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Radar observations of the Leonid meteoroid stream in 2001

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Summary. — Results of the Leonid meteoroid stream observed in 2001 are presented. Data have been collected during November 13-23, 2001 by using a forward-scatter radar operating along the two long baselines of Bologna-Lecce (700 km) and Bologna-Modra (600 km). The profile of the reflection time shows a broad component on November 18 in the 00–12h UT time interval with maxima between 09:00h and 11:00h UT. About 90% of the reflection time was recorded at the two receiving stations of Lecce and Modra during the peak hour with an associated mass index of $s = 1.72$. The flux reached a value of 4.5×10^{-11} m^{-2} s^{-1} at the solar longitude $236^\circ.09 \pm 0^\circ.02$ (November 18, 9h 30m UT) for echoes with duration $T \geq 1$ s corresponding to a limiting mass of $m \simeq 10^{-5}$ kg. For longer-duration ($T \geq 8$ s) echoes, the main activity peak was found a hour later at the solar longitude $236^\circ.13 \pm 0^\circ.02$ (November 18, 10h30m UT), similarly as reported by visual observations. The perspective of high levels of Leonid activity in 2002 is discussed.

PACS 96.50.Kr – Meteors, meteoroids, and meteor streams.
PACS 95.85.Bh – Radio, microwave (> 1 mm).

1. – Introduction

The Leonid meteor display occurs usually between 15 and 21 November each year, with peak activity on the nights of 17-18 November. The observed meteors are produced by the collision with the Earth's atmosphere of small dust particles ejected from the parent comet Tempel-Tuttle. The Leonids exhibited enhanced activity in mid-November of both 1999 (when they reached storm levels) and in 2000 [1,2]. Strong meteor displays were expected a few years after the perihelion passage on February 28, 1998 of the parent comet 55P/Tempel-Tuttle that shows a periodicity of about 33 years. Scientists have recently mounted airborne campaigns, as the Leonid Multi-Instrument Aircraft Campaign (MAC) consisting of two research aircraft that flew 120 kilometers apart for stereoscopic viewing [3]. Missions in 1998 and 1999 collected a huge amount of information, leading to a new understanding of meteoroid streams, meteors, and their persistent trains. As a

TABLE I. – *Activity maxima in terms of reflection time* $\geq 25\%$ *recorded by the BLM radar in the 13-23 November 2001 period as a function of the solar longitude (J2000.0).*

λ [J2000.0]	Date	UT	Reflection time
$235^\circ.96 \pm 0^\circ.02$	18 November 2001	06 h 30 m ± 30 m	82.5 %
$236^\circ.02 \pm 0^\circ.02$	18 November 2001	09 h 30 m ± 30 m	86.7 %
$236^\circ.68 \pm 0^\circ.02$	18 November 2001	23 h 30 m ± 30 m	32.4 %
$236^\circ.80 \pm 0^\circ.02$	19 November 2001	02 h 30 m ± 30 m	45.1 %
$236^\circ.89 \pm 0^\circ.02$	19 November 2001	04 h 30 m ± 30 m	35.0 %
$237^\circ.01 \pm 0^\circ.02$	19 November 2001	07 h 30 m ± 30 m	36.0 %
$237^\circ.10 \pm 0^\circ.02$	19 November 2001	09 h 30 m ± 30 m	26.6 %
$238^\circ.06 \pm 0^\circ.02$	20 November 2001	08 h 30 m ± 30 m	29.6 %
$238^\circ.15 \pm 0^\circ.02$	20 November 2001	10 h 30 m ± 30 m	64.1 %

piece of new information, it was discovered that meteor rates at 10 km altitude peaked four to five times higher than reported from the ground and that meteors provide a surprisingly soft landing for complex organic molecules. Analysis of 1999 and 2000 airborne meteor counts show that the pattern of trails may be shifted slightly inward relative to the calculated positions. These small displacements could be due to the presence of a jet of gas and dust, that astronomers saw during the comet's 1998 return. Jets tend to shoot the dust particles in a specific direction rather than spread them around equally.

2. – Activity and mass distribution

Since 1996, a forward-scatter system is transmitting radio signals simultaneously along two mutually almost rectangular baselines from Budrio (44°.6N, 11°.5E) near Bologna, to the receivers at Lecce (40°.3N, 18°.2E) in Southern Italy and Modra (48°.4N, 17°.3E), Slovakia. The baseline distances Bologna-Lecce and Bologna-Modra (BLM) are about 700 and 600 km, respectively. The equipment utilises a continuous wave transmitting frequency at 42.7MHz and a 0.5 kW mean power transmitted in the direction of both receiving stations. Further information on technical aspects of the multistatic radar is described elsewhere [4].

Radar observations were conducted between November 13 and 23 of 2001, with interruption on November 17 due to technical problems at the receiving station in Lecce. Leonids are observable by radio techniques from a mid-latitude northern hemisphere site from about 22h to 14h LT each day in mid-November, since the radiant culminates around 6h 30m LT. The mean echo counts on November 13, 14 and 22 were considered to be the sporadic background activity. To obtain the shower echo rates, mean sporadic echo counts were subtracted in the quoted period, by assuming that the sporadic background exhibits a similar variation throughout each day close to the time of the shower maximum. Hourly counts were then corrected for the "dead time" due to multiple simultaneous long-duration meteor echoes that affect counts of faint and short-duration echoes during the activity maxima. As in 1998-2000 years, the number of long-duration echoes (lasting up to several minutes) created saturation effects mainly at the time of the peak. The reflection time of the radioechoes was thus found to be a good marker of the shower activity. Figure 1 shows the average reflection time (in percentage) of the radioechoes at the two receiving stations of Lecce and Modra on November 13-23, 2001, during the display of Leonids. Leonids can be clearly identified only for echoes of longer

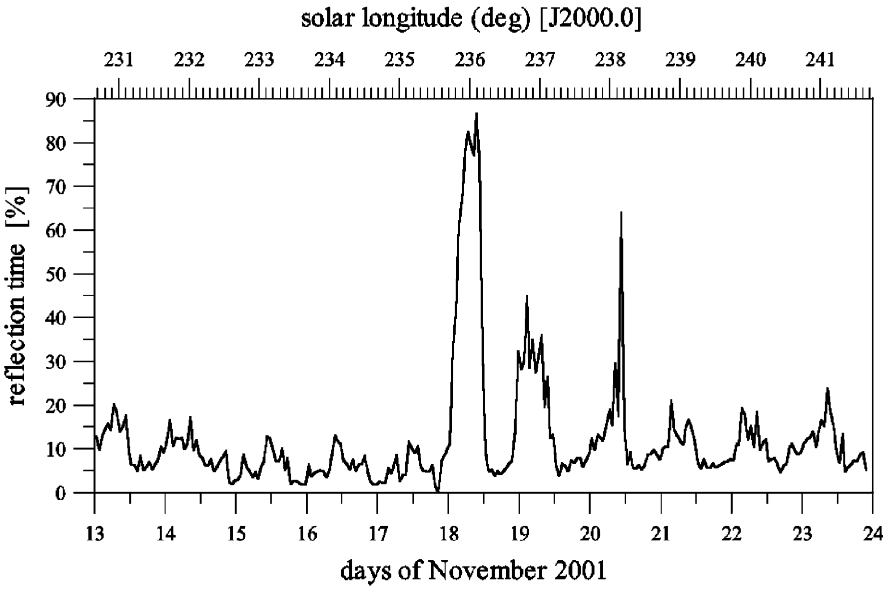

Fig. 1. – Mean reflection time (in percentage) of the radioechoes recorded by the BLM radar on November 13-23, 2001 during the activity of the Leonids.

duration that give a prominent contribution of the reflection time. The curve of the reflection time shows that the shower was particularly active starting from November 18 (see also table I). The reflection time in the 06–11h UT time interval of November 18 ($235°.92$–$236°.15$ solar longitude) was 80–90%, peaking at 09–11h UT. The large number of persistent (overdense) echoes at the two quoted receiving stations obscured in part echoes of underdense trails. Fluxes relative to different class durations of the echoes were calibrated by using the dead time. The 2001 data from the BLM radar enable us to derive the mass distribution index s from the observed echo durations of the shower and sporadic meteor echoes. The mass distribution is usually determined from the echo duration distribution which is a function of mass distribution. If the diffusion is the dominant process of an echo decay, the distribution of the cumulative numbers of echo duration T_{D} makes it possible to derive the exponent s from the relation [5]

$$N_{\mathrm{c}} \propto T_{\mathrm{D}}^{-(3/4)(s-1)} \tag{1}$$

in the form

$$\log N_{\mathrm{c}} = \left(-\frac{3}{4}\right)(s-1)\log T_{\mathrm{D}} + \mathrm{const}\,, \tag{2}$$

where N_{c} is the cumulative number of echoes with the duration equal to and greater than T_{D}.

Table II shows the positions of the flux maxima recorded on November 18, 2001 by the BLM radar during the Leonid display. The fluxes are calculated in four different duration classes of the radioechoes (all echoes, $T \geq 1$ s, $T \geq 4$ s, $T \geq 8$ s) corresponding to meteoroids of increasing masses.

TABLE II. – *Positions of the flux maxima recorded on November 18, 2001 by the BLM radar during the Leonid display, for different duration classes of radioechoes.*

Duration class	$\lambda\,[J2000.0]$	18 Nov. 2001 (UT)	Flux ($m^{-2}s^{-1}$)
All echoes	$236°.09 \pm 0°.02$	09 h 30 m ± 30 m	1.6×10^{-10}
$T \geq 1$ s	$235°.96 \pm 0°.02$ $236°.09 \pm 0°.02$	06 h 30 m ± 30 m 09 h 30 m ± 30 m	2.0×10^{-11} 4.5×10^{-11}
$T \geq 4$ s	$235°.96 \pm 0°.02$ $236°.09 \pm 0°.02$	06 h 30 m ± 30 m 09 h 30 m ± 30 m	1.3×10^{-11} 2.1×10^{-11}
$T \geq 8$ s	$235°.96 \pm 0°.02$ $236°.13 \pm 0°.02$	06 h 30 m ± 30 m 10 h 30 m ± 30 m	8.5×10^{-12} 1.4×10^{-11}

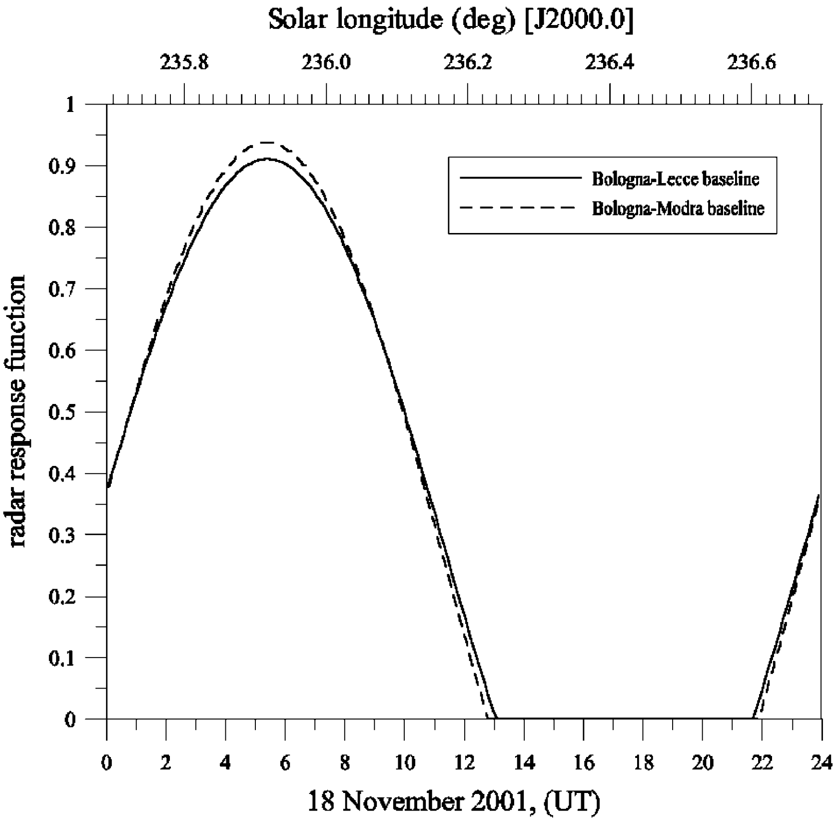

Fig. 2. – Radar response functions of the Bologna-Lecce (continuous line) and Bologna-Modra (dashed line) baselines for overdense Leonid meteors recorded on November 18, 2001.

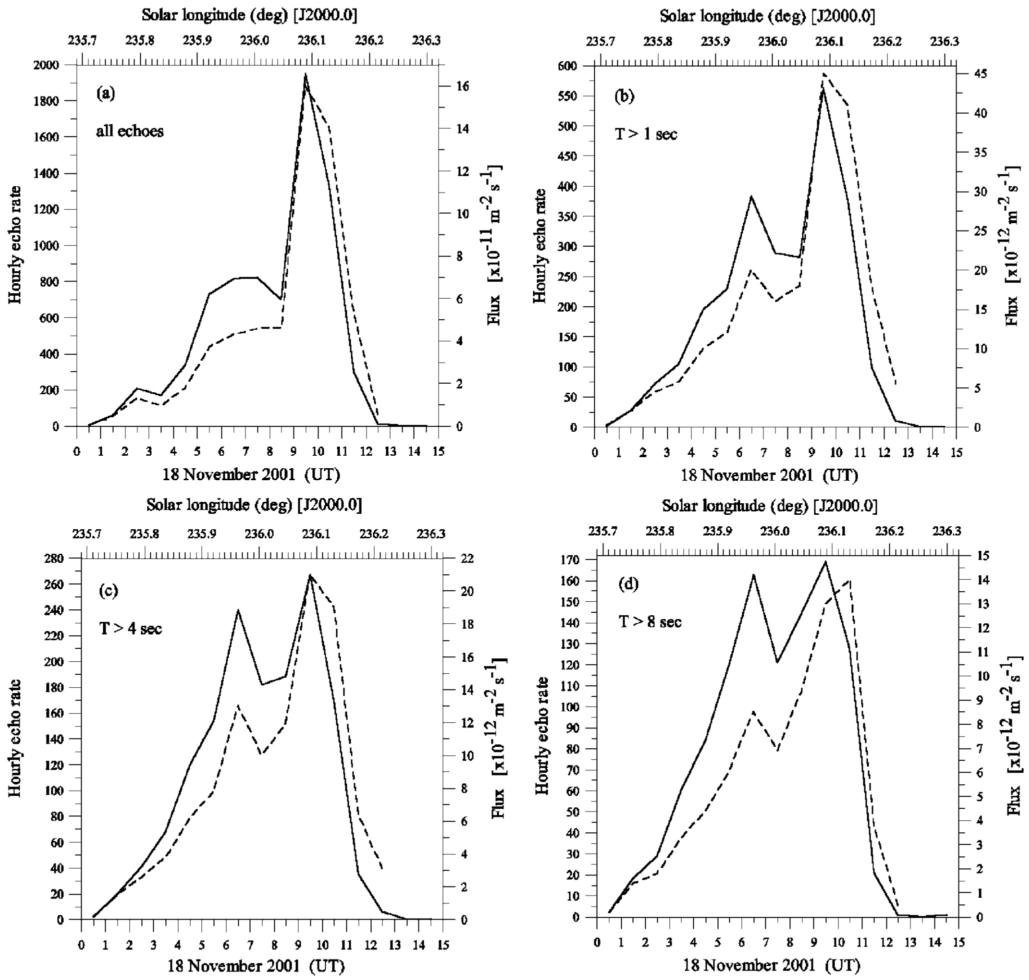

Fig. 3. – a)-d) Hourly rates (full line) and mean fluxes (dashed line) of the echoes at the time of the Leonid peak activity on November 18, 2001, for all echoes, $T \geq 1$ s, $T \geq 4$ s and $T \geq 8$ s.

The 2001 Leonid data were reduced and analysed for each station separately, and then averaged after combining together. The values of s were determined at different solar longitudes for the day of maximum activity of Leonids (November 18).

3. – Discussion of the results

According to models [6-8], two major peaks (late in the morning the first, and in the afternoon the second one) were expected to occur on November 18, 2001. Nevertheless, the radar response function which depends on the radiant elevation angle θ (as a function of $\sin\theta$), allowed us to observe only the first maximum (fig. 2).

To identify a possible correlation between the meteoroid mass (proportional to the echo duration) and the position of the peaks, we calculated the activity profiles of the stream in four different duration classes of the radioechoes (all echoes, $T \geq 1$ s, $T \geq 4$ s,

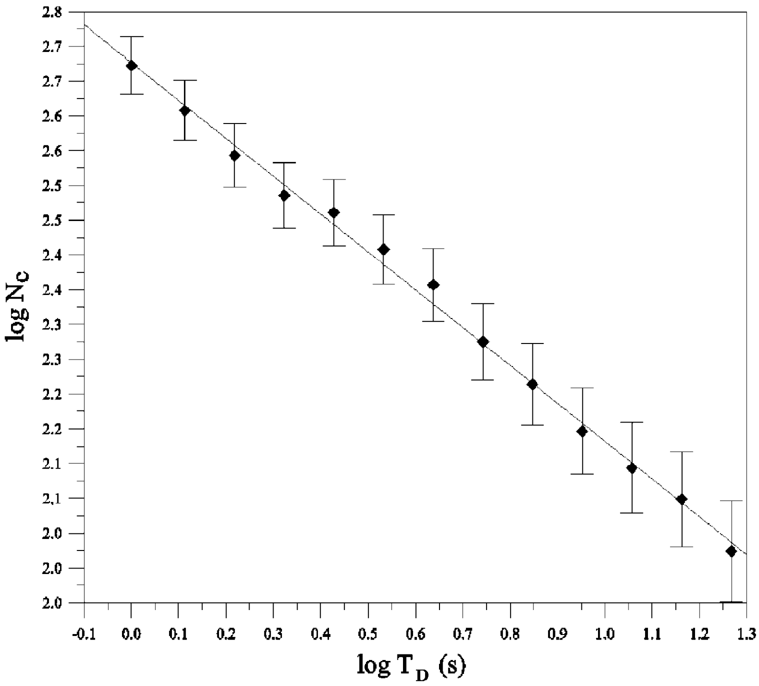

Fig. 4. – Cumulative distribution of the number N_c of radioechoes *vs.* their duration T_D, recorded during the maximum of the Leonid 2001 display (November 18, 10:00–11:00 UT).

$T \geq 8$ s), extrapolating for each of them the mean hourly flux of the stream. Figures 3 a)-d) show hourly rates (full line) and mean flux (dashed line) of echo counts at the time of the Leonid peak activity on November 18, 2001, for different duration classes (all echoes, $T \geq 1$ s, $T \geq 4$ s, $T \geq 8$ s).

When taking into account all echoes (fig. 3a), the maxima of echo counts and fluxes occurred at the same interval of solar longitude $236°.09 \pm 0°.02$ (November 18, 9–10h UT). At longer-echo durations (figs. 3c-d), a secondary peak appears at $235°.96 \pm 0°.02$ (November 18, 6–7h UT) which is more prominent for long enduring meteor trails. Furthermore, at longer-duration echoes (fig. 3d) the position of the maximum flux at 236°.13 (November 18, 10–11h UT) is shifted one hour later with respect to the hourly rate maximum, in agreement with visual observations [9]. The contributions of different numerical models from individual perihelion passages are centered near 10h and 17–18h UT (the second one not revealed by the BLM being the Leonids below the horizon at that time) (fig. 2).

At a first analysis, the model of Lyytinen *et al.* [6] appears to match more properly our radar findings. This model assumes that particles leaving the comet suffer from solar radiation pressure which increases the semi-major axes of orbits and moreover, the dust relative to the major peak in the morning originates from the perihelion passage of the parent comet in 1766 (7 revolutions ago).

Radio data enable us to derive the mass distribution index s and the population index r ($s = 1 + 2.5 \log r$) from the observed echo durations of the shower and sporadic meteor echoes. The mean mass indices obtained for the Leonids and sporadic background

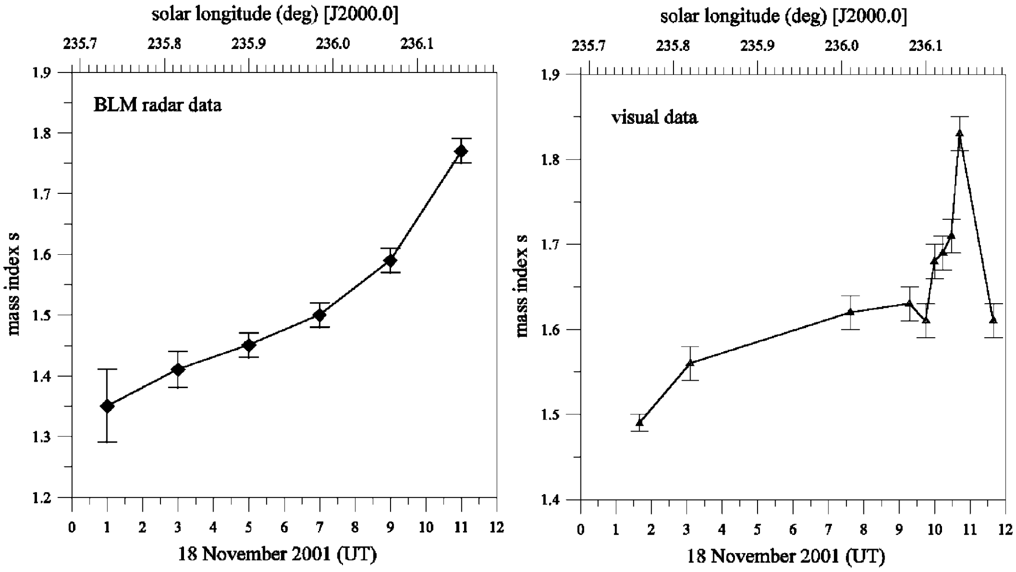

Fig. 5. – Variations of the mass index on November 18, 2001 (01–12 UT) relative to BLM radio data (left) and visual data (right) [9].

observed in 2001 have been obtained by a linear interpolation of the cumulative number of the radioechoes having a duration $T \geq 1$ s (fig. 4).

At the peak, mean mass (s) and population (r) indices for Leonids in 2001 (duration $T \geq 1$ s) are 1.72 and 1.94, respectively. As a comparison, population indices for visual data (r_{vis}) were found to be at the peak close to 2.15. For sporadics, mean mass indices were calculated to be close to 2.5. The radio mass indices, obtained at 2h bins by the slopes of cumulative distributions of radioechoes corrected for chemical effects [10], exhibit large variations similar to the visual ones observed in the morning of November 18 (fig. 5).

The clear peak with the associated mass index $s = 1.72$, coincides with the activity maximum of the Leonids. The period before the peak shows indices below this value when an abundance of long-duration echoes (bright meteors and fireballs) was recorded (see, for instance, the flux maximum at solar longitude $235^{\circ}.95$, November 18, 6h 30m UT). An abundance of faint meteors is conversely observed once the Earth is passing through the actual young dust trail. The temporal flux variations observed on November 18 seem to coincide with periods that the Earth crossed the inhomogeneous Leonid dust trail, which is composed of the "background" component and several narrow "dust filaments" ejected from the parent comet in the last several perihelion passage [1, 2]. When debris is released from a comet during a given return to perihelion, the first stage of evolution is to stretch gradually in a long, dense, narrow trail of meteoroids and dust. Therefore perturbations at all points along the trail and their consequent effects on the trail's location, can be reliably calculated until chaotic behaviour (*i.e.* after some centuries).

4. – Conclusions

Very recent observations of the Leonid meteoroid stream give an opportunity to develop new models of comet dust trails, meteor ablation and persistent trains, and, in addition, to deepen our knowledge on the interaction processes of meteoroids with the Earth's atmosphere at hypersonic velocities ($\geq$ 70 km/s). Results of the Leonid campaigns [3, 11] brought new light on: i) modeling of meteor physical processes; ii) studies of the erosion of organic matter in meteoric plasma; iii) mass distribution of meteoroid fragments; iv) presence of tiny (1 nm sized) dust grains of recondensed vapor in the upper atmosphere. Furthermore, we must mention some unusual atmospheric phenomena observed during the 1999 storm, which had a positively glowing effect on the Earth's atmosphere. At the peak of the storm, an unusually large number of elves and sprites, which are induced flashes of light in the upper atmosphere, was observed just below the meteor layer. At the same time, the nighttime hydroxyl (OH) airglow became 30% brighter during the storm [12]. We cannot be certain that the meteor storm was responsible for the observed increase in OH, or had anything to do with the observed elves and sprites. We need thus to continue these studies and validate results from further observation of Leonids in 2002. After the minor 2001 Leonid storm, another impressive storm is in fact predicted on November 2002, with potentially intense displays over North America and Europe. After 2002, encounters with Leonid dust trails will decline. Models predict little activity for three years followed by normal Leonid rates (10 to 15 per hour). Thereafter, it appears that the 33 year cycle of intense display will end for nearly 100 years as Jupiter will deflect the whole system of trails just enough to prevent further encounters with Earth.

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