# MASS DISTRIBUTION OF THE LEONID METEOROID STREAM AND SATELLITE THREAT BY SYSTEMATIC RADIO OBSERVATIONS

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ABSTRACT

A comprehensive survey of the results from joint campaigns of the Leonid meteoroid stream observed on Novembers of 1995-2000 by the BLM (Bologna-Lecce-Modra) forward scatter radar is given in terms of structural aspects and stream mass-distribution variations in connection with satellite threat. Trends of long duration echoes and variations of reflection time exhibit a multiple peak activity, which is seen to be associated to a filamentary structure of the Leonid meteoroid stream. The particle density/stream width relationship is found to match observations of IRAS (Infrared Astronomical Satellite) dust trails of short-period comets. The mass distribution indices of the Leonid meteoroids in coincidence with the peak activity, are shown to change significantly throughout the 6-year observational period in agreement with visual findings. A representation of extended components of larger particles in 1996 and mainly in 1998, and of relatively smaller particles during the minor meteor storm of 1999, is evidenced.

The consequences of meteoroid high fluxes and low mass indices in 1998-2000 are examined in relation to spacecraft interactions and effects. The different values of the mass indices for the 1966 and 1999 storm meteoroids might account for the comparable critical impact probability values determined for these two years as a function of the exposed area of space platforms. On the basis of the measured fluxes, critical impact probabilities for the 1995-2000 years appear to be generally low even for large extension orbiting structures, but prospects for storm encounters are from 2001 and 2002 [1].

## 1. INTRODUCTION

Sharp outbursts or storms occur in a few meteoroid streams when the Earth passes through a dust trail, a narrow structure where the spatial density of meteoroids is very high. Among these meteoroid streams, the 33-year-period Leonid stream produced by the comet Tempel-Tuttle is the most hazardous since Leonids encounter the Earth with a velocity of about 71 km/s. Clearly, under these conditions the impact parameters of meteoroids deserve particular attention, since a Leonid has seven times the momentum of a common space debris at the same mass, and nearly fifty times its kinetic energy [2] .

Recent studies [1, 3, 4] have provided a better understanding of the Leonid phenomenon and are able to predict the time and intensity of the Leonids with a great accuracy.

In these years, the Leonid meteoroid stream exhibited an intense and irregular flux rate, and offered an idea of the potential risk to the satellite population in coincidence with an enhanced activity (*outburst or storm*) of the stream [5,6]. Basically, meteor trails become dispersed after many orbital revolutions so that the spatial density of meteoroids is thought to decrease during this time. However, resonant mechanisms can cause meteoroids in the Leonid and other streams to remain very concentrated on longer time scales, leading to outbursts that are rich in larger particles [7]. The potential Leonid hazard to satellites was taken into account after the failure of the Olympus communication satellite due to an impact with a Perseid meteoroid during the night of the predicted peak on August 12, 1993 [8].

The main goals are to determine structural aspects and mass distribution of the meteoroid stream, and to provide mass-dependent flux information from the flux and activity of the Leonids in the 1995-2000. An accurate calibration of the fluxes and the spatial number density of particles in the Leonid meteor stream is of paramount concern to satellite operators.

## 2. ACTIVITY OF LEONIDS IN 1995-2000

Radio observations of Leonids were carried out throughout 2 weeks, between November 10 and 24 of each year in the 1995-2000 period by using a forward-scatter radar system operating along two mutually almost rectangular baselines, having the transmitter at Budrio (44°.6N, 11.°5E), near Bologna, and 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 are about 700 and 600 km, respectively. The equipment utilises a continuous wave transmitting frequency at 42.7MHz and a 1 kW mean power [9].

The data reduction and analysis are described elsewhere [10]. Since the perihelion passage of Comet P/Tempel-Tuttle occurred on 28 February 1998, a significant increase in the shower activity was expected from 1998. However, the activity profiles of Leonids as deduced from the BLM radio data in the 1995-2000 period, show an increase in the activity even in years prior to the perihelion passage (Fig.1).

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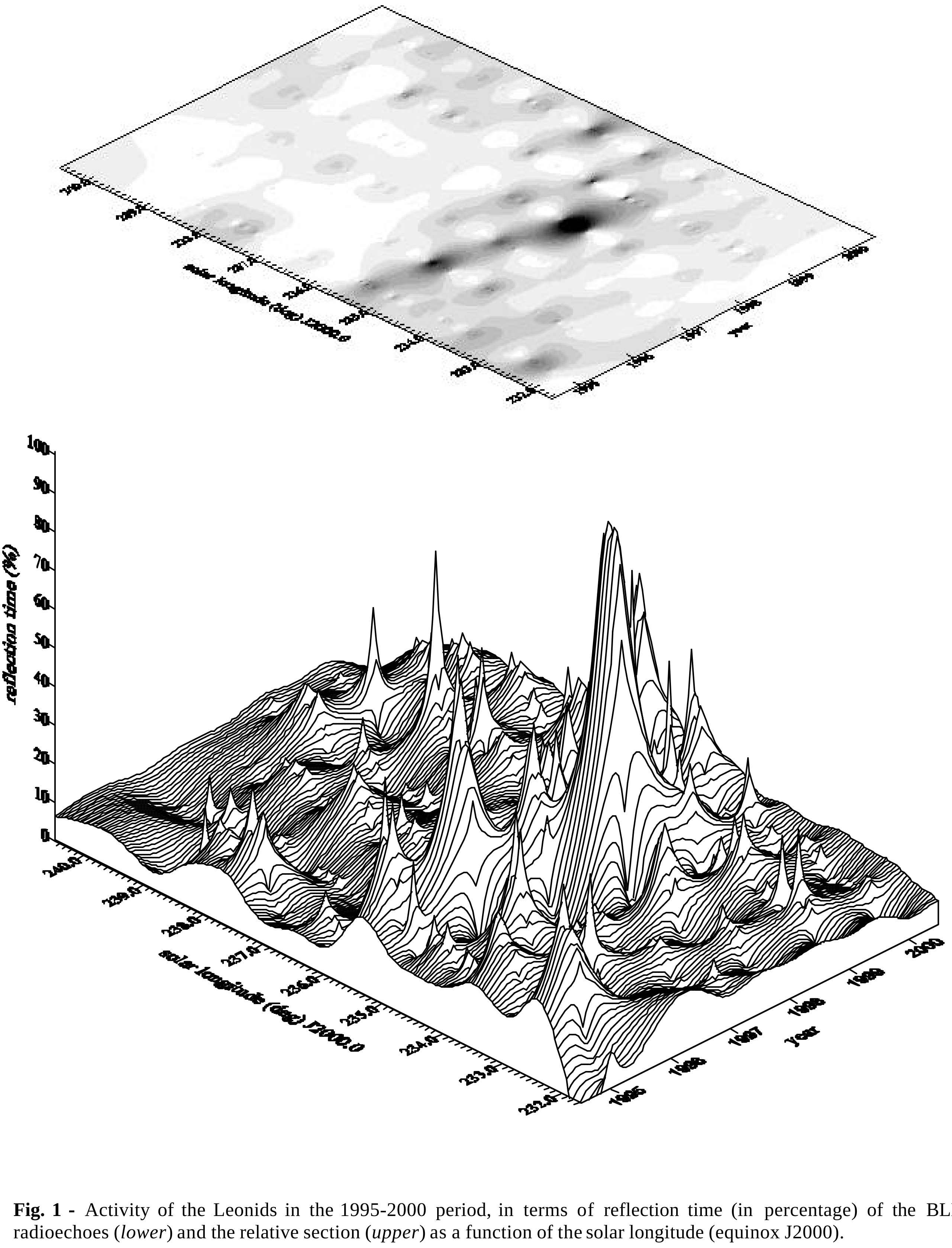



**Fig. 1 -** Activity of the Leonids in the 1995-2000 period, in terms of reflection time (in percentage) of the BLM radioechoes (*lower*) and the relative section (*upper*) as a function of the solar longitude (equinox J2000).

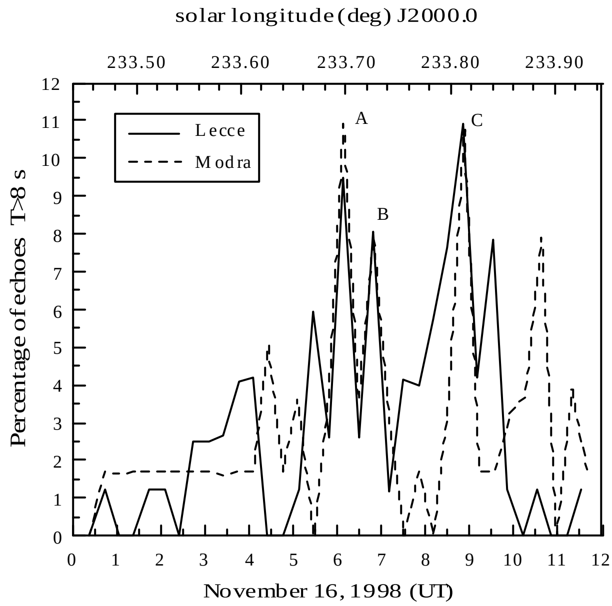
In fact the ejection velocities of the fragments released by the comet, lead these to display onward and backward with respect to the position of the parent body, anticipating in this way the arrival of the comet. As for the risk assessment, the first interesting episode occurred on November 1998 when the BLM radar evidenced an unusual activity in the 16-17 November night. During the outburst, the calculated mass indices were extremely low, so evidencing the presence into the stream of large meteoroids with a highly ionizing power. The duration of single events were surprisingly able to obscure the receiving system throughout almost ten consecutive hours at the solar longitudes $\lambda_M$= 234°.4 – 234°.9 (equinox J2000.0) (November 17, 00-10 UT). Reflection times were 91% and 88%, respectively at the two receiving stations of Lecce and Modra causing obscuration of underdense trails by the numerous persistent echoes. These percentages represent the highest values recorded so far at our meteor radar stations during 25-year observations of meteor showers.

In 1999, strong evidence of a short (less than 1 hour) and extremely intense activity has been pointed out at the nodal longitude of the parent comet, in agreement with previous findings that indicate the duration of a storm approximately of the order of 0.01-0.1 day [11]. It is important noticing that a storm was visually observe from different locations exactly at the same solar longitude ($\lambda_M$=235°.248), corresponding to November 18, 1999, 02:07h UT. At that time an equivalent peak ZHR of 3700 ± 100 based on about 3-minute intervals was observed (only observations with limiting magnitudes between +6 and +7 were taken into account to produce the ZHR-profile) [10].

Another return of Leonids with prolific meteor rates was monitored in 2000. Radio data exhibit a multiple peak activity, the two major peaks being consistent with the anticipation [1]. These enhancements cover the predicted time of the dust trails released in coincidence with previous perihelion passages of the parent comet.

Fig.2 shows the number of long-duration (T > 8 sec) radioechoes (in percentage) recorded at the stations of Lecce and Modra on November 17, 1998 during the Leonid display (*upper part*). The full width at half maximum of the common peaks (A, B and C) recorded at both stations is 0°.02 - 0°.03 corresponding to trail widths of about 20.000-25.000 km if an angle of about 163° with respect the Earth motion is taken for Leonids. Similar results can be obtained in the case of the 2000 Leonids. The *lower part* of Fig.2 shows the number of long-duration (T > 8 sec) radioechoes recorded by the BLM radar on November 18, 2000 during the Leonid display when a multipeak structure was observed into the meteoroid stream. Two major peaks were predicted by orbital integrations of dust trails produced by the parent comet at perihelion passages [3]. A first maximum was expected on november 18 at 03h44m UT ($\lambda_M$= 236°.104) caused by the 1733 trail after 8 orbital revolutions and at 7h51mUT ($\lambda_M$=236°.278) caused by the 1866 trail after 4 orbital revolutions. These two peaks were observed at the same solar longitude by the BLM radar that evidenced another intermediate peak at about 5h45h UT ($\lambda_M$=236°.185).

The first and the third radar maxima in Fig.2, recorded at about 03h45m UT ($\lambda_M$=236°.1) and 07h10m UT ($\lambda_M$=236°.24), respectively, correspond to the visual peaks. The third maximum occurs about 40 minutes before the predicted 1866 dust trail passage. Moreover, the BLM radar recorded in addition another peak on November 17, 2000 at about 08h30m ($\lambda_M$=235°29) quite close to the visual peak ($\lambda_M$=235°.28) observed at the predicted 1932 dust trail passage.



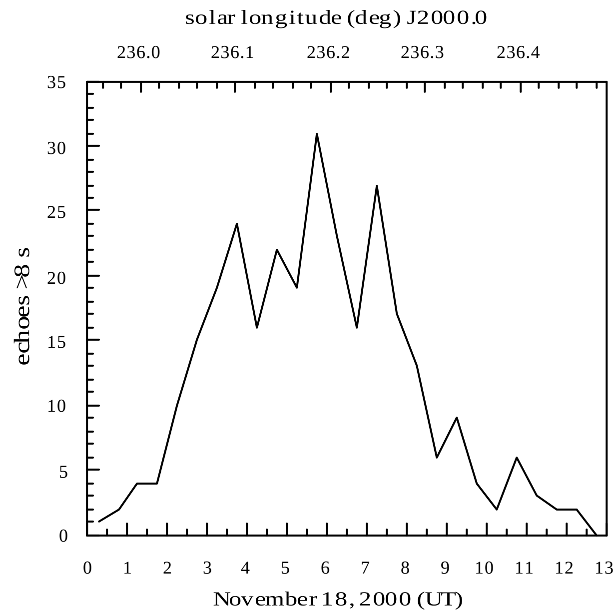




Fig. 2 - Number of long-duration (T > 8 sec) radioechoes (in percentage) recorded by the BLM radar on November 17, 1998 (*upper part*) and on November 18, 2000 (*lower part*) during the Leonid display

The width at half maximum of the radar peaks recorded on November 18, 2000, is again about 0°.02 and corresponds to trail widths of about 20.000 km. These values are in good agreement with sizes of the dust trails ejected by short-period comets at heliocentric distances of 1 AU, discovered by the IRAS satellite. Kresak [11] indicates a typical width of 30.000 ±10.000 km at 1 AU distance for IRAS dust particle density exceeds 400 ± 200 times that of the sporadic background at 1 AU.

## 3. THREAT TO SATELLITES

One of our main goals was to establish the Leonid flux in order to assess the hazard posed to satellites. The flux is expressed in terms of number of meteors which would impact one square kilometer surface perpendicularly oriented to the Leonid radiant in one hour. Flux densities of Leonids in the 1995-2000 years have been determined from results of radio and visual observations, with a particular attention to the 1998-2000 episodes. As a comparison, the extremely intense storm episode occurred in 1966 (ZHR=150,000) was considere, by assuming a Gaussian model for the duration and the ZHR peak value, and adopting a mass index of s=2.5 [2].
The 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 mass-distribution is usually determined from the echo duration distribution which is a much more sensitive function of mass distribution (see $N \propto m^{1-s}$, where N and $m$ are number and mass of meteoroids, respectively). The distribution of the cumulative numbers of echo duration allows us to derive the exponent s from the relation [10]:

$$N_c \propto T_D^{(-3/4)(s-1)} \qquad (1)$$

where $N_c$ is the cumulative number of echoes with the duration equal to and greater than $T_D$.
The mean mass indices obtained for the sporadic background and Leonids observed in the 1995-2000 years have been obtained by a linear interpolation of the cumulative number of the radioechoes having a duration greater than T (Tab.1).

Tab.1 - Mean mass (s) and population (r) indices for Leonids and sporadics in 1995-2000 (duration T > 1 sec) (population indices for visual data are reported as a comparison).

| **Leonids** | **s sporadics** | **s shower** | **r** | **$r_{vis}$** |
|---|---|---|---|---|
| 1995 | 2.34 | 1.69 | 1.89 | 1.80 |
| 1996 | 2.46 | 1.56 | 1.67 | 1.66 |
| 1997 | 2.75 | 1.66 | 1.84 | 2.00 |
| 1998 | 2.46 | 1.36 | 1.39 | 1.20 |
| 1999 | 2.39 | 1.54 | 1.64 | 2.20 |
| 2000 | 2.50 | 1.84 | 2.20 | 2.05 |

Fig. 3 shows the variations of the population indices of Leonids in the 1995-2000 period obtained from radio and visual data (Tab.1). The radio mass indices obtained after combining together the data gathered at both the receiving stations of the BLM radar exhibit

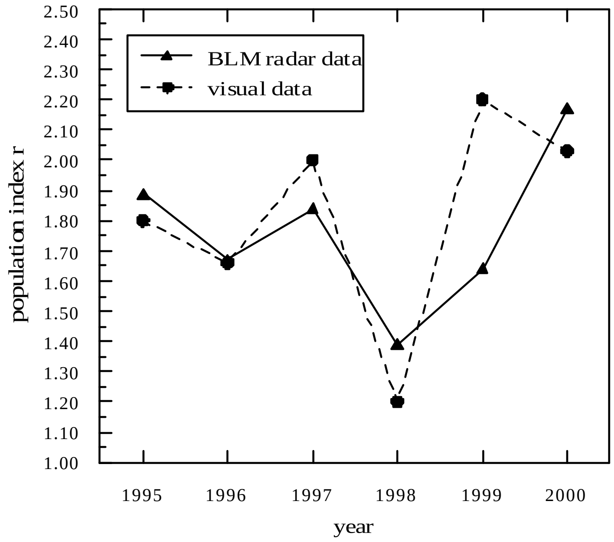



Fig. 3 - Variations of the population indices of Leonids in the 1995-2000 period obtained from radio and visual data (Tab.1).

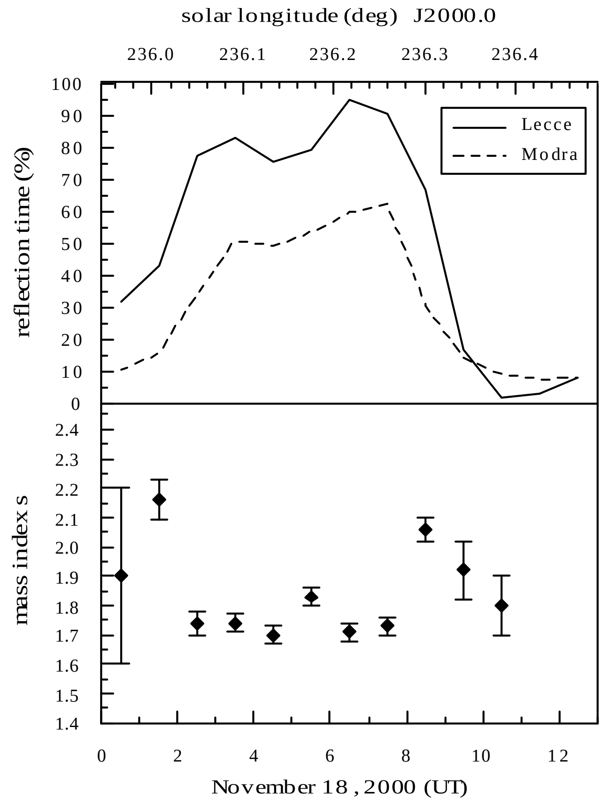



Fig. 4 shows the reflection time in percentage of the radioechoes (*upper part*) and variations of the mass index s (*lower part*) recorded by the BLM radar at the two stations of Lecce (continuous line) and Modra (dashed line) on November 18, 2000 during the maximum of the Leonid display.

large variations similar to the visual ones, except for 1999 when a low mass index (s = 1.54 ± 0.02) was extracted by the BLM data at the time of the maximum (November 18, 01:50-02:10UT). On the other hand, from a comparison of simulated flux versus observed

Aircraft Campaign), Gural and Jenniskens [12] indicate approximately for the same time a magnitude mass index $s = 1.64 \pm 0.06$ (a close value to radio data) and an average spatial density at the peak equal to $0.82 \pm 0.19$ particles $km^{-2}$ $hr^{-1}$ for particles of at least absolute visual magnitude +6.5.

Fig. 4 shows th*e* reflection time in percentage of the radioechoes *(upper part*) and variations of the mass index s (*lower part*) recorded by the BLM radar at the two stations of Lecce (continuous line) and Modra (dashed line) on November 18, 2000 during the maximum of the Leonid display.

If the mass index s is constant in a certain mass interval, we can convert in this way the fluxes measured at any mass from the equation:

$$f(m_1) = \left(\frac{m_1}{m_2}\right)^{1-s} f(m_2) \qquad (2)$$

where $f(m_1)$ and $f(m_2)$ are the fluxes of meteoroids having the mass greater than $m_1$ and $m_2$, respectively.

The observed flux densities were converted to those relative to a mass greater than the critical mass for Leonids, corresponding to $2.8\times10^{-5}$ kg [6]. From the duration of the event and the average flux density of the meteoroids having mass greater than the critical mass, critical impact probabilities have been calculated as a function of the target cross section, normally exposed to the flux (Fig.5). Calculations are relative to a duration centred around the peak of the outburst (10 hrs for 1998 and 2000, and 5 hrs for 1999) and to the $10^{-9}$ - $10^{-3}$ kg mass range.

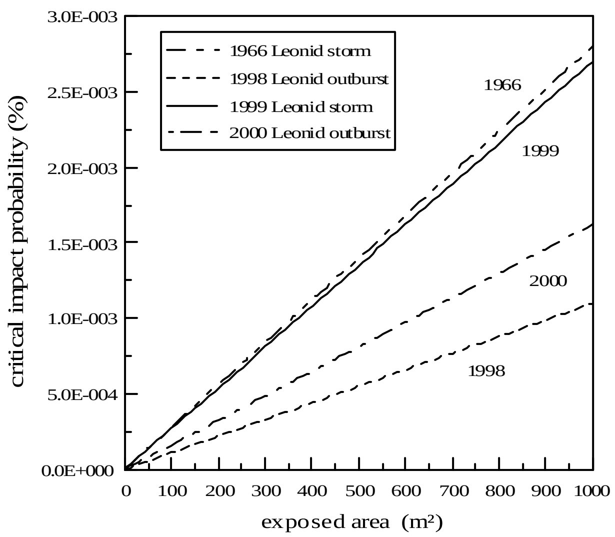



Fig. 5 - Critical impact probabilities (%) as a function of the exposed area for Leonids

Critical impact probabilities (Fig. 5) at a prefixed area are surprisingly quite similar during the meteor storms of 1966 and 1999, even if the reported ZHRs for the observed during the 1999 storm. We can account for this apparent discrepancy by comparing the corresponding mass indices. High mass indices (s = 2.5), as those for the 1966 episode, are consistently lowering the fluxes, if masses greater than $7.7\times10^{-8}$ kg (corresponding to visual meteoroids with limiting magnitudes of +6.5) are taken into account. As for the 1999 storm, this flux decrease was less significant since during the peak time of the episode only low mass indices (s = 1.54) were observed (see Tab.1). On the basis of the measured fluxes for $10^{-9} \div 10^{-3}$ kg meteoroid mass range, critical impact probabilities for analogous episodes as in 1966 and 1999 appear to be low even for large extension orbiting structures. For instance in the case of ISS, by assuming an exposed area of 1000 $m^2$, values of the critical impact probability are less than 0.003%.

The ballistic limit $F_{max}$, i.e. the maximum thickness of material that can be penetrated for a given set of impactor parameters, was derived by the penetration equation (with slight rearranging for the target in aluminium, and a Leonid meteoroid of spherical shape and of a $2 g/cm^3$ mean density), so that [13]:

$$F_{max} = 2.35 \times 10^{-2}\ m^{0.532} \qquad (3)$$

where $F_{max}$ is expressed in cm and the meteoroid mass m in kg.

If for meteoroid masses a lower extreme of $10^{-9}$ kg is considered and the fluxes are calculated from radio and visual observations, the expected number of impacts on ISS during the peak activity of Leonids in 1966, 1998 and 1999, is determined as a function of the crater depth at an incidence angle of 90° [13] (Fig. 6).

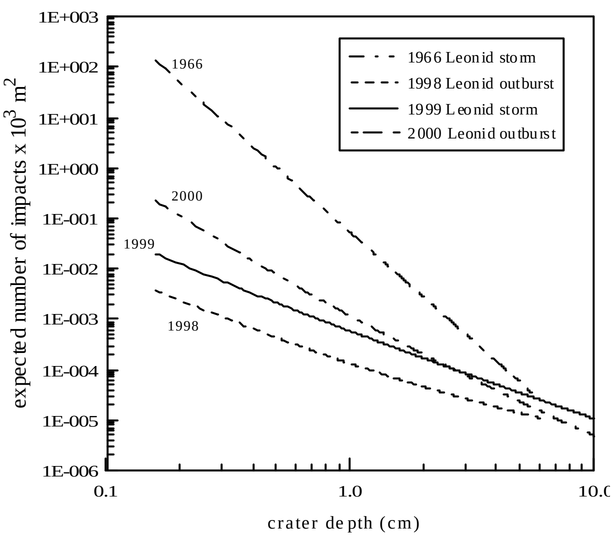



Fig. 6 - Expected number of impacts as a function of the crater depth (cm) for Leonids (a $10^3$ $m^2$ exposed area is assumed).

Concerning the erosion effects provoked by non critical impacts with lower-mass meteoroids, a number of expected impacts was found to be decisively higher in episodes of 1998, 1999 and 2000. An analogous trend is evidenced by analysing impact probabilities on ISS, as a function of the released electric charge (Fig.7). For an impact velocity of 71.2 km/s we obtain [13]:

$$Q = 1.96 \times 10^{6}\ m^{1.02} \qquad (4)$$

where $m$ is the meteoroid mass in $kg$ and $Q$ the release charge in *coulomb*. Although the peak is very intense as for the minor storm of November 18, 1999, it is relatively short lived and so we must consider the total integrated fluence over a reasonable time.

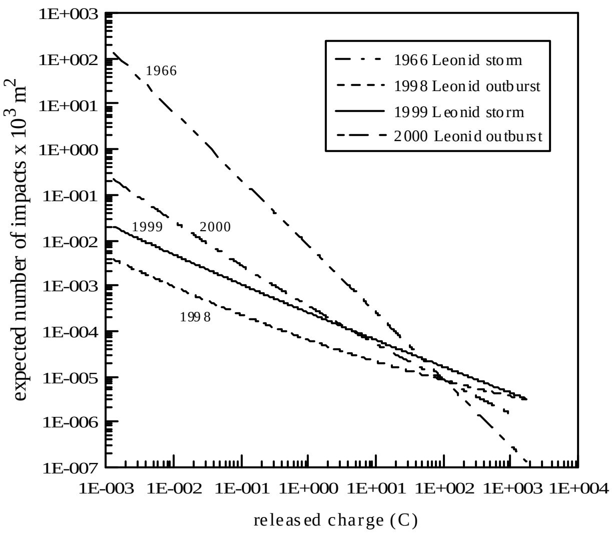



Fig. 7 - Expected number of impacts as a function of the released charge for Leonids (a $10^3$ $m^2$ exposed area is assumed)

## 4. CONCLUSIONS

Systematic observational campaigns of the Leonid meteoroid stream revealed that key meteor shower parameters, such as the mass index and the spatial number density, present large yearly variations. Investigations of the perturbed motion of Leonid dust trails indicate that the Earth had a series of close approaches to trails, evidenced by the outbursts in 1998 and 2000, and the minor storm in 1999.

Today, it is possible to predict with a a great accuracy the time of Leonid maximum activity, and the direction and distance of the closest approach to the dust trail [1]. Therefore, Leonid meteor storms can be predicted by calculating the nodal positions of the parts of trails that pass through the ecliptic in mid-November. Storms can be expected in 2001 and 2002, but estimation of their intensity is strongly limited by the scarcity of observational data [3]. In 2001, the densest part of the dust trail at the time of the encounter is almost certainly near the GEO satellite belt over the Far-Eastern Pacific. This allows the satellite operators to use proficously strategies to minimize the threat to GEO satellites.

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