DMS electronic databases; for Sirko Molau, George Zay, Bob Lunsford, and Norman McLeod, they have been published in (Arlt, 1997) and are stored in the IMO electronic database. Sirko Molau (pers. comm.) additionally supplied his data in small time-units for the purpose of the current analysis. Essential raw data and individual ZHR results as well as magnitude distributions are summarized in Tables 1a,b.

TABLE 1b. Magnitude distributions

Observer	−4	−3	−2	−1	0	+1	+2	+3	+4	+5
MISKO	4	3	2	1	3	11	12	20	25	23
LANMA	3	3	3	2	3	8	10	17	25	26
MOLSI	1	2	1	1	9	7	11	13	7	0
MCLNO	2	5	6	9	21	20	21	20	7	3
LUNRO	1	4	8	7	22	22	17	28	14	3
ZAYGE	2	3	7	5	13	17	20	7	7	1

*Data observers MISKO, LANMA, and MOLSI for November 17.156 to 17-.212 UT; data observer MCLNO for November 17.271 to 17.448 UT; data observers LUNRO and ZAYGE for Nov. 17.354 to 17.563 UT. Limiting magnitudes are listed in Table 1a.

Meteor Magnitude Distributions

The meteor brightness distribution is an essential piece of information, not only to indicate the meteor brightness characteristics, but also to correct the observed rates for deviations in limiting magnitude in order to normalize data to ZHRs. The observed brightness distribution is influenced by an increasing proportion of missed meteors in the fainter magnitude classes. To obtain the true (corrected) brightness distribution, this has to be corrected.

Figure 1 shows the corrected meteor brightness distribution for the Leonids obtained. Raw counts (Table 1b) were corrected into real numbers using a probability function (for details, see Jenniskens, 1994), allowing a correction for the limiting magnitude, and results were then pooled. Figure 1 shows separate distributions for the meteors obtained between 3:30–5:05 UT (activity period narrow peak) by Langbroek, Miskotte, and Molau (dots); and data obtained from the USA by McLeod, Zay, and Lunsford (blocks) from 6:30–13:30 UT. The U.S. data are displaced by one decade for clarity. The two data sets show a different slope of the distribution: the U.S. data result in a distribution that is flatter than the European data from the 3:30–5:05 UT interval, which suggests an influx of fainter meteors during the activity period of the narrow peak (see also Langbroek, 1996a; Brown and Arlt, 1997) compared to the broader background structure sampled by the U.S. observers. Porubcan *et al.* (1998) also provide evidence for fainter meteors in the solar longitude interval 235°.10–235°.22 (3–6 h UT) from forward scatter data of the Bologna–Lecce–Modra radar.

The slopes of the curves determine the meteor brightness distribution index r, that is used in the correction for limiting magnitude (see Eq. 1). The value r signifies the proportional increase in true number of meteors per magnitude bin, as defined by the equation (Jenniskens, 1994, 1996):

$$r = n(m+1)/n(m) \tag{4}$$

The European data from the narrow peak period result in $r = 2.5 \pm 1.3$ for magnitude –2 to +4. There is perhaps a hint of a non-exponential distribution made up of a combined flat and a steep component (see also Langbroek, 1996a). The emphasis on fainter meteors compared to the U.S. data is shown by all three observers (Molau, Langbroek, and Miskotte) individually. The distribution of the observations obtained from the USA result in $r = 1.9 \pm 0.9$ for the magnitude interval –4 to +5 and the distribution appears exponential. The depicted slopes in Fig. 1 are for $r = 1.9$ and $r = 2.5$. The r value of 1.9 is slightly higher than the r value of 1.7 reported by Porubcan *et al.* (1998) from their radar forward scatter data (long-duration echoes) if we ignore the error margin. Using the lower r value of Porubcan *et al.* (1998) does not, however, lead to a large difference in the obtained ZHRs compared to the values reported below; the difference amounts to <10%. Moreover, it is not clear how well the mass distribution exponent obtained by radar is comparable to the magnitude distribution exponent from visual observations. Earlier work with the Bologna-Lecce forward scatter setup on the 1991 Perseids and 1992 Quadrantids revealed that the r values obtained for overdense echoes (bright meteors) with this setup come out slightly lower than values obtained for these streams from visual observations (Cevolani and Hajduk, 1993) and, additionally, Simek (1993) has found a diurnal effect in radar mass distributions (from which the r value is derived in radar observations) that seems to be connected to diurnal variations in atmospheric conditions.

The visual data reported in the current paper do not allow for the construction of a diagram showing the details of evolution of the r value over time. For this purpose, the two data sets as presented in Fig. 1 would have to be broken up in smaller units introducing very large error margins (note that even the large data set used by Brown and Arlt (1997) was barely sufficient for that purpose, as evident from their Fig. 2 (Brown and Arlt, 1997)). Instead, the pooling of data in the format of Fig. 1 was therefore chosen. It provides the clearest indication available of a difference in r value between the activity period of the shortlived narrow peak observed by the European observers and the broader background activity sampled by the American observers (see discussion on activity behaviour below). The radar data by Porubcan *et al.* (1998) indicate that some low-amplitude variations might have been present during the activity period of the broad structure, too, but these variations are too small to introduce serious error in the obtained visual activity profile. Moreover, the mass distribution exponent evolution over time as charted by Porubcan *et al.* (1998) for the 1996 Leonids is consistent with the diurnal variation pointed out by Simek (1993), except for the shortlived rise in mass distribution between solar longitude 235°.10–235°.22 (3–6 h UT) corresponding to the activity period of the narrow activity peak.

Activity Behaviour

Figure 2 shows the activity curve obtained by averaging individual ZHR results in 20 min intervals (narrow peak period) and 1 h intervals (activity period broad activity structure). Shown standard deviations depict the statistical 1 σ uncertainty only where

$$\sigma = \mathrm{ZHR}/\sqrt{(n_{Leo})}\,.$$

In ZHR-calculation an r value of 2.5 has been used for the narrow peak period, an r value of 1.9 outside the narrow peak period, and an assumed intermediate r value of 2.1 near the base of the narrow peak. The depicted rate evolution for both peaks show the exponential behaviour typical of outburst structures and meteor activity in general. The slopes can be represented by the equation (Jenniskens, 1994, 1995):

$$\mathrm{ZHR} = \mathrm{ZHR}_{\max} \times 10^{-B|\lambda - \lambda_{\max}|} \tag{5}$$

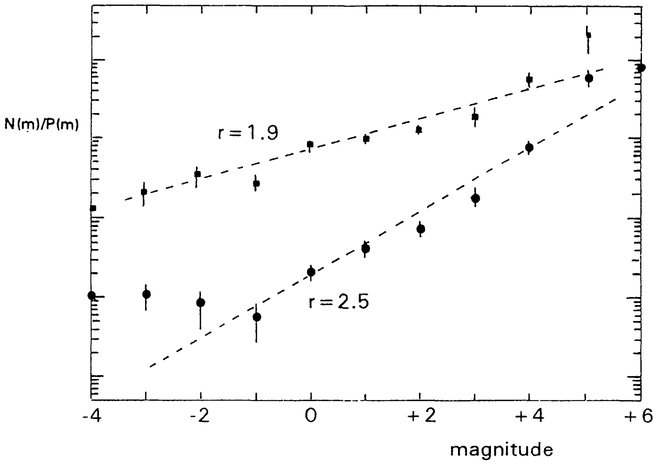

FIG. 1. Corrected magnitude distributions employing data from Table 1b (see main text for details). Dots represent the period November 17.156–17.212 UT covering the activity period of the narrow structure. Blocks represent the period November 17.354–17.563 UT covering the descending slope of the broad structure and have been displaced by a decade for clarity. Trend lines indicate slopes for $r = 1.9$ and $r = 2.5$. The data gathered by American observers covering the descending slope of the broad structure (blocks) imply a flatter distribution and, hence, stronger emphasis on bright meteors compared to the magnitude distribution obtained by the European observers (dots) during the activity period of the narrow peak.

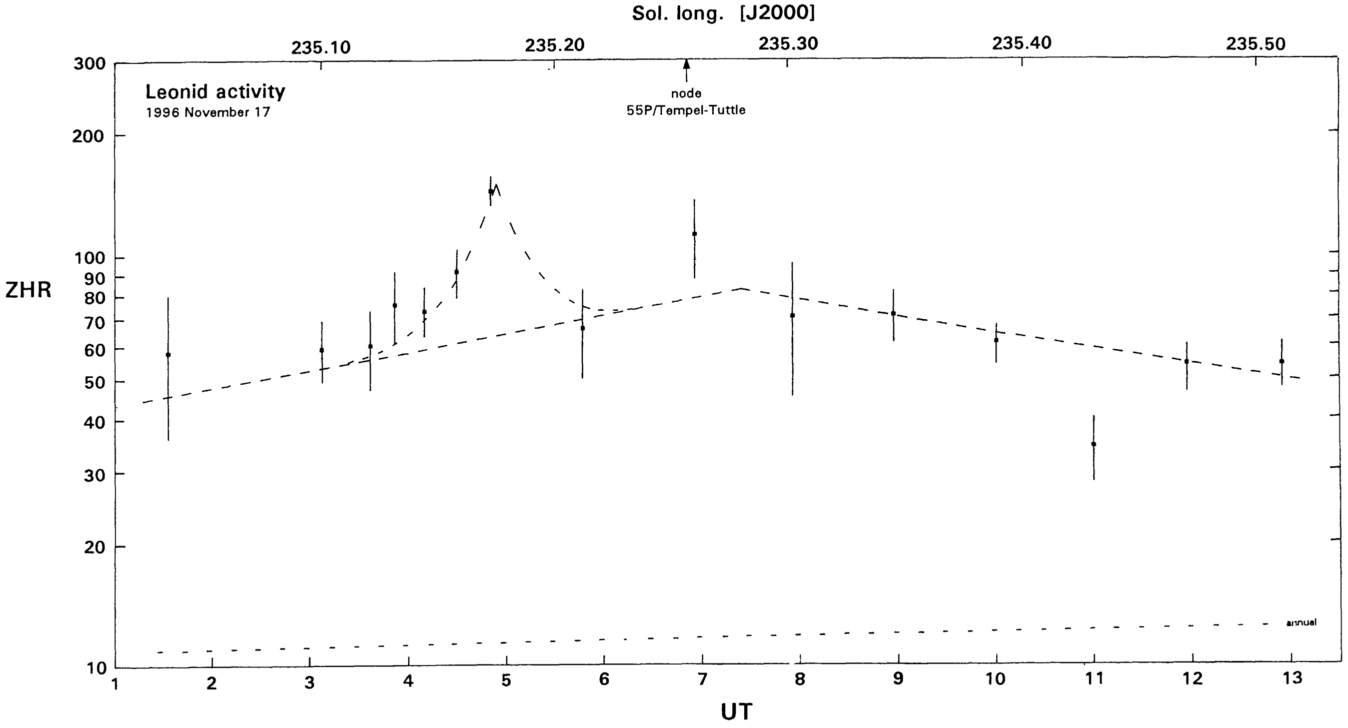

FIG. 2. Activity behaviour for the core of the 1996 Leonid outburst as reconstructed from the data analysed in this paper, showing the composite of a broad background activity structure peaking near solar longitude 235°.28 ± 0.04 and a narrow activity structure peaking near solar longitude 235°.172 ± 0.007. Dots represent ZHR values obtained by averaging individual ZHR results (see Table 1a) obtained over the interval in which the dot is centered. The reduction intervals do not overlap: no smoothing procedure has been employed. Depicted error bars show the statistical uncertainty only ($\sigma = \text{ZHR}/\sqrt{(n_{Leo})}$). The shown trend lines for the activity behaviour are explained in the text. The arrow in the solar longitude scale at the top of the diagram marks the node of the comet 55P/Tempel-Tuttle orbit. Solar longitudes refer to 2000.0.

In this equation, λ signifies the solar longitude (the orbital position of the Earth). The value B is a measure of activity slope steepness and relates to the effective duration and cross-section of the peak (Jenniskens, 1994, 1995). Usually, outbursts of the same stream have similar values for B (and thus similar effective durations) regardless of a difference in peak strength (Jenniskens, 1995). For example, both the 1866 and 1966 narrow Leonid storm peaks (and the strong narrow 1867 peak) had a B value of 30. By contrast, the broad Leonid outburst structures of 1994, 1995, and 1996 all have B values in the order of 1.1–1.2 (see Table 2. The B value for 1994 was 1.15 ± 0.30 (Jenniskens, 1996); for 1995, 1.1 (Langbroek, 1996b); for 1996, 1.2 ± 0.3 (see below)). Quite often, outbursts connected to the nearby passage of the parent comet ("near comet type" outbursts (Jenniskens, 1995)) display a combination of two different structures, each with its own B value superimposed on each other (Jenniskens, 1995), in the form of a broad background and a more narrow "main peak". The Leonids show this very clearly for the 1866 activity profile (Jenniskens, 1995). Presumably, these different activity structures represent different stages in meteoroid stream evolution (Jenniskens, 1995, 1996).

The obtained activity curve for the Leonids of 1996 (Fig. 2) shows that two such structures have been active in 1996—a broad structure of bright meteors similar to the activity structure observed in 1994 and 1995, and an additional narrow structure.

Broad Structure–The broad structure of bright meteors (r = ~1.9) peaked at November 17.31 ± 0.04 UT (λ 235°.28 ± 0.04) with a peak ZHR of 70 ± 10 (outburst structure only; including the annual activity structure hidden under the outburst (Jenniskens, 1996), this results in a combined ZHR just over 80) and shows an activity behaviour (Eq. 5) with $B = 1.2 \pm 0.3$ for the ascending and descending slopes. It has an effective 2 × 1/e duration of 0.77 days (0°.72 in solar longitude) corresponding to an effective cross-section of 0.0127 AU parallel to the Earth orbit.

The peak is quite similar to the 1994 outburst peak in strength and cross-section (Jenniskens, 1996) but differs in the position of maximum as measured in solar longitude (λ), the orbital position of

TABLE 2. A comparison of Jenniskens' (1996) predictions, and observed activity behaviour for the broad structure.*

	Jenniskens (1996)			Observed			
Year	$\lambda_{\max}$	$\text{ZHR}_{\max}$	r	$\lambda_{\max}$	$\text{ZHR}_{\max}$	r	Reference
1994	–	–	–	235°.92	85 ± 15	2.1 ± 0.3	Jenniskens (1996)
1995	235°.9	~30	2.0	235°.2	30 ± 10	2.0 ± 0.3	Langbroek (1996b)
1996	235°.8	~100	1.9	235°.28	70 ± 10	1.9 ± 0.9	This analysis

*Solar longitudes refer to 2000.0

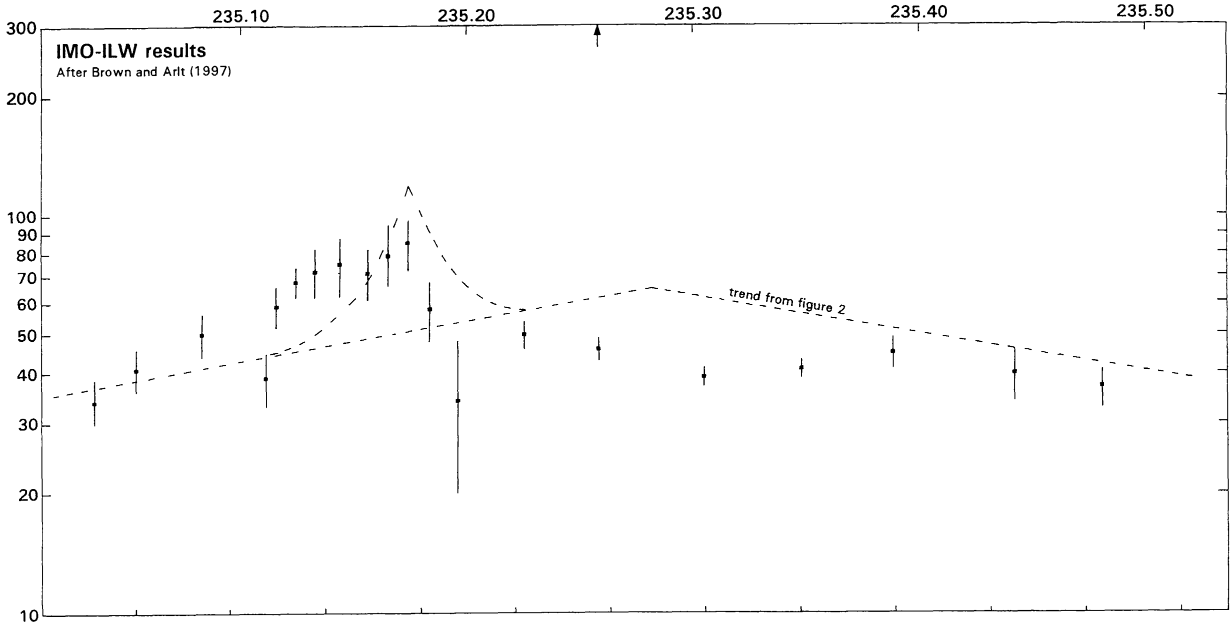

FIG. 3. Activity behaviour for the core of the 1996 Leonid outburst according to an analysis by Brown and Arlt (1997) of the International Meteor Organization. Data taken from Brown and Arlt (1997) have been depicted in the same format as Fig. 2 with the trend behaviour from Fig. 2 (the dashed lines) scaled down to match the activity level of the IMO analysis in order to aid comparison (see main text for details). Solar longitudes refer to 2000.0. Note the broadening and flattening of the narrow activity structure near solar longitude 235°.17 compared to Fig. 2, and the "dip" displayed near the peak of the broad background structure from Fig. 2 (see discussions in main text).

the Earth. Peak rates are found near solar longitude 235°.28 ± 0.04 (2000.0), while in 1994 peak rates occurred much later at solar longitude 235°.92 (Jenniskens, 1996). Both displays included many bright meteors. The obtained position of the maximum for 1996 is slightly earlier than that at solar longitude 235°.4 reported by Brown and Arlt (1997) (see discussion below) and corresponds well with a reported peak position at solar longitude 235°.27 according to observability-function corrected radio meteor scatter data by Bus (1997) and uncorrected forward scatter radar data by Porubcan *et al.* (1998). The 1996 peak position found in the current analysis nearly coincides with crossing of the node of comet 55P/Tempel-Tuttle, which is at λ 235°.258 (Yeomans *et al.*, 1996) and indicated by an arrow in the top of Fig. 2. Note that the apparently slightly higher rates near crossing of the node should be looked at with caution, since this particular ZHR determination is based on limited early U.S. east coast data obtained with a low radiant altitude and thus relatively large correction factors are involved.

Narrow Structure–The narrow structure of fainter meteors ($r = {\sim}2.5$) peaked at November 17.20 ± 0.01 UT (λ 235°.172 ± 0.007) with a peak ZHR of 65 ± 15 (narrow peak alone; including the broad background structure and the annual structure, this results in a combined ZHR near 150) and shows an activity behaviour (Eq. 5) with $B = 30 \pm 10$ for the ascending slope (the descending slope was not well covered due to cloud interference and onset of twilight after 5:00 UT in both France and Germany). It has a $2 \times 1/e$ duration of only 0.7 h (0°.029 in solar longitude) corresponding to an effective cross-section of 0.0005 AU parallel to the Earth orbit.

The peak bears a strong resemblance to the narrow "main peaks" (the storm peaks) in the Leonid profiles of 1866 and 1966 (see Jenniskens, 1995, 1996) in terms of B value of the ascending slope and the emphasis on fainter meteors. The peaks of 1866/1966 only differ compared to 1996 in the peak strength. A similar appearance of a narrow peak with "modest" activity compared to the strong storm-level peak of 1966 has been reported for 1965, while another similar occurrence is reported for 1969 (Jenniskens, 1996). Those peaks however appeared after passage through the cometary node, unlike the 1996 peak. Nevertheless, the narrow 1996 peak of faint meteors is best explained as a first modest appearance of the meteoroid component that will be responsible for the expected meteor storm activity in 1998 and/or 1999 (see Yeomans *et al.*, 1996; Jenniskens, 1996).

Outburst peaks usually show a gradual shift towards the cometary node when approaching the year of perihelion passage of the parent comet, and then shift away from it again after perihelion passage (Jenniskens, 1995, 1996). For example, the Leonid outburst peaks of 1866 and 1867 clearly show this behaviour, with peak position shifting from solar longitude 233°.325 in 1866 to 233°.411 in 1867 (Jenniskens, 1995), away from the cometary node then situated at 233°.252 (Yeomans *et al.*, 1996). Therefore, the similarity in solar longitude between the 1996 peak position and the peak position of the 1966 storm occurrence (solar longitude 235°.166; Jenniskens, 1995) as noted by Brown and Arlt (1997) is probably a coincidence. The mentioned historic peak behaviour also puts constraints on the importance to be attached to the apparent strong similarity of the 1996 narrow peak position with the model results of Brown and Jones (1993), because their predictions assume that the solar longitude at which the meteoroid component responsible for the narrow peak will be encountered is stationary over a cycle of several years, in contrast to the historic picture of previous outburst cycles. (We should, however, be aware that the current cycle does not necessarily have to follow the pattern of previous historic cycles, although it is likely that it will.) There is still a lack of understanding about what determines the behaviour of the shifting peak positions. Nevertheless, 1997 results (Arlt and Brown, 1998) discussed briefly below do suggest that the narrow peak during the current cycle also shows this behaviour. Notwithstanding this, their general results can be taken to indicate that the possible narrow storm structure of meteoroids will be encountered before the time of node crossing in the current outburst cycle, which matches the appearance of a narrow structure at a solar longitude in front of the cometary node in 1996.

Possible Error

The depicted standard deviations in the activity profile of Fig. 2 depict the statistical error only. Systematic errors due to flaws in the reduction method or the quality of the data could still be hidden in the profile. The weakest point in this respect is the junction of European and American data near 6–7 h UT, the moment of passage through the node of comet 55P/Tempel-Tuttle. Unlike the other parts of the curve, there is no data overlap at this point due to the "Atlantic gap". The results near nodal passage are based on limited American east coast data gathered with a still low radiant altitude only. Later in the profile, the good match between the partly overlapping data from the west coast and the east coast (see Table 1a) gives confidence in the general results for the descending slope of the broad activity structure. Likewise, the close agreement between the overlapping European data from the narrow peak period gives confidence in the results.

The reported results for the narrow peak considerably improve on the very preliminary results published earlier (Langbroek, 1996a). Corrections for perception have been improved, reducing scatter between individual results. The inclusion of the independant data-set obtained by German observer Sirko Molau hightens confidence in the reality of the reported narrow peak occurrence. The observing locations of the Dutch group and Molau were over 800 km apart, which shows that the reported peak is not a "local" phenomenon (Langbroek, 1996a) but a true structure in the activity profile. As Table 1a shows, both the obtained absolute activity level as well as rate development over time agree closely when we compare Molau's results with the results of the Dutch observers in France. Given the clear differences in limiting magnitude, this also gives confidence in the *r* values used, which otherwise form another potential weak spot (see previous discussions and discussion of IMO results below).

The addition of the American data, broadening the window of activity reconstruction, helps to put the results from the narrow peak occurrence in a broader context. This is relevant for the reconstruction of the narrow peak rate behaviour, too. By defining the activity behaviour of this background structure, the characteristics and activity behaviour of the meteoroid component responsible for the narrow peak can be better confined: the observed peak is due to an interaction of this meteoroid component with the meteoroid component of the broad background activity structure.

COMPARISON WITH OTHER AVAILABLE ANALYSES

It is instructive to compare the reported results with other available analyses of 1996 Leonid activity behaviour. Two analyses are suitable for comparison.

Porubcan *et al.* (1998)–Porubcan *et al.* (1998) report radar forward scatter results obtained by the Bologna-Lecce-Modra network operating from Italy and Slovakia during the 1996 Leonids. They present uncorrected data (counts) only. Data have not been corrected for observability (*i.e.,* no corrections for radiant altitude and radiant-antenna geometry (*e.g.,* Yrjölä and Jenniskens, 1998) have been applied), only a sporadic background reconstructed from observations a few days before and after the maximum has been substracted. This hampers detailed comparison with the current analysis, but a broad range comparison suggests that there are clear agreements. Like the current analysis, Porubcan *et al.* (1998) reconstruct the presence of a broad activity structure that was active over many hours and consisted of very bright meteors. Their uncorrected data suggest a peak near solar longitude 235°.27 (2000.0) for this structure, which is in excellent agreement with the solar longitude found in the current analysis (235°.28 ± 0.04). On the other hand, no narrow structure near solar longitude 235°.17 is present in their data. Instead, the (uncorrected) rates seem to suggest a dip in activity near this solar longitude (Porubcan *et al.,* 1998), coinciding with a rise in the obtained mass distribution (*i.e.,* a rise in *r* value) indicating an emphasis on smaller meteoroids and thus fainter meteors (Porubcan *et al.,* 1998). In this respect, it should be noted again that they do not correct their data for observability as should be done to obtain a reliable reconstruction of variability in activity behaviour (Porubcan *et al.,* 1998). Part of the activity variation reported (with "peaks" at solar longitude 235°.07 and 235°.27) might be due to changing observability connected to the changing radiant-antenna geometry and/or the change in *r* value near solar longitude 235°.17. Looking at the counts from the individual Lecce and Modra receiving stations (Porubcan *et al.,* 1998), it is evident that a strong dip in the counts of Modra station near 4 h UT is solely responsible for the "dip" in the combined results of both stations near the solar longitude discussed. This decrease in counts for Modra coincides with the moment that the antenna-receiver azimuth direction (224°) and radiant azimuth direction of the stream are perpendicular, the most unfavourable observing geometry conditions for a forward scatter setup (Yrjölä and Jenniskens, 1998). Hence, it appears to be an instrumental effect.

The change in mass distribution (Porubcan *et al.,* 1998) between solar longitude 235°.10–235°.22 (see above discussion of meteor magnitude distributions) is however consistent with the rise in *r* value near solar longitude 235°.17 during the activity period of the narrow peak as reconstructed from the visual observations reported in the current analysis and by Brown and Arlt (1997).

Faint meteors extinguish higher in the atmosphere, the more so when they have greater speed. Altitude ceiling effects can restrict the detection of such faint, fast meteors in radio wavelengths (*e.g.,* Elford 1993; cf., McKinley, 1961, for details) and, therefore, a component of faint Leonids (which are among the fastest meteors that exist) can be missed by a forward scatter setup. The lower mass distribution values obtained for the short duration echoes (fainter meteors) compared to the long duration echoes (brighter meteors) (Porubcan *et al.*, 1998) suggest that perhaps a portion of the fainter Leonid meteors is indeed missed, hampering the detection of a narrow peak with an emphasis on faint meteors. Indeed, according to Porubcan (pers. comm.), the narrow peak of faint meteors is not likely to be detectable in the data that Porubcan *et al.* (1998) report.

Brown and Arlt (1997)–Another independant analysis of 1996 Leonid outburst activity based on a large data-set of visual observations gathered by the IMO has been published as Bulletin 10 of the International Leonid Watch (Brown and Arlt, 1997). Results from the Brown and Arlt analysis are depicted in Fig. 3 and given in a similar format as the results in Fig. 2. Due to a slightly different method of correction for radiant altitude dilution and a difference in the definition of the standard observer, the absolute levels of activity of the IMO and the current analysis are not directly comparable. The difference amounts to a factor of 1.22–1.24 in general (Jenniskens, 1996; Langbroek *et al.*, 1998). The activity trends as shown in Fig. 2 have been scaled down by a similar factor and depicted in Fig. 3 to aid comparison.

In general terms, the results of the IMO analysis compare well with the results of the current analysis. In details, however, there are deviations. Both analyses agree with the presence of a broad background structure of bright meteors, and superimposed on this is the presence of a more narrow structure near solar longitude 235°.17 featuring fainter meteors (Brown and Arlt, 1997). However, the narrow peak as reconstructed by Brown and Arlt is lower and broader and appears considerably flattened in comparison to the results reported in the current analysis. Similarly, the broad background activity structure appears to be more flattened in comparison to the current analysis. Brown and Arlt (1997) report a peak position for this structure that is slightly later (solar longitude 235°.4 ± 0.1) than that reported in the current analysis (solar longitude 235°.28 ± 0.04) and the analysis by Porubcan *et al.* (1998), but the values overlap when the uncertainties are taken into account. As can be seen in Fig. 3, the IMO activity curve displays a gentle dip around the peak of the activity obtained in the current analysis; but near the edges of the profile, the reconstructed activity behaviour appears to be in agreement. The differences most likely derive from problems pertaining to the analytical methods and database quality employed by IMO for their analysis. Three effects artificially influence the obtained activity curve: two that are endemic to the general analytical method employed, and a third related problem that is endemic to the peculiar characteristics of the 1996 Leonid activity.

One endemic problem pertaining to the IMO analytical method is their use of a running average and relatively large data intervals, which is a method not fit for the analysis of narrow fine structure as discussed in this paper. For the narrow peak period, Brown and Arlt have used 0°.02 smoothing intervals in solar longitude (corresponding to intervals of ~50 min in time over which obtained individual ZHRs were averaged) shifted in steps of 0.°01. For the broad background structure, they used 0°.1 smoothing intervals (corresponding to 2.4 h) shifted in steps of 0°.05. This contrasts with the 20 min intervals for the narrow peak period and 1 h intervals for the broad background activity structure and no smoothing procedure at all as employed in the current analysis. The 50 min intervals used in the IMO analysis are larger than the actual 40 min 2 × 1/*e* peak duration as reconstructed for the narrow peak in the current analysis. This introduces a considerable deflating contribution of the pre- and postpeak activity periods in the ZHR determinations for the narrow peak (even near the core of the peak) and an inflating contribution from the slopes of the peak into the activity reconstructed for the immediate pre- and postpeak periods. This—and the additional smoothing procedure which multiplicates and enhances the phenomenon pointed out above—act to smear out the structure, which becomes artificialy broader and flatter in shape and less prominent in peak rates as a result. Similar processes presumably also act to some extent on the reconstructed broad background structure.

Another endemic problem with the IMO analysis is a lack of quality control over the data. The IMO employs a very large database (*e.g.*, data from 109 observers in the discussed analysis; Brown and Arlt, 1997). Yet, a look in the 1996 data inventory as published in the annual *WGN Report Series* (Arlt, 1997) reveals that only a comparatively small number of these observers contribute significant amounts of observational data per year. No method of shifting less experienced from experienced observers is employed, and it is quite certain that the data set includes data gathered by casual observers with no previous formal experience in meteor observing. As a rule of thumb, less or even nonexperienced observers have low perceptions and miss (most notably) a considerable proportion of the fainter meteors (and, in addition, such observers are more prone to making classification errors, errors in the estimates of limiting magnitudes, and meteor brightness estimates). In contrast to the method of Jenniskens (1994) employed in the current analysis, IMO analysts do not employ a correction for perception differences between observers. When data gathered by low-perceptive observers take an uneven share in the employed data set, these differences do not cancel out with the contributions by high-perceptive observers. As a result, the reconstructed activity levels can become considerably deflated. Moreover, differences in the make-up of the observer population over the activity profile can introduce artificial peaks and lows in the activity curve in this way.

Related to this, a problem induced by the peculiar characteristics of the 1996 Leonid outburst activity becomes influential. As mentioned in the introduction, the high fireball activity (due to combined high rates and low *r* values) near the core of the broad activity structure was exceptional and exciting. With the radiant high in the sky, several fireballs per hour and many additional bright meteors could be noted during the core of the activity period. Reports by many observers (for example, some observers reporting to IMO (see data in Arlt, 1997) and observers quoted in (Anonymous, 1997)) suggest an almost complete lack of faint meteors during the outburst; but by contrast, highly experienced observers like Lunsford, Zay, and McLeod all reported a substantial number of faint Leonids. It appears quite certain that a fair number of observers started to miss the fainter meteors because they became too preoccupied with the numerous brighter meteors appearing (and again, it is most likely inexperienced casual observers that are most easily taken in by this process).

The last two problems mentioned are most likely responsible for the gentle "dip" in the IMO activity curve around the core of the broad structure in comparison to the current analysis. This apparent dip most likely represents the contribution by many relatively inexperienced casual observers on the American east coast who experienced peak rates with the radiant high in the sky near 8–9 h UT. Note that the underrepresentation of faint meteors not only results in a deflation of meteor rates at this point in the curve, but also in deviating *r* value determinations. Indeed, a coinciding and again most likely artificial dip in the *r* value near solar longitude 235°.30 is present in the IMO analytical results (Brown and Arlt, 1997). Arlt and Brown seem to have realized this, as they mention that: "the abundance of bright meteors in this interval may be due to reduced observer attention to the fainter meteors as fewer experienced observers contributed data at the time of the minimum in the *r* profile" (Brown and Arlt, 1997). They do not discuss this point in relation to their ZHR curve, however, for which this conclusion has clear importance.

COMPARISON WITH 1997 ACTIVITY

If the 1996 narrow peak is a precursor of the upcoming 1998–1999 storm activity, then a recurrence in 1997 would be expected. As discussed above and by Langbroek (1996a), this recurrence would be expected at a solar longitude closer to the node of comet 55P/Tempel-Tuttle compared to the 1996 peak position (*i.e.,* somewhere between solar longitudes 235°.17 and 235°.26). Given the proximity of the 1997 Leonid return to the passage of the parent comet itself through its node, a recurrence of the narrow structure could have happened very close to passage through the node, which happened near November 17.565 UT in 1997 (Yeomans *et al.*, 1996). Unfortunately, the 1997 observing conditions with regard to this possible recurrence have been extremely unfavourable. A near full Moon severely hampered observations, most notably severely hampering the ability to see a component of faint meteors such as the expected narrow peak. In addition, the relevant time window near passage through the node of

55P/Temple-Tuttle was located unfavourably in geographic terms: it was visible only from the western Pacific, with twilight setting in at the American west coast.

Results on the activity behaviour of the 1997 Leonids have been published by Arlt and Brown (1998) who used visual data gathered by IMO. Their activity reconstruction should be considered with some caution, both because of the strong moonlight as well as for the reasons outlined earlier when discussing IMO's 1996 results. In general terms, their analysis again points to the presence of a broad activity structure of bright meteors similar to that of the previous years, with peak rates perhaps near solar longitude 235°.3–235°.4. As Arlt and Brown (1998) discuss, the activity reconstruction of this broad structure suffered much from problems (among others) with quality control over the data caused by the strong moonlight. Of relevance for the current discussion, is the reported recurrence of a narrow component, with peak rates reported near solar longitude 235°.22 ± 0.04 (Arlt and Brown, 1998) or November 17.51 ± 0.04 UT, close to passage through the node of 55P/Tempel-Tuttle and in line with the expectations for a possible recurrence (Langbroek, 1996a).

Anecdotical accounts from America and Hawaii (*e.g.*, reports in Green, 1997) suggest a possible shortlived surge in activity near November 17.5–17.6 UT, with a short peak in the occurrence of bright meteors near November 17.52–17.57 UT as observed from Hawaii (O'Meara quoted in Green, 1997). This could have been the brightest fraction of a display connected to the narrow peak recurrence that perhaps would have been impressive if moonlight had not interfered.

SUMMARY AND CONCLUSIONS

The 1996 Leonid outburst activity shows a combination of two activity structures, representing two separate meteoroid structures and presumably two different evolutional stages in meteoroid stream formation. As in 1994–1995, a broad symmetric structure of bright meteors with an effective duration of 0.77 days and with $B = 1.2 \pm 0.3$, $r = 1.9$ and maximum ZHR of 70 ± 10 (broad structure only) peaking near solar longitude 235°.28 ± 0.04 (November 17.31 ± 0.04 UT) was present. In addition, a narrow peak of fainter meteors has been observed with $B = 30 \pm 10$, $r = 2.5$ and a maximum ZHR of 65 ± 15 (narrow structure only) peaking at solar longitude 235°.172 ± 0.007 (November 17.20 ± 0.01 UT). This observation marks the first certain detection of such a narrow activity structure in the new series of Leonid outbursts, one year earlier than expected (Jenniskens, 1996).

The occurrence of the narrow peak can best be explained as a first modest sign of presence of the meteoroid structure that should be responsible for the expected storm activity in 1998–1999. The appearance 0.°085 before the node of 55P/Tempel-Tuttle suggests that the 1998–1999 storms might peak just before nodal passage (*contra* Jenniskens, 1996, and in line with predictions in Brown and Jones, 1993; Arlt and Brown, 1998), unlike the 1866 and 1966 storms that peaked just after nodal passage (Jenniskens, 1995, 1996). Caution is asked for however with regard to this conclusion, because many aspects of Leonid outburst peak behaviour are still not understood. Documenting the behaviour of this narrow peak over several years of the current outburst cycle is of potentially high importance for forecasting future appearances in the next century, as well as for modelling stream evolution in order to arrive at a better understanding of stream behaviour and meteoroid stream formation.

The activity of the broad structure of bright meteors over the period 1994–1996 so far agrees well with the predictions by Jenniskens (1996) in terms of strength of activity but deviates considerably in the time of peak activity (Table 2). A safe prognosis for future appearances is clearly still hard to produce. This underlines the need for a continuous survey of meteor activity for a full day around passage of the node of comet 55P/Tempel-Tuttle in the coming years.

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