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Leonid fluxes: 1994–1998 activity patterns

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Abstract–The Leonid meteor shower was observed worldwide in 1998 November in an intensive campaign without precedent. During this international effort ~35 500 meteors were reported by members and collaborators of the International Meteor Organization (IMO) using a standard methodology. Despite the absence of a meteor storm in 1998, the rich observational data allow us to obtain a detailed unprecedented knowledge of the stream structure between 1994 and 1998.

INTRODUCTION

We present here the results from long-term visual monitoring by members and collaborators of the International Meteor Organization (IMO) and photographic and charge-coupled device (CCD) monitoring research obtained by members of the Spanish Photographic Meteor Network (SPMN) between 1994 and 1998. Our network is dedicated to study interplanetary matter under the auspices of three universities (University Jaume I, University of Valencia and University of Barcelona) and one space institute (IEEC, the Catalonian Institute for Space Studies).

The international cooperation in IMO allows us to organise meteor work on a scale never achieved in the past. The visual data here analysed have been provided by Rainer Arlt who compiled them in the Meteor Report Series published by IMO. We have realised a global study of 1994–1998 activity patterns by means of these visual data. Additionally we have computed meteoroid spatial number densities from photographs, including some historical images obtained of the 1966 storm (Milton, 1967, 1969). Using these photographs we will compare 1966 and 1998 meteoroid fluxes.

VISUAL OBSERVATIONS, REDUCTION AND METHODOLOGY

All data considered was reduced following IMO visual commission criteria. It is extremely important to standardise all meteor observations in order to globally compare results from several years. In fact, important information of other historical meteor storms has been partially lost because the absence of accurate counts and data on sky conditions (Kresak, 1993; Jenniskens, 1995; Yeomans *et al.*, 1996; Brown, 1999; Wu and Williams, 1996).

Our standard procedure consists of obtaining the zenithal hourly rates (ZHRs) and the population index from each visual count with its corresponding error bars. Due to the great volume of data, we developed software that calculates averaged ZHRs and, from them the spatial number densities and meteoroid fluxes for the 1994–1998 IMO data. The spatial coverage allows us to obtain a detailed analysis on the stream's spatial flux densities. Our high-resolution analysis has been realised between $\lambda_0 = 234.0$ and 236.0° (2000.00) trying to determine the stream behaviour around comet node. The 1994–1997 data included in this solar longitude interval was divided into 60 steps of 0.033° in solar longitude. The impressive amount of data recorded in 1998 allowed us to consider shorter steps of 0.01° in solar longitude, a spatial resolution not obtained before from visual observations. All data are compiled in Table 1.

Zenithal Hourly Rates and Population Index Values

Our software divided the selected period in equal intervals to compute the averaged ZHRs and population indexes from observational data. To improve the quality of the final results we considered only observing intervals with radiant elevations over 20° and a maximum correction factor smaller than 5. This correction factor software includes correction by limiting magnitude, radiant altitude and cloud cover. The ZHR is the number of shower meteors that an observer would see in 1 h under clear skies, the radiant at the zenithal and a faintest visible star in the field of view equal to +6.5. Usually the ZHR is calculated as:

$$\mathrm{ZHR} = \frac{CNr^{6.5-Lm}}{T(\sin\theta)^{1.4}} \tag{1}$$

where C is a correction for the perception of the observer relative to an average observer, N is the number of shower meteors recorded in T hours of effective time, 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 class M to those in class $M-1$, usually called population index.

Using Eq. (1) we have obtained averaged ZHR for each selected period. Figure 1 represents all acceptable ZHR data obtained in years 1994–1997 and Fig. 2 data obtained in 1998. The error bars indicate the standard errors for a 68% confidence interval as a function on the total number of observed meteors in each observing period. To correctly interpret changes in ZHR values we present with the ZHR profiles additional graphs

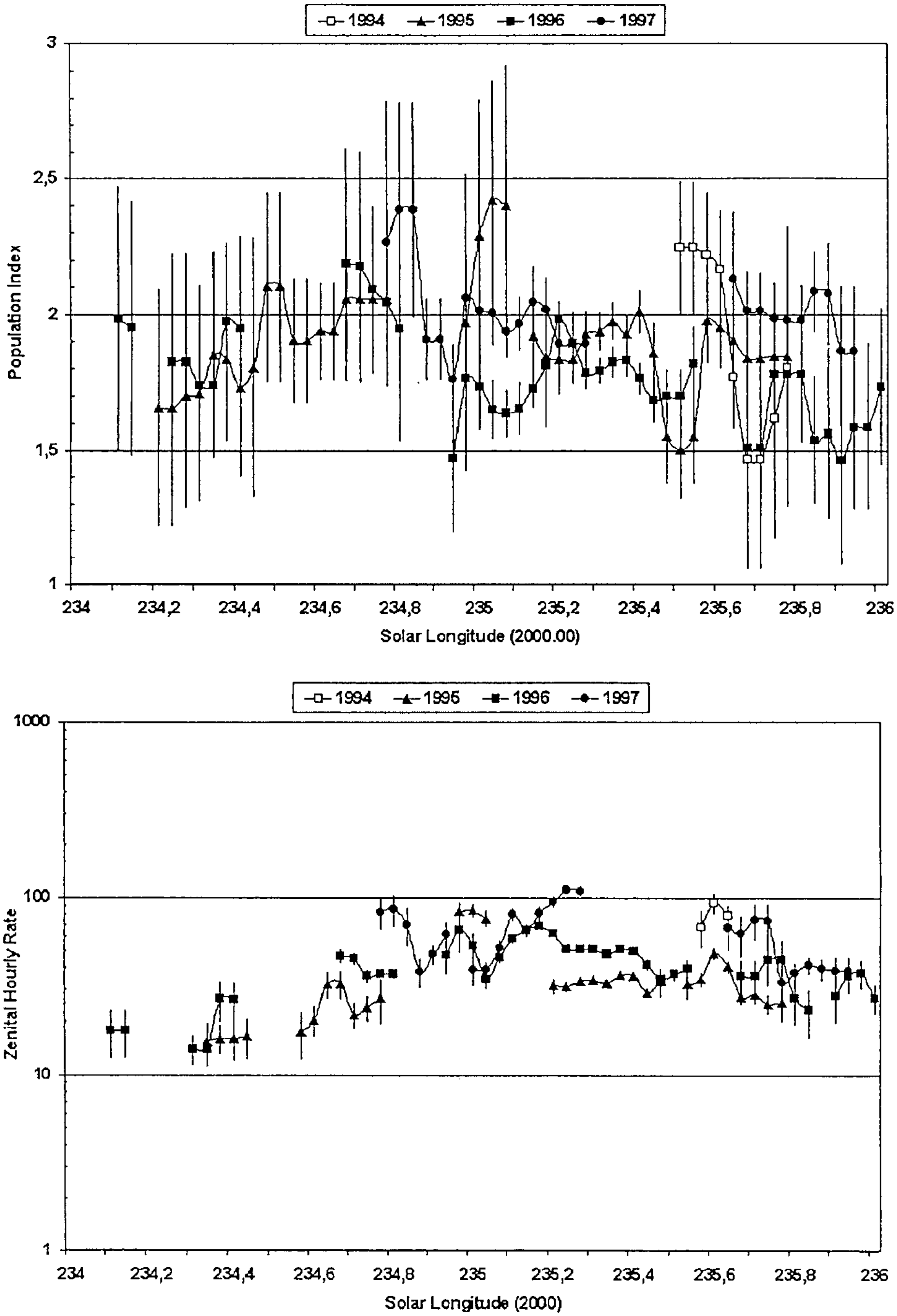

FIG. 1. Two detailed graphs showing the population index and the ZHR values for the 1994–1997 IMO data. Individual values were averaged in solar longitude intervals of 0.033°. Note in 1996 data the presence of a narrow structure detected previously by Langbroek (1996, 1999) where population index reaches a value of 2 around solar longitude 235.2°.

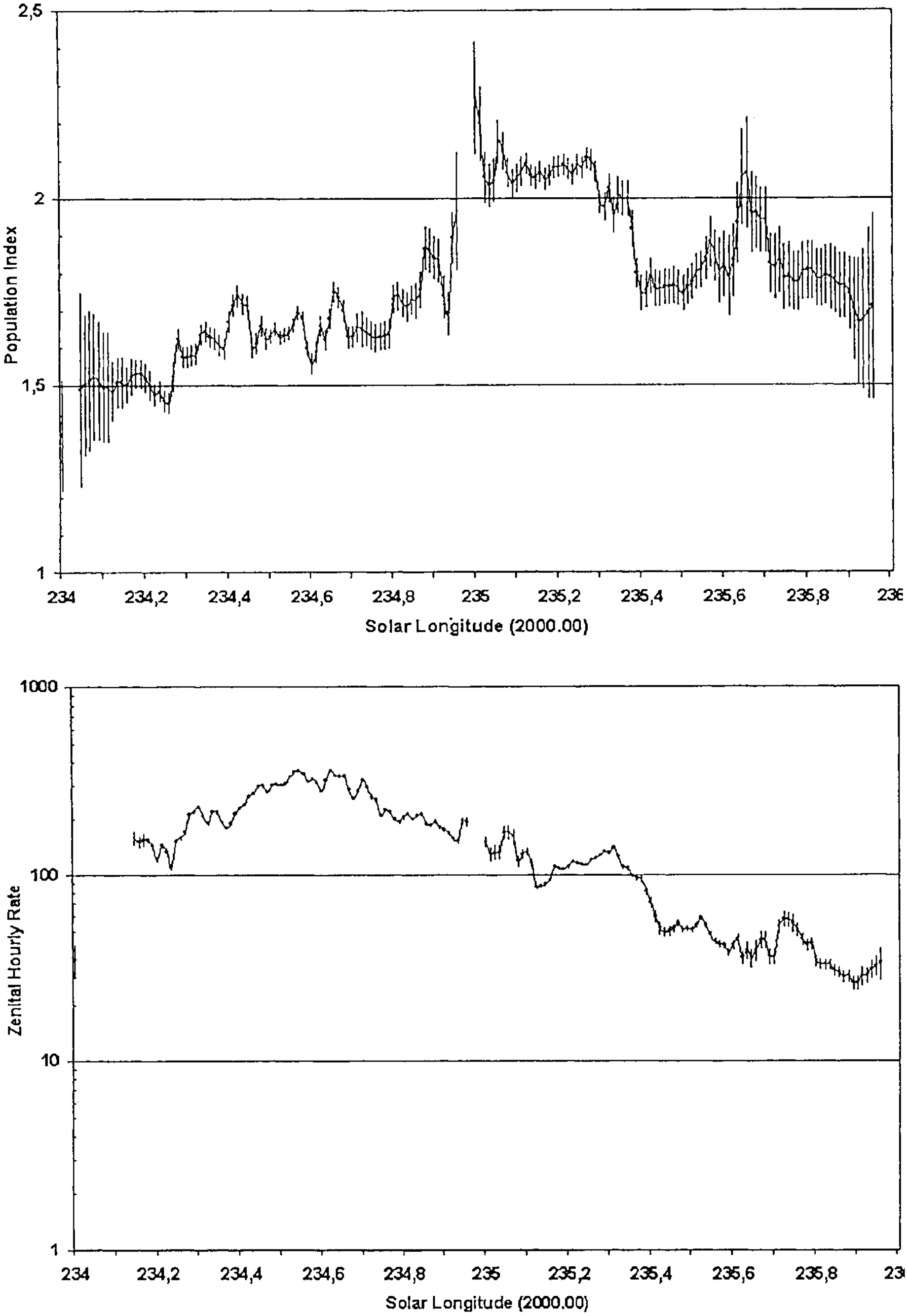

FIG. 2. Two high-resolution graphs of population index and ZHR values from the 1998 IMO data. The observations were averaged in solar longitude intervals of 0.01°. The data reveal an increase of activity observed in 1998 between $\lambda_0 = 234$ and 235°. This increase before the comet node reveals a "blanket" structure rich in large meteoroids as is derived from a decrease in the population index values plotted below. After it, at 235° the population index suffers an abrupt change from 1.7 to 2.3 showing the presence of a narrow "sheet" of little meteoroids, that produced meteor storms in the past. A comparison with previous return values can be seen in Fig. 1.

including changes in population index values (r) of Leonids in the analysed magnitude range ($-\infty$, $+6.5$). Population index changes show stream regions composed of particles of different mass distribution (Hughes, 1995). We calculated population index values following the procedure of Koschack and Rendtel (1990), taking into account the probability of perception of each magnitude class depending on limiting magnitude:

$$r = \frac{N(M)}{N(M-1)} \tag{2}$$

where $N(M)$ is the real number of meteors in the magnitude class M. This $N(M)$ is obtained from the observed number of meteors taking into account the probability of perception (p) for each magnitude class depending on the limiting magnitude in each interval. To improve the quality of the data we include only magnitude distributions with a population index error <0.95. Comparing Figs. 1 and 2, ZHR profiles evidence important changes every year. For example, while in 1997 the Earth crossed the densest part of the stream in 15 h (Trigo-Rodriguez, 2000); in 1998 the spatial cross section was twice this amount. This region produced the exceptional "fireball night" observed in Europe on 1998 November 16–17. Figure 2 shows extremely low population index values that night (between $\lambda_0 = 234.0$ and 235.0°) showing an abundance of large meteoroids.

Meteoroid Flux Densities

From the visual meteor observations we obtained initially two basic data: the ZHR and a population index r. These values should not be the final ones, since we are interested in obtaining a detailed vision of the stream structure, and getting the meteoroid flux densities. From the ZHR and population index data we can determine the flux density of meteoroids causing meteors of magnitude at least +6.5 by means of the method developed by Koschack and Rendtel (1990). These authors standardise the flux meteoroid density, following the relationship:

$$Q_{6.5} = \frac{\mathrm{ZHR}_0 \times C(r)}{A_{red}(r)} \qquad (3)$$

where ZHR_0 is the observed zenithal hourly rate, corrected by a function $C(r)$ that depends on the population index and the probability of perception p of each meteor of magnitude M as a function of the star limiting magnitude. The projected geometrical area at meteor level (A_{red}) corrected to population index was also obtained by the same authors.

For the low population indices registered in 1998, Rainer Arlt suggested the introduction of a modification in the calculation of the "reduced area" (A_{red}) and the factor $C(r)$. This last factor corrects the observed ZHR to a true ZHR in the observing field, taking into account the different probability to detect meteors in function of different magnitude classes. In essence we used the same methodology and values used by Arlt (1998) to calculate more realistic 1998 fluxes. The flux density profile of the 1994–1997 and 1998 returns separately are shown in Figs. 3 and 4. These graphs exhibit a different shape to the ZHR profiles due to the fact that ZHR is affected in particular by the perception properties of the human eye. The stronger the population index varies, the more the flux density profile will differ from the ZHR profile.

RADIANT AND SPATIAL NUMBER DENSITIES FROM PHOTOGRAPHY

In 1998 the changing weather on Spain impeded our team to obtain double-station photographs during the Leonids maximum. Despite this, we obtained in 1998 November 17 ($\sim\lambda_0 = 234.65°$) accurate astrometry of 15 single-station meteors trails recorded on 35 mm plates. We used them to determine the apparent Leonid radiant in $\alpha = 152 \pm 0.5°$ and $\delta = +22 \pm 0.5°$, following the procedure used in Trigo-Rodríguez (1996). On 1998 November 18 (between $\lambda_0 = 235.50$ and 235.60°) the radiant deplaced to $\alpha = 153.5 \pm 0.5°$ and $\delta = +21.8 \pm 0.5°$. This radiant position was obtained from high-resolution CCD images centered in the radiant (but from only four Leonid meteors) using the burst observer and optical transient exploring system (BOOTES) described in Castro-Tirado *et al.* (1999).

In order to obtain spatial densities from photographs we need to know the area that each photograph surveyed at the meteor level, depending on camera field and altitude on the horizon and of the population index in the observational interval. We use the methodology initially developed by Trigo-Rodriguez (1994) and later improved in several aspects by Bellot (1994). The photographic procedure consists in locating the longest edge of the photograph parallel to the horizon with a field center above 45° of altitude. The reduced effective area A_{red} that collect meteoroids may be computed from Bellot (1994)

TABLE 1. IMO visual data obtained between $\lambda = 234.0$ and 236.0° during 1994 and 1998, which allowed us to obtain the population index, ZHRs and meteoroid fluxes.

Year	Magnitude distributions (MD)	Number meteors in MD	Individual counts	Total number of meteors
1994	12	237	43	326
1995	90	1918	262	2691
1996	80	2812	333	4215
1997	52	1431	225	2390
1998	593	41299	2250	35449
All years	827	47697	3113	45071

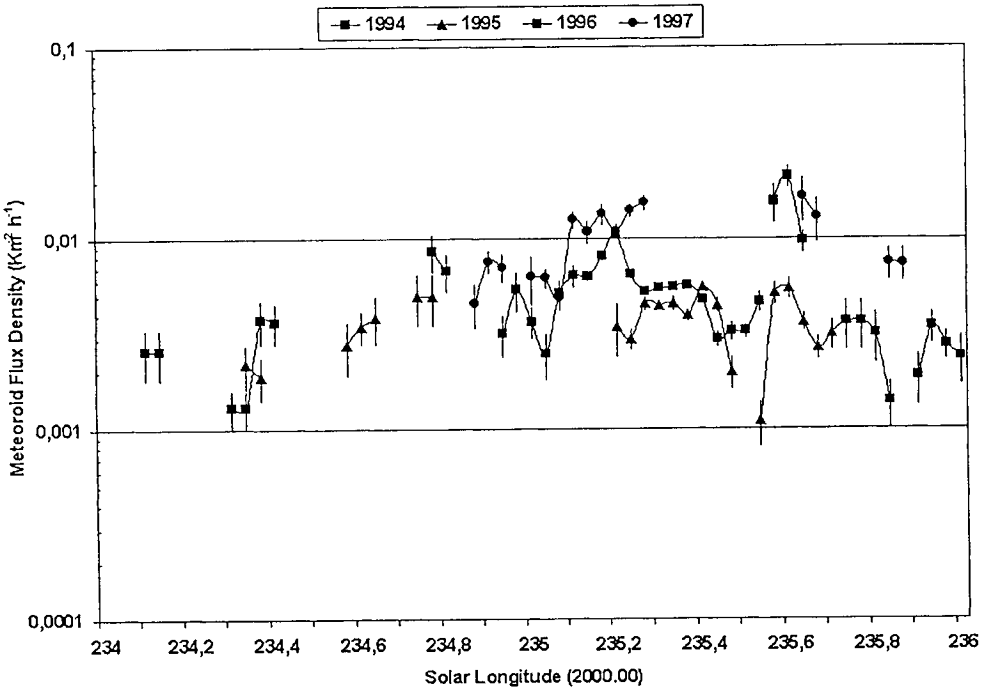

FIG. 3. Flux Leonids density from the 1994–1997 IMO data. Individual values were averaged in solar longitude intervals of 0.033°. We
a great similarity between the different patterns from year to year.

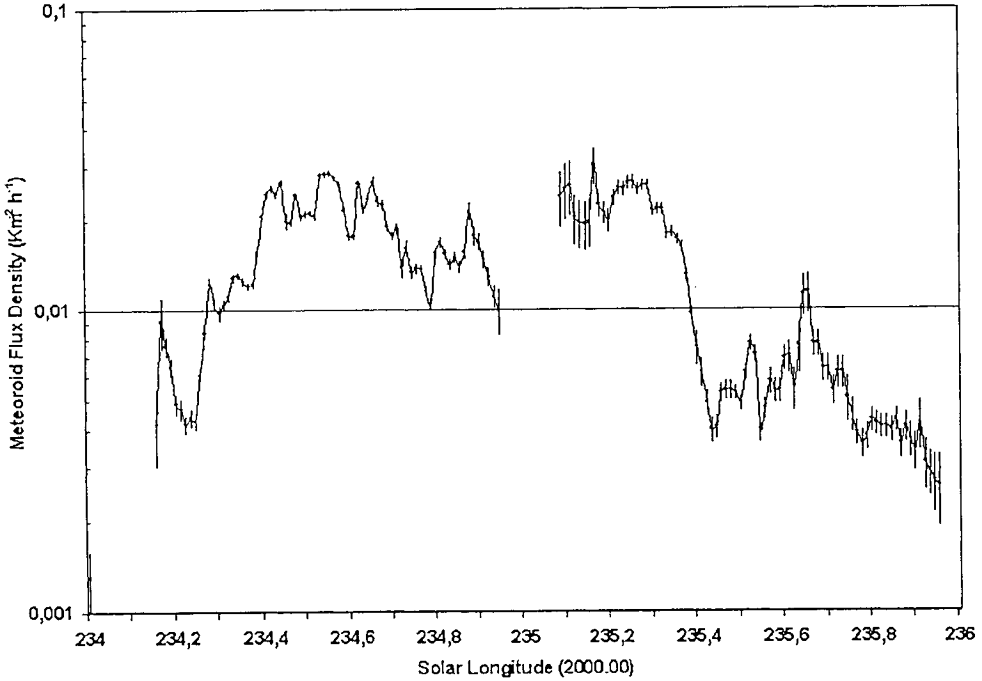

FIG. 4. High-resolution graph showing the Leonids flux density from the 1998 IMO data. The observations were averaged in
longitude intervals of 0.01°. Note the apparition of a non-expected peak between $\lambda_0 = 234$ and 235° probably associated with a reso
clump of great meteoroids (Asher *et al.*, 1999). Comparing with Fig. 3 we noticed that this component was nonexistent in prev
1994–1997 patterns.

TABLE 2. Spatial number densities (particles in a cube of 1000 km of edge) obtained from Spanish Fireball Network photographs during the night of November 16–17 and successives.*

Interval (UT)	Date	λ_o (°) 2000.0	Photographic effective time	F	Number Leonids	$\rho_{6.5}$	ε ($\rho_{6.5}$)	$\rho_{-0.5}$	ε ($\rho_{-0.5}$)
0000–0100	1998 November 17	234.45	0.51	1.00	1	82	4	0.7	0.7
0100–0230	1998 November 17	234.53	0.92	1.00	7	94	3	1.9	0.7
0430–0530	1998 November 17	234.65	0.66	1.00	17	98	4	14	3.4
0130–0300	1998 November 18	235.55	1.26	1.30	1	19	2	0.1	0.1

F is a cloud correction, according to the percentage of camera field covered by clouds. We compare spatial number density ($\rho_{6.5}$) obtained from visual data with the density obtained in the photographic magnitude range ($-\infty$, -1), here denoted as ($\rho_{-0.5}$). The error values are in the 66% confidence interval, from the square of the number of observed meteors.

$$A_{red} = \sum_i A_i r^{5\log(100\ \mathrm{km}/d_i\ -\ \varepsilon_i)} \tag{4}$$

where A_i represents the projected geometrical area of a small portion of the photograph at distance d_i from the camera and extinction ε_i. Note that the index i is such that all zones of the photograph enter the summation. For each photograph we obtain the corrected area depending on the field size, the altitude of photographic center and the population index in the observational time interval. Results are given in Table 2.

To obtain the *limiting photographic meteor magnitude* for each lens we realised simultaneous visual and photographic observations. We came to the conclusion that a good estimation of the limiting meteor magnitude photographed is the following equation developed by Hawkins (1964):

$$m_{\mathrm{meteor}} = 2.512 \ \log(d^2 f^{-1} g) - 9.95 \tag{5}$$

where d is the effective aperture, f is the focal of the lens and g is the sensitivity of the emulsion in the international standard way of rating films (ISO).

Table 2 shows the spatial number density of 1998 Leonid meteors in the photographic magnitude range ($-\infty$, -1) (here called $\rho_{-0.5}$) compared to the obtained from visual data ($\rho_{6.5}$) in the range ($-\infty$, $+6.5$). To determine the spatial number density of meteoroids causing meteors of magnitude +6.5 we used the method developed by Koschak and Rendtel (1990). These authors standardise the number of meteoroids in a cube of a 1000 km edge using the equation:

$$\rho_{6.5} = \frac{\mathrm{ZHR_o} C(r)}{3600 A_{red}(r, h_f, H) v_g} \tag{6}$$

where $\mathrm{ZHR_o}$ is the zenithal hourly rate observed, corrected by a function $C(r)$ that depends on the population index and the probability of perception p of each meteor of a determinate magnitude M. A_{red} is a standard area for which there is no extinction ε and the distance to the observer is assumed to be 100 km.

As a comparison of these results, during the 1966 storm, the spatial number density in the range ($-\infty$, $+6.5$) was close to 10^5 meteoroids in the volume of 10^9 km^3 according to Williams (pers. comm.). We present in Table 3 the obtained spatial number densities ($\rho_{-0.5}$) from three historical photographs of the 1966 storm that can be directly compared with data shown in Table 2.

DUST DENSITY DISTRIBUTION AROUND THE COMET

The importance of our detailed 1994–1998 analysis of the Leonids activity focuses in the reconstruction of the stream spatial structure during this cometary return. We have combined 40 independent ZHR determinations obtained in the last two centuries with their corresponding orbital geometry. Initially we placed all ZHR points and the software applied a precise numerical contorning technique to define the averaged density of the Leonid stream in a similar way as was made by Yeomans (1981). We used historical observations obtained after the 1800 return and the ZHR determinations revised by several authors (see for more details Jenniskens, 1996; Brown, 1999). The result is Fig. 5 that shows an averaged contour plot with the corresponding log(ZHR) isolines. As we can infer from this graph, the greatest dust concentration is close to the orbit of 55 P/Tempel–Tuttle. We observe several zones with a contour density of 3 > log(ZHR) > 2, showing an extended activity often accompanied by brighter Leonid meteors. Zones with log(ZHR) > 4 usually provide showers rich in faint meteors more close to the comet orbit. Finally we did find a region with log(ZHR) > 5 that, composed of small meteoroids, is distributed like a narrow "sheet" in the vicinity of the 55 P/Tempel–Tuttle. The last time that the Earth crossed this densest region (1966) an impressive meteor storm was produced (Yeomans *et al.*, 1996). According to McNaught and Asher (1999) dust trail model dust density distribution around 55 P/Temple–Tuttle must be in fact much more complicated than our averaged Fig. 5. In any case, our graph provides an interesting great scale view of dust distribution around the comet orbit.

TABLE 3. Spatial number densities (particles in a cube of 1000 km of edge) from three historical photographs obtained during the 1966 storm.*

Approximate time (TU)	Exposure (h)	Radiant altitude (°)	Field center altitude (°)	A_{red}	Leonids photographed	$\rho_{-0.5}$ ($n/10^9$ km^3)
11 h 50 m	0.20	65	35	5800	82	220
11 h 55 m	0.03	60	35	7600	20	840
11 h 47 m–11 h 50 m	0.05	55	55	7300	88	2300

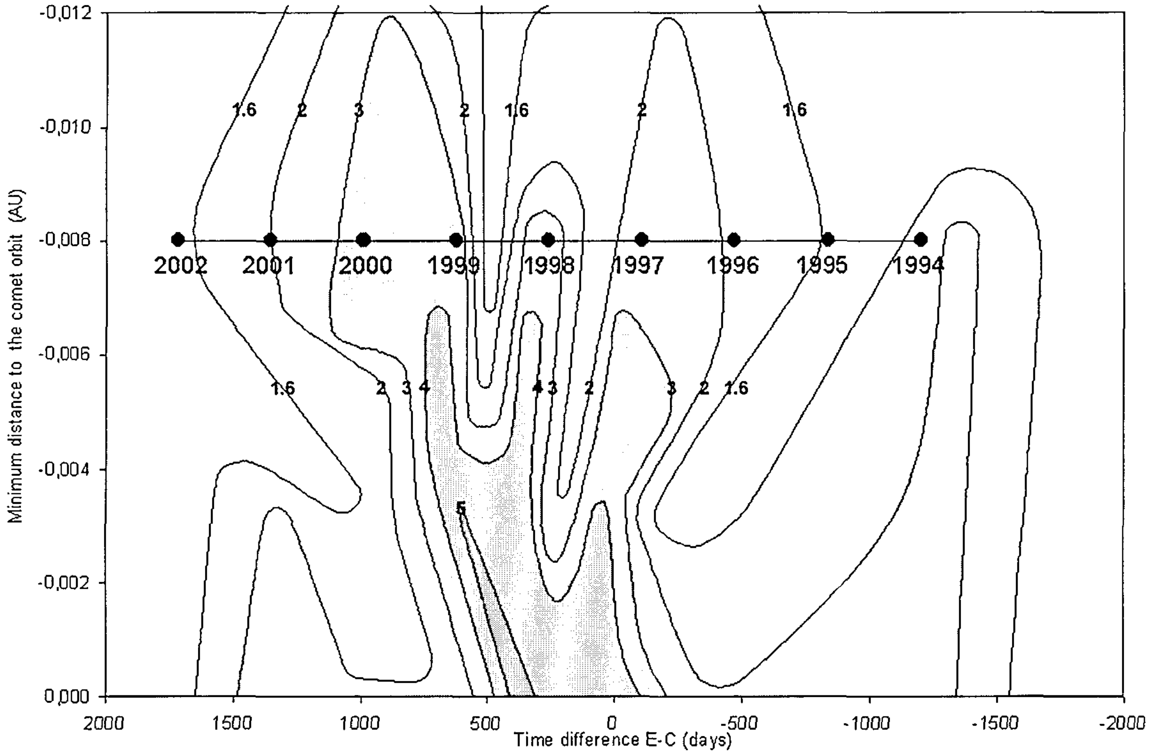

FIG. 5. Great scale dust density distribution around 55 P/Tempel–Tuttle. We plotted time difference between the moment when the Earth a comet cross the descending node (in days) *vs.* the minimum distance to the comet orbit (in AU). Taking into account maximum ZH obtained in the last two centuries and their corresponding orbital geometry, our software adjust line contours of equal density. Numeri values are in units of log(ZHR). Earth geometrical path in the years 1994–2002 is also included.

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