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Modern radar techniques and the hazard of meteoroids to space platforms

Giordano Cevolani
Istituto FISBAT/CNR, Bologna, Italy

Abstract
Modern radar techniques, and in particular ground based radars, are a powerful tool to observe space objects (natural meteoroids and artificial space debris) on account of their all-weather and day-and-night performance. Natural meteoroids are an important component of the near-Earth space environment and represent a potential risk for all Earth-orbiting space platforms, which could significantly increase in coincidence of enhanced (outburst or storm) activity of meteoroid streams. A review of the currently active meteoroid streams suggests that a few streams have shown a quasi-periodic outburst activity in the two last centuries and may even undergo a storm activity in the next few years. The Leonids, the most intense of meteor showers, present a potentially serious damage to spacecraft in November of 1998 and 1999, after the perihelion passage of the parent body. Impact probability values of storm meteoroids on space platforms in Low Earth Orbit (LEO) were calculated using the data recorded during systematic observational campaigns carried out by the FS radar facility Bologna-Lecce in Italy. Meteoroid flux predictions and directionality, and investigation on impact parameters at very high velocities (up to 71 km/s) for penetration, charge production and plasma generation, are relevant aspects to develop strategies for safe deployment of the near Earth-orbiting space platforms.

Key words *radar – meteoroid – meteor storm – space debris – space platform*

1. Introduction

The near-Earth meteoroids and orbital debris environment present documented hypervelocity impact threats to spacecraft. Knowledge of this environment is of increasing importance for the scientific, commercial and environmental interests of all nations involved in space exploration. Investigation of the flux of impacting particles is also required to analyse the impact risk for orbiting spacecraft and to take protective measures. Furthermore, meteoroids (natural space debris) and artificial space debris represent a probable cost impact to the system design and a threat to the successful completion of spacecraft missions. US SPACE COMMAND tracks and catalogues Earth orbiting active spacecraft and space debris employing their world-wide Space Surveillance Net of radar and optical sensors. In March 1997, the NASA-Catalog, the basic source for international Space Agencies, contained a total of about 8200 objects characterised as payloads (25%), rocket bodies (17%), debris (57%) and unknown objects (1%). Only 5-6% of these objects are operational satellites. An important aspect is that at present 1 m sized objects can be tracked in Geosynchronous Orbits (GEO) whereas 2 cm sized are detectable by modern radars at 1000 km range (LEO) (Mehrholz, 1997).

The analysis of material returned from space, *e.g.*, satellites or their parts (Shuttle, Solar Max, Palapa, Westar, LDEF, MIR, EURECA, HST) and experiments *in situ*, have

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Mailing address: Dr. Giordano Cevolani, Istituto FISBAT/CNR, Via Gobetti 101, 40129 Bologna, Italy; e-mail: G.Cevolani@fisbat.bo.cnr.it

widened our knowledge on millimetre- and micrometer-size particles which are the most abundant. The retrieval of the EURECA satellite and Hubble Space Telescope (HST) solar arrays from prolonged exposure in LEO has generated a wealth of impact data which permitted (Drolshagen *et al.*, 1996, 1997): a) a recording of the impact features; b) an analysis of the impact craters assessing potential damage caused by meteoroids and space debris; and c) validation and improvement of current models of meteoroids and space debris populations in LEO. For spacecraft in LEO typical impact velocities are for space debris particles from 5 to 15 km/s (with an average around 10 km/s), and for meteoroids are from 10 to 70 km/s (with an average around 17-20 km/s).

Recently it became clear that the environment of artificial space debris has to be investigated in close connection with the activity of meteoroids. On GEO, the natural particle flux dominates the artificial one whereas collisions on LEO are thought to be caused mainly by artificial objects. Nevertheless, in periods of activity of strong meteor streams natural particles may prevail over artificial ones even in LEO. Meteoroid particles become hazardous for spacecraft since their impact energy is more than 2 kJ, a value which corresponds for sporadic meteoroids to a particle mass greater than 3.10^{-4}g, and for comet-type meteor streams to the mass of about 10^{-3}g (Smirnov and Barabanov, 1997). For more 500 satellites in GEO with a surface exposure of about 10 m^2, one impact of a meteoroid may occur almost every two years.

There are many examples, which stress the importance of meteoroids as hazardous impactors for spacecraft. During the 1993 Perseids the Russian Space Station (MIR-1) experienced about 60-70 impacts and the Space Shuttle (STS-51) launch date was delayed (Beech *et al.*, 1995). Moreover, the failure of the Olympus satellite is thought to be due to an impact with a Perseid meteoroid (Caswell *et al.*, 1995) during the night of the predicted peak (August 11-12, 1993. The EURECA satellite post-flight analysis of 932 recorded impact features (ranging from about 30 μm and 6.5 mm) suggested that meteoroids are the main source of impactors (Drolshagen *et al.*, 1996). Studies of impact residues on EURECA and HST which were performed to distinguish between meteoroids and space debris remained, however, inconclusive because of the complexity of the targets (Drolshagen *et al.*, 1997). Other data stress the importance of studies on the hazard of meteoroids for space platforms. Impacts observed on November 20, 1995, during the EuroMir-95 mission, are thought to be connected with the Leonid meteoroid stream (Maag *et al.*, 1997). Furthermore, the Leonid meteor stream is expected to undergo enhanced activity, possibly to storm levels, in mid-November of both 1998 and 1999 (Kresàk, 1993a,b; Beech *et al.*, 1995; Levin *et al.*, 1996). Of the meteor storms, the 33 year period Leonid storms, produced by the comet P/Tempel-Tuttle are the most hazardous since the velocity of Leonid particles (71 km/s) amplifies the penetration depth over that of space debris by a factor of 3.7 (Levin *et al.*, 1996). There are already clear signs that Leonid stream activity, measured according the greatest hourly radar rate of the shower maximum, is on the increase since 1995 (Cevolani and Foschini, 1996; Trivellone *et al.*, 1997). High meteoroid fluxes at the Earth expected also by detailed numerical modelling of the stream (Beech *et al.*, 1997) may raise to 10^{-2} % per m^2 the meteoroid impact probability upon space platforms on Earth.

2. Meteor shower outbursts and storms

Meteoroids are small bodies of the solar system, which form through the ejection of dust grains from comets and, to a lesser extent, from asteroids. After ejection these meteoroids are subject to forces arising from solar radiation and the gravitational fields of the planets. Meteoroids may also break up into smaller ones through collisions and other effects. A meteor shower is a concentration of meteors apparently emanating from a particular direction (radiant) at a given time, whose location is determined by the orbit of the meteoroid stream and that of the Earth. A meteoroid stream is a family of small bodies all moving on similar orbits about the Sun.

Meteoroid streams from comets are produced by interaction of solar radiation with the cometary surface, when the cosmic body is close to the perihelion of its orbit. The meteoroid stream is structured with discrete filaments with high meteoroid spatial density, typically 20 000-35 000 km wide (Hughes, 1995).

Annual stream activity is not the only manifestation of meteor stream since annual streams, too, have significant variations in activity due to the distribution of dust in the meteoroid debris. Usually a meteor stream is periodically enforced, even with high mass particles, by the comet perihelion crossing and enhanced meteor activity (outburst or storm) can be expected from every meteoroid stream. Meteor storms occur when the Earth passes through an extremely dense portion of a cometary dust trail. The Earth is inside the densest and most hazardous part of these dust trails for a maximum of several hours. While more than 20 known meteor showers occur every year, the average meteor shower presents only a very minor increased hazard to human space flight. Occasionally, the Earth passes through a particularly dense portion of one of these dust trails and the number of meteors rises dramatically. The higher the local density is, the stronger the storm. At a given solar longitude, an outburst will occur if the observed ZHR exceeds the annual average of 5 times the standard error deviation of the stream's annual mean. (ZHR is the number of hourly observable meteors greater than visual magnitude + 6.5 under perfect conditions with the radiant directly overhead). When the Earth passes the node shortly after, or shortly before the parent comet, then we can record an increased flux given by $F\cdot$(ZHR), where F is the storm enhancement factor. For example, Kresàk (1993b) adopted an ZHR of 3600 (1 meteor every second) as the minimum value ZHR to determine a storm, whereas Brown and Jones (1993) considered ZHRs in excess of 500 (1 meteor every 8 s) in the context of the Leonid meteor storm. More recently, Beech *et al.* (1995) fixed a storm criterion with a ZHR in excess of 1000 and enhancement factors F between 50 and 10^4 for those meteoroid streams that produced meteor storms in the past (table I). The meteoroids sampled during a meteor storm form a cloud of newly ejected material from the parent comet and have little time to spread significantly around the stream orbit. A greater number of smaller mass meteoroids (and obviously of higher mass meteoroids) is expected in the population of storm meteoroids in comparison to those observed during normal annual activity. In fact, the Poynting-Robertson (P-R) effect and the solar radiation pressure which have an important in-

Table I. Documented meteor storms since 1799. The storm ZHR and non-storm yearly averaged ZHR are given by Kresàk (1993b) and McBeath (1993), respectively. F is the storm enhancement factor.

Date	Meteor shower	ZHR (storm)	ZHR (max)	F
1799	Leonids	30000	15	2000
1803	Lyrids	1500	20	75
1832	Leonids	20000	15	1300
1833	Leonids	100000	15	6700
1866	Leonids	6000	15	400
1867	Leonids	5000	15	330
1872	Andromedids	8000	10	800
1885	Andromedids	15000	10	1500
1933	Draconids	20000	10	2000
1946	Draconids	7000	10	700
1965	Leonids	5000	15	330
1966	Leonids	150000	15	10000

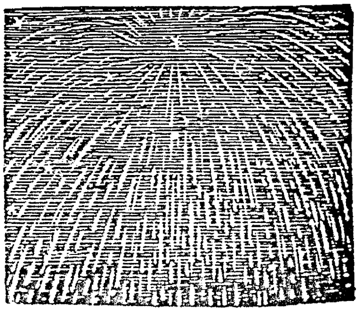

Fig. 1. Top: the most famous meteor picture of the Leonid meteor storm occurring on November 13, 1833. Bottom: another representation of the event, taken from the *Mechanics' Magazine*, New York, November 1833, p. 288. This last engraving was executed under the direction of Henry J. Pickering, one of the editors of a New York weekly journal, who witnessed the scene. (See text for details).

fluence on stream evolution over long-time scales, will not be able to remove fainter particles from the newly ejected population of storm meteoroids in a short time. Porubcan and Stohl (1991) found that at the time of enhanced Leonid and Lyrid activity the proportion of fainter meteors tends to be higher than normal, showing an increase in mass index. This finds confirmation in recent observations of meteoroid streams.

Kresàk (1993a) demonstrated that all active short-period comets give rise to narrow compact streams with typical lifetimes of about 60 years (analogously to the IRAS dust trails) and utilised orbital long-term integrations for prediction of future meteor storms.

In the case of the P/Tempel-Tuttle, the parent comet of the annual Leonid meteor shower each November, the Earth regularly encounters localised concentrations of dust particles every 33 years (the period of the parent body). At that time the observed Leonid meteor rates may increase by factors of up to 10 000 or more for a few hours as Earth passes through these concentrations of meteoroids. In the worst case, the Leonid storm can produce 100 000-150 000 events per hour, whereas the normal background is 10-15 events per hour. Table I shows documented meteor storms since 1799. The storm ZHRs and non-storm yearly averaged ZHRs are given by Kresàk (1993b) and McBeath (1993), respectively. *F* is the storm enhancement factor.

The next Leonid outburst or storm is suggested to occur in November of 1998 and/or 1999, but already during the last few years an enhanced activity has been observed (Foschini *et al.*, 1995; Cevolani and Foschini, 1996; Levin *et al.*, 1996; Trivellone *et al.*, 1997).

Figure 1 shows (top) the most famous meteor picture of the Leonid meteor storm occurring on November 13, 1833 and (bottom) another representation of the event, taken from the *Mechanics' Magazine*, New York, November 1833, p. 288. This last engraving was executed under the direction of Henry J. Pickering, one of the editors of a New York weekly journal, who witnessed the scene. Denison Olmstead, Yale University, reported at the time: «*To form some idea of the phenomenon, the reader may imagine a constant succession of fire-balls, resembling sky rockets, radiating in all directions from a point in the zenith, and following the arc of the sky towards the horizon...*».

3. Radar meteor observations

Radar systems operating in the frequency range of 2-100 MHz have been employed for general studies of meteoric ionisation, both as probes of atmospheric aeronomy and dynamics (see for example, Cevolani, 1991, 1992) or of meteor physics (see for instance, Cevolani *et al.*, 1995a,b). Meteors have been studied by radio methods using a variety of techniques including Back-Scatter (BS), Forward-Scatter (FS), Continuous Wave (CW), single and multi-station.

The amplitude and phase characteristics of the radio echo contain information on the rate of formation of the trail, ionisation distribution along the trail, electron line density, rate of diffusion of the ionisation and drift of the trail due to the motion of the neutral atmosphere (the ionised trails drift with a velocity that is easily measured by pulse Doppler radars).

Radar techniques enjoy these particular benefits:

1) No operation restrictions imposed by weather conditions. From a given location, there is no substantial limitation because of sunshine and cloudiness.

2) A complete diurnal coverage without any time limitation. Occasional interference from both radar ground-scatter signals (mainly ionospheric *E*-sporadic) and broadcast services may occur for radars using the lower HF band and at the time of near sunspot maximum.

3) Higher sensitivity when detecting faint meteors. Compared with the magnitude limit of $+2$ for small camera facilities, $+4$ for Super-Schmidt cameras and $+8$ for TV operations, radars are operational with limits in the range $+8 \div +13$ (corresponding to $10^{-4} \div 10^{-6}$ g mass or 0.5 mm $\div$ 100 μm size). The dominant particle size associated with a meteor storm is 0.1 mm, even if particles as large as 1 cm can be statistically significant.

On the other hand, radar can measure only some physical parameters which do not provide a complete diagnosis as optical techniques. Moreover, there are high uncertainties in these measurements due to instrumental effects and it is not possible to obtain absolutely calibrated fluxes based on individually determined masses, so that some restrictive hypotheses (for instance, the assumption of a constant mass distribution index throughout the overall mass range) are needed in order to estimate the meteoroid influx onto Earth (Foschini, 1997). Other complications are due to the influence of the ionosphere on radio waves, which causes attenuation, refraction and a rotation of the plane of polarisation (Faraday rotation). These effects are inversely proportional to frequency squared and occur mainly at High Frequencies (HF).

Two distinct regimes exist in the detection of meteor trails by radar, these being the so-called *underdense* and *overdense* conditions. If the linear density of ionisation q is sufficiently low ($q \leq 10^{14}$ el/m), the trail is said to be *underdense* and in this case the scattering is by individual electrons active independently. For $q > 10^{14}$ el/m the trail is said to be *overdense* with the incident wave totally reflected (the electron density is so high that the radio wave cannot penetrate the trail rather like a metallic sheet).

At present, there is an interest in over-the-horizon communications by the Forward Scatter (FS) arrangement which offers in addition a great opportunity to astronomers and space physicists in learning more about the distribution and sizes of meteoroids in the near Earth space environment (Cevolani *et al.*, 1995a). In the case of an FS arrangement, the peak received signal power due to an underdense trail at $t = 0$ is

$$P_R = \frac{P_T G_T G_R \lambda^3 \sigma_e}{64\ \pi^3} \cdot \frac{q^2 \sin^2 \gamma}{R_1 R_2 (R_1 + R_2)(1 - \sin^2 \phi \cos^2 \beta)} \tag{3.1}$$

and the maximum received power for an overdense trail case at $t = 0$ is

$$P_R = \frac{P_T G_T G_R \lambda^3}{32\ \pi^3} \cdot \frac{(r_e / e)^{1/2}\, q^{1/2} \sin^2 \gamma}{R_1 R_2 (R_1 + R_2)(1 - \sin^2 \phi \cos^2 \beta)} \tag{3.1a}$$

where P_T is the transmitter power; G_T and G_R, the transmitter and receiver antenna gain; R_1 and R_2, the distance (m) from the transmitter and receiver to the trail; λ, the wavelength (m); q, the electron line density (electrons/m); σ_E, the classic cross section of an electron; γ, the angle between the incident and received electric field vectors; ϕ, the propagation angle formed by vectors R_1 and R_2; β, the angle of the trail relative to the plane formed by R_1 and R_2. The eq. (3.1) reduces to the back-scatter case, when $R_1 = R_2$, $\phi = 0°$, $\beta = 90°$ and $\gamma = 90°$.

An example of FS facility is the bistatic meteor radar at Budrio (ϕ_B = 44.6°N; λ_B = = 11.3°E), near Bologna, and Lecce (ϕ_L = 40.3°N; λ_L = 18.2°E) in Southern Italy, which utilises a continuous wave transmitting frequency at 42.7 MHz and about 1 kW peak power. The transmitting and receiving antennas at the two separated places are vertically polarised with an elevation angle of 15° along the Bologna-Lecce direction (53° southeast). For further details, see Cevolani *et al.* (1995a).

Figure 2a shows the geometry of Forward Scatter (FS) and fig. 2b shows the map of the FS radar system with the transmitting station at Bologna (I), and the receiving stations at Lecce (I) and Modra (Slovakia), that is operating from 1996.

A simple calculation of the peak received power from a typical FS meteor echo suggests that most meteors with $q \geq 5 \times 10^{12}$ el/m will be detected by the system (Cevolani and Gabucci, 1996). Values of $q \cong 10^{12}$ el/m correspond to 150-200 μm diameter and to 10^{-5} g particles, whereas values of $q \cong 10^{13}$ el/m correspond to 400-500 μm and 10^{-4} g particles. Table II gives some characteristics of meteoroids as a function of their mass m.

Figure 3 gives a description of interconnection among fundamental parameters of meteor-

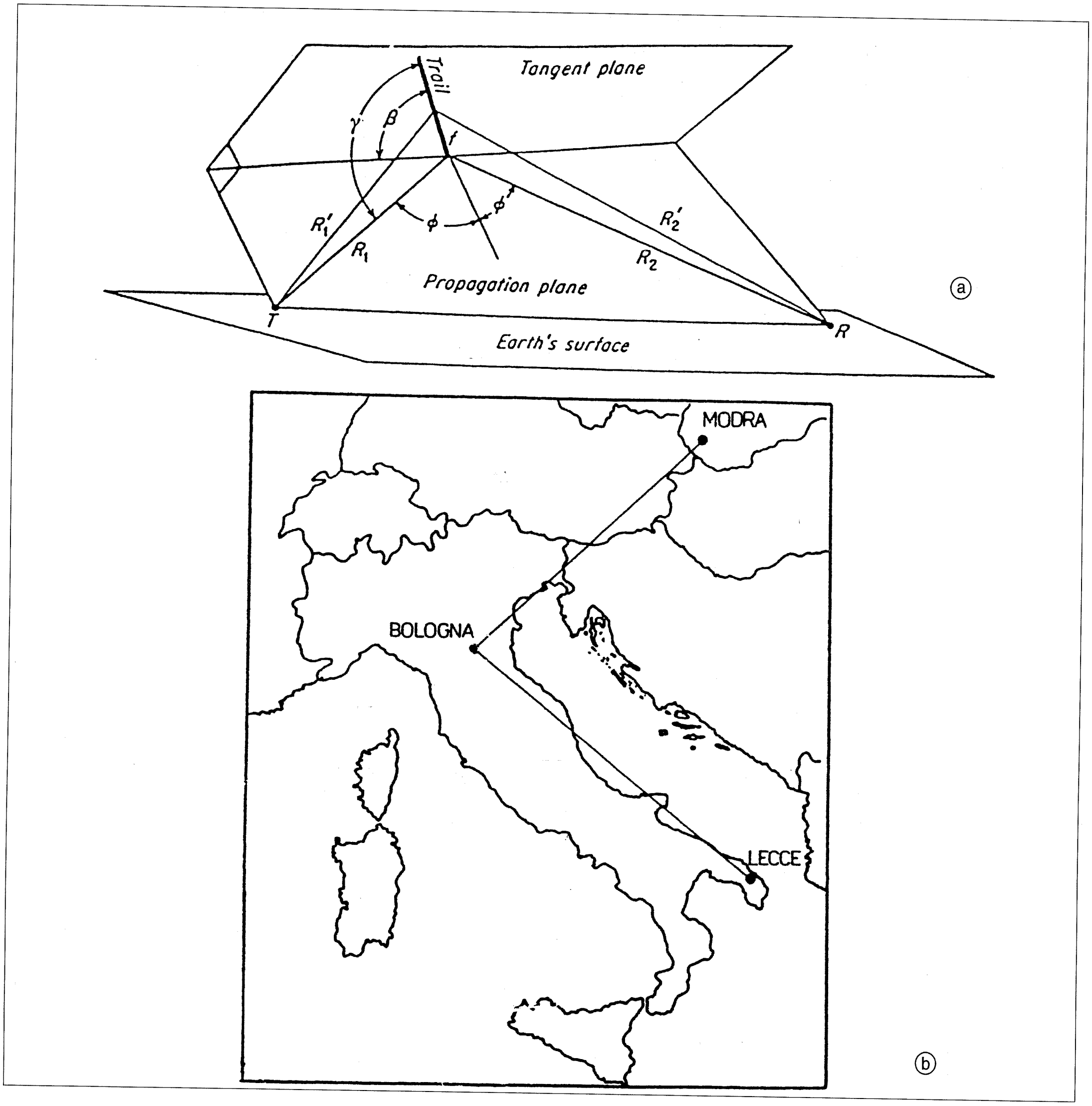

Fig. 2 a,b. a) The geometry of Forward Scatter (FS); b) the map of locations of the FS radar with the transmitting station at Bologna (I), and the receiving stations at Lecce (I) and Modra (Slovakia).

oids (the echo duration T, the electron line density q and the radar magnitude M_r) for different meteor showers and sporadic background, observed at the Bologna-Lecce radar. q is a function of the geocentric velocity V of meteoroids, the echo duration T and the radar wavelength λ. M_r depends on q through the equation, $M_r = 40 - 2.5 \log q$ (Cevolani and Gabucci, 1996). It is seen that only showers with higher geocentric velocity (Leonids, Orionids and Perseids) are

Table II. Some characteristics of meteoroids as a function of their mass m. d = diameter; N = number of meteoroids entering into atmosphere each year; E_k = kinetic energy; q = electron line density of the ionised meteor trail; M_v = visual magnitude. (E_k and q are calculated for an intermediate velocity 40 km/s between 11 and 72 km/s).

Meteoroids	m (kg)	d (m)	N (year^{-1})	E_k (joule)	q (el/m)	M_v
	10^7	~20	10^{-1}	~10^{16}	?	?
	10^6	~10	5-10	~10^{15}	?	?
	10^5	~4	8×10	~10^{14}	?	?
Bolides	10^4	~2	6×10^2	~10^{13}	?	(−20)
	10^3	8×10^{-1}	3×10^3	~10^{12}	?	(−15)
and	10^2	4×10^{-1}	1×10^4	~10^{11}	~10^{21}	(−12.5)
	10^1	2×10^{-1}	3×10^4	~10^{10}	~10^{20}	(−10)
Fireballs	1	1×10^{-1}	2×10^5	~10^9	2×10^{19}	(−7.5)
	10^{-1}	4×10^{-2}	5×10^5	~10^8	3×10^{18}	−5
Photographic	10^{-2}	2×10^{-2}	2×10^6	~10^7	4×10^{17}	−2.5
meteors	10^{-3}	8×10^{-3}	1×10^7	~10^6	4×10^{16}	0
	10^{-4}	4×10^{-3}	3×10^8	~10^5	5×10^{15}	2
	10^{-5}	2×10^{-3}	1×10^9	~10^4	6×10^{14}	4
Radar meteors	10^{-6}	1×10^{-3}	6×10^9	~10^3	6×10^{13}	6
	10^{-7}	5×10^{-4}	1×10^{11}	~10^2	8×10^{12}	8
	10^{-8}	2×10^{-4}	2×10^{13}	~10	1×10^{12}	10.5
	10^{-9}	1×10^{-4}	8×10^{14}	~1	1×10^{11}	12.5

able to create highly-ionised channels (q = = 10^{17}-10^{18} el/m and over) (Cevolani *et al.*, 1998).

Radio results of Leonids revealed an enhanced activity in recent last years with an increase in overdense and faint meteor trails (Levin *et al.*, 1996; Cevolani and Foschini, 1996; Trivellone *et al.*, 1997). In 1996, overall activity was significantly above normal with a large increase in long-duration echoes and a possible sporadic-*E* (*Es*) events associated with the Leonid peak. Leonid meteors are known to be able to produce a great deal of ionisation

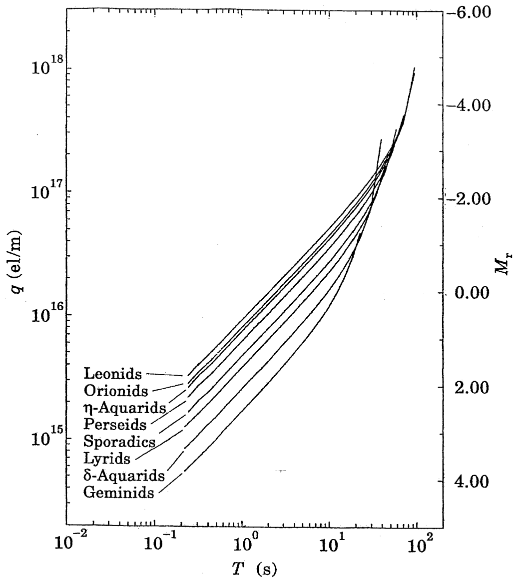

Fig. 3. A description of interconnection among fundamental parameters of meteoroids (the echo duration T, the electron line density q and the radar magnitude M_r) for different meteor showers and the sporadic background, observed at the Bologna-Lecce radar.

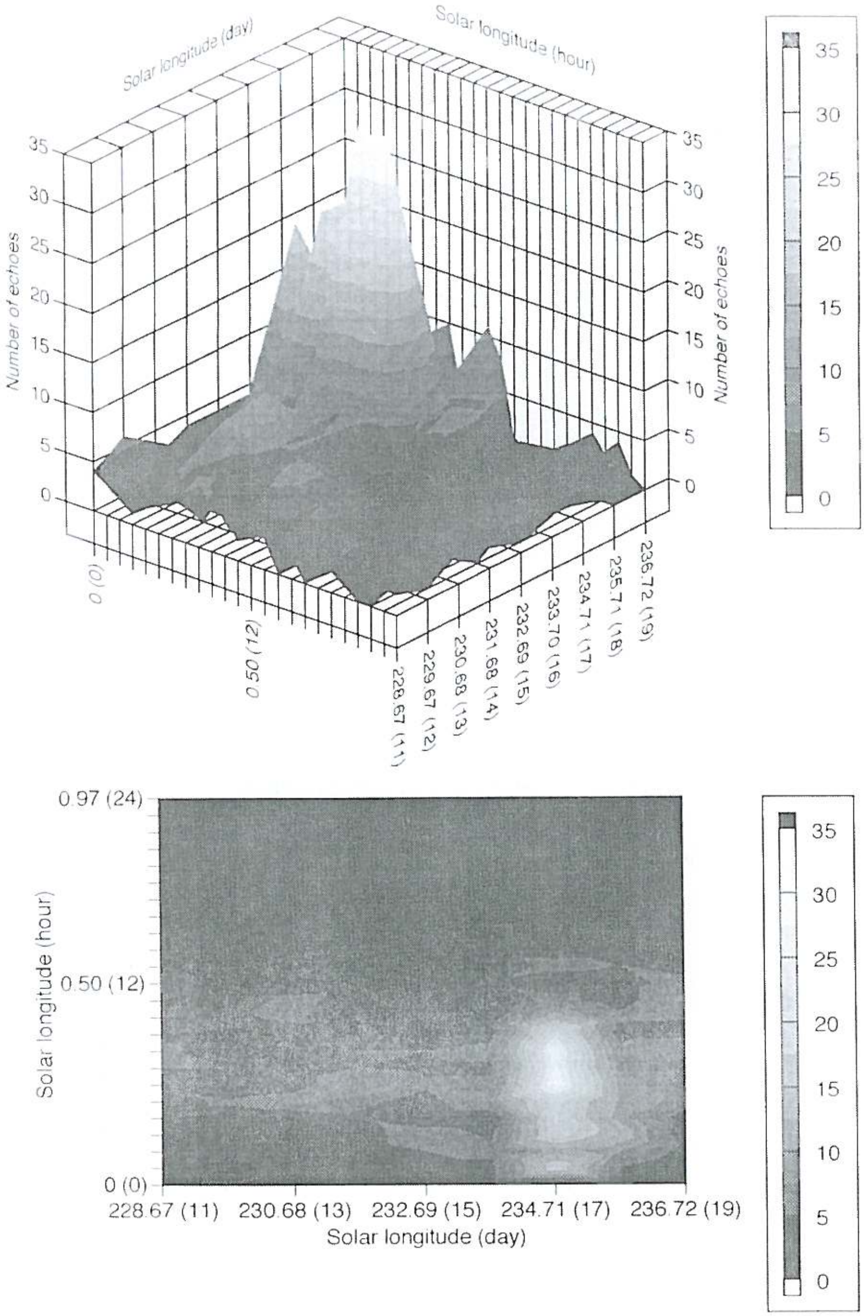

Fig. 4a. Time variations of the hourly number of radioechoes (upper part) and the relative section (lower part) of the Leonids recorded in the period 11-19 November 1997 at the Bologna-Lecce FS radar in Italy, relative to the durations of $T > 16$ s (long enduring meteors).

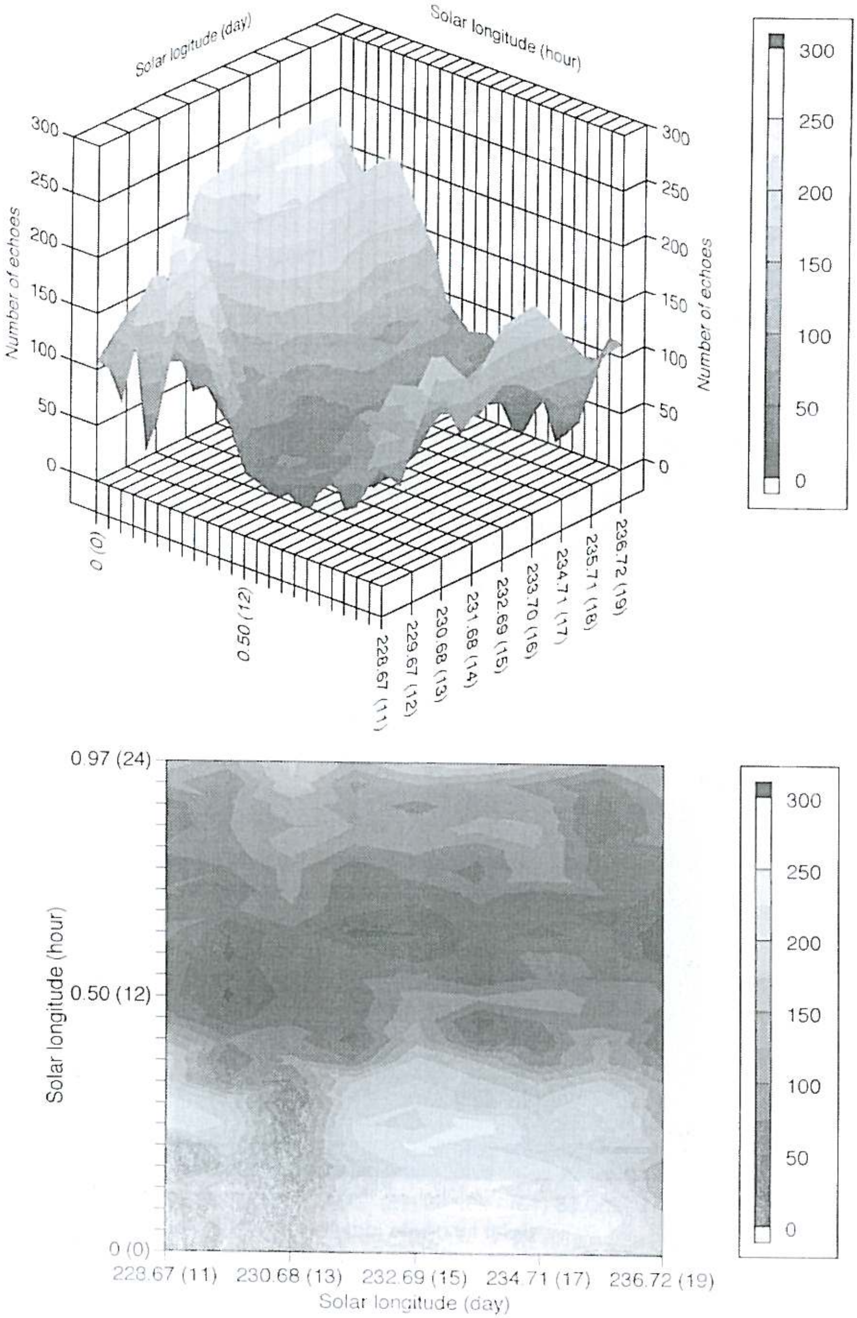

Fig. 4b. Time variations of the hourly number of radioechoes (upper part) and the relative section (lower part) of the Leonids recorded in the period 11-19 November 1997 at the Bologna-Lecce FS radar in Italy, relative to the durations of T < 0.25 s (faint meteors).

into the Earth atmosphere because of their high atmospheric velocity, and with the longest-lasting trains thus far reported being of 12 min duration. The meteoric ionisation probably forms most of the typical *Es* sheets, although these usually occur from April to September in the Northern Hemisphere. However in coincidence with unusual meteor shower maxima *Es* sheets have been recorded simultaneously, as in the case of the 1991 Perseids when an impressive *Es* event immediately followed the meteor shower's outburst (McBeath, 1996).

Figures 4a,b exhibit time distributions of the hourly number of radioechoes (upper part) and the relative sections (lower part) of the Leonids recorded in the period 11-19 November 1997 at the Bologna-Lecce FS radar in Italy, relative to the durations of (a) $T > 16$ s (long enduring meteors) and (b) $T < 0.25$ s (faint meteors).

The analysis of hourly raw counts of the Leonids reveals a lower activity with respect to the 1996 Leonids as far as the flux of long-duration echoes is concerned, whereas the number of the overall overdense meteors with duration $T > 1$ s is significantly increased. From November 15, even the number of the fainter meteors with $T < 0.25$ s corresponding to tiny particles is increased similarly to 1996 when many evanescent meteors (up to 50-60% of the overall echoes) were recorded during the time of maximum activity. The increase in the number of fainter meteors is consistent with the interpretation that these evanescent meteors are composed of very young material possibly associated with the more active material of the stream.

4. Meteoroids-spacecraft interactions

High velocities of meteoroids can lead to very high efficiency of charge generation. In the assessment of the impact effects, besides the penetration damage, the charge production and the plasma current must be taken into account. During a collision encounter, meteoroids and spacecraft behave as fluids rather than solids, since the impact generated pressure will greatly exceed the material strength of the meteoroid and the target (Kysar, 1990). The maximum penetration $F_{\max}$, the charge production Q and the plasma current are given by (McDonnell *et al.*, 1997)

$$\begin{aligned} F_{\max} &\propto m^{0.352} V^{0.806}, & \gamma &= 2.29 \\ Q &\propto m^{1.02} V^{3.48}, & \gamma &= 3.41 \qquad (4.1) \\ I &\propto m^{1.02} V^{4.48}, & \gamma &= 4.39. \end{aligned}$$

Where m and V are the mass and the geocentric velocity of the meteoroid, and γ is the ratio of the exponential of the velocity and the mass.

Figure 5a shows a comparison of the impact effects when considering penetration F, charge production Q and plasma current I; and fig. 5b shows the instantaneous flux throughout the year for meteoroids with respect to the $F_{\max}$ size regime, the plasma charge production and the plasma current (after McDonnell *et al.*, 1997). Note the importance of the Leonid stream even without any storm enhancement.

Furthermore, high velocities of meteoroids produce larger impact crater scales. From the study of impact craters displayed by spacecraft retrieved from Earth orbit, Laurance and Brownlee (1986) found that the diameter D (cm) and the depth T of an impact crater vary with the impact velocity V (km/s) and mass m (g), as

$$D = 1.081\, m^{0.4} V^{0.88}, \quad \mathrm{T} \approx 0.62\, D. \qquad (4.2)$$

(a meteoroid density of 1 g/cm^3 and an aluminium target have been assumed).

In general, artificial satellites and even space platforms are not at risk from collisions of sporadic meteoroids and meteor showers, because of the low impact probability. Geminids, for instance, which represent the meteor shower having the higher mean echo hourly rate (Cevolani *et al.*, 1995b), have an impact probability of about $7 \cdot 10^{-3}$ % for meteoroid masses greater than 10^{-8} kg and 1-h exposure (assuming an exposed area of 1000 m^2 as for the International Space Station) (Foschini and Cevolani, 1997). The impact probability for an annual av-

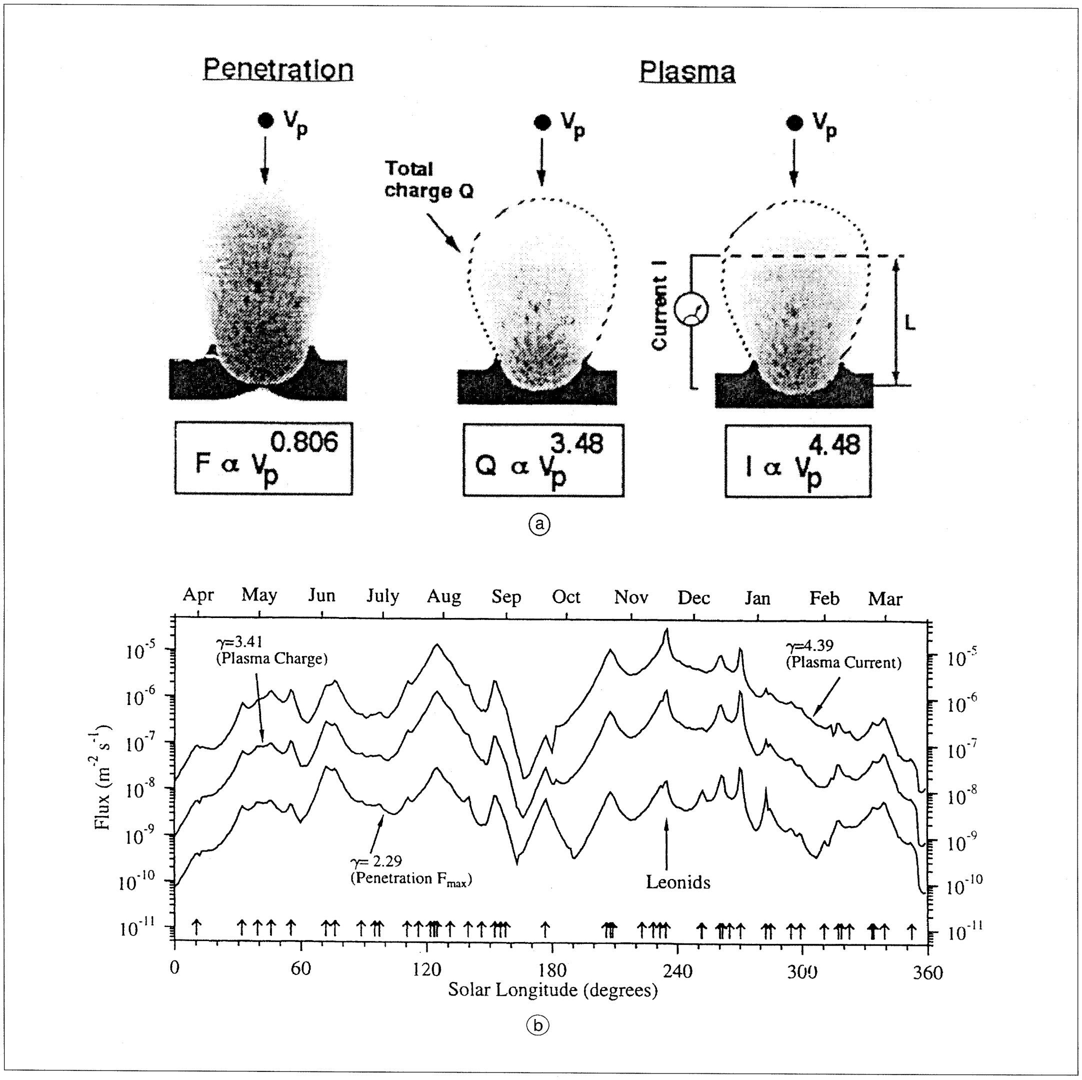

Fig. 5a,b. a) A comparison of the impact effects when considering penetration *F*, charge production *Q* and plasma current *I*; b) the instantaneous flux throughout the year for meteoroids with respect to the $F_{\max}$ size regime, the plasma charge production and the plasma current (after McDonnell *et al.*, 1997).

erage activity only decreases to $4 \cdot 10^{-3}\%$. Nevertheless, some showers have been shown to increase their activity periodically, possibly reaching the highest values and generating meteor storm. To compare the damage that a meteor storm may inflict on satellites, it is necessary to consider the equivalent impact from a sample having the same kinetic energy. The sample is a 1-cm aluminium sphere travelling at 10 km/s, that is the typical space debris and is called Critical Space Debris Sphere (CSDS). A CSDS has a mass of 1.4 g and can release in the impact 7.1×10^4 joule of kinetic energy. The equivalent mass m_{eq} of a meteoroid of the same kinetic energy can be written as $m_{eq} = C/V^2$, where $C \cong 1.42 \times 10^5$ [kg m^2 s^{-2}] (Foschini and Cevolani, 1997).

In the case of enhanced meteor activity, the impact probability of meteoroids with artificial satellites (expressed as a percentage), is given by (Beech and Brown, 1994):

$$I = F\, n\, V A\, t\, 10^{-13} \;[\%] \qquad (4.3)$$

where n is the number density of stream meteoroids with mass usually greater than 10^{-8} kg (in the case of radio meteors) contained in a volume of 10^9 km^3; A the exposed satellite area in m^2; and t the exposure time in seconds. The factor F is the storm enhancement factor that indicates the increase in the spatial number density of meteoroids during storm conditions. The values of F for Leonids vary from about 300 to 10 000 (Beech and Brown, 1994), whereas for Lyrids a value of $F = 10$ is considered. For visual and radio observations n is the number density of stream meteoroids capable of producing a meteor of absolute visual magnitude greater than + 6.5 and + 10.5 per 10^9 km^3 respectively, values corresponding to the minimum observable meteoroid mass. An important aspect is that the meteoroid mass distribution has to be known in order to deduce the impact probability of a critical stream meteoroid mass m_{eq}. The mass index s is defined so that the number of meteoroids dN in the mass range m

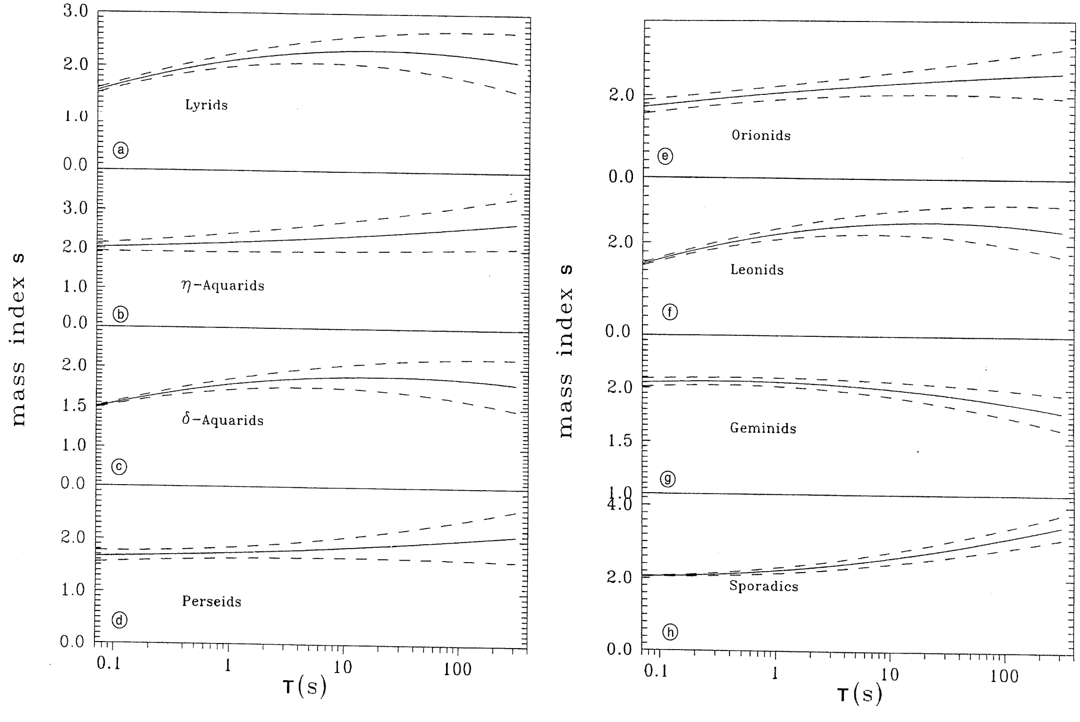

Fig. 6a-h. Variation of the mass distribution exponent s *versus* echo duration T including errors (dashed curves) for some meteor showers and sporadic background. The meteor showers and dates of the peak observations at the Bologna-Lecce radar, are: a) Lyrids (21-22/4/1995); b) η-Aquarids (1-7/5/1995); c) δ-Aquarids (28-29/7/1994); d) Perseids (9-14/8/1994); e) Orionids (20-26/10/1994); f) Leonids (16-22/11/1994; g) Geminids (12-13/12/1994); and h) the sporadic background (Cevolani and Gabucci, 1996).

and $m + dm$ is given by the relation $dN = k\, m^{-s}\, dm$, where k is a constant. In radio results, the index s is derived from the cumulative distributions of echoes *versus* the observed echo duration T (Cevolani and Gabucci, 1996).

Figure 6a-h gives the mass distribution exponent s *versus* echo duration T including errors (dashed curves) for some meteor showers and sporadic background (Cevolani *et al.*, 1998). The meteor showers and dates of the peak observations at the Bologna-Lecce radar, are: a) Lyrids (21-22/4/1995); b) η-Aquarids (1-7/5/1995); c) δ-Aquarids (28-29/7/1994); d) Perseids (9-14/8/1994); e) Orionids (20-26/10/1994); f) Leonids (16-22/11/1994); g) Geminids (12-13/12/1994); and h) sporadic background.

Even if the examined meteor showers have different mass index-duration dependence, s values ranging from 1.5 to 2.5 are normally obtained so that an average value of $s = 1.8$ was assumed to calculate the number density n of each meteoroid stream.

The impact energy of the CSDS can be utilised to determine the critical stream meteoroid mass that represents the threshold for any stream meteoroid. Beyond this value the meteoroid will have a sufficient energy to exceed the shielding limit set for a satellite.

Table III gives values of equivalent mass m_{eq} of a CSDS for different meteoroid streams together with the relative geocentric velocities (Foschini and Cevolani, 1997). The table shows that for the Perseid and Leonid streams which have very high encounter velocities, the critical masses are roughly 30-40 mg. Lower dimensions of CSDS are also suggested to create possible damage to space platforms (Levin *et al.*, 1996).

Table III. Values of equivalent mass m_{eq} of a CSDS for different meteoroid streams together with the relative geocentric velocities (Foschini and Cevolani, 1997).

Shower	V (km/s)	m_{eq} of CSDS* (kg)
Lyrids	48.4	$6.0 \cdot 10^{-5}$
Perseids	60.4	$3.9 \cdot 10^{-5}$
Leonids	71.0	$2.8 \cdot 10^{-5}$
Geminids	36.5	$1.0 \cdot 10^{-4}$
Sporadic	42.0	$8.0 \cdot 10^{-5}$

* Critical Space Debris Sphere (a 1 · cm aluminium sphere travelling at 10 km/s) expressed in meteoroid mass.

Figure 7a,b shows impact probabilities *versus* the exposed satellite area (in m^2) for meteoroids of different streams (Leonids, Perseids, Geminids and Lyrids) and sporadic background, with masses greater than (a) 10^{-8} kg, and (b) m_{eq} of CSDS (Foschini and Cevolani, 1997). In all cases the considered exposure time is 1 h.

It clearly appears that Leonids are the most hazardous meteor stream for space platforms. Furthermore, in the case of a storm occurring between 1998 and 2000 (as in 1966 when a meteor storm with a factor $F = 10\,000$ was recorded), there is a 41% impact probability that a meteoroid of mass higher than 10^{-8} kg will collide with the International Space Station (1000 m^2 exposed area). In the worst case ($F = 10\,000$) the impact probabilities of storm meteoroids on space platforms in low Earth orbit are found to increase by factors in excess of 10^4 over the sporadic background.

In mitigation scenarios, one of the most efficient solution to protect a space platform from collision damage is to place a thin «bumper» shield around the main structural bulkheads. This shield should be able to fragment a meteoroid before the direct impact on a critical component of the spacecraft. Thin spaced shields and specialised materials with considerable mass savings, are only some of the currently adopted variants of the original bumper shields (Christiansen *et al.*, 1993; Lambert, 1993). Furthermore, a series of Risk Cutailment Scenarios (RCS) appear to be advisable, such as to minimise the surface area that a space platform exposes to the stream radiant (see the case of the HST Mission during the 1993 and 1994 outbursts of Perseids). Since the outburst or storm is a short duration event, it may be possible to set the space platform on the side of the Earth opposite to the stream radiant in order to reduce the meteoroid damage risk.

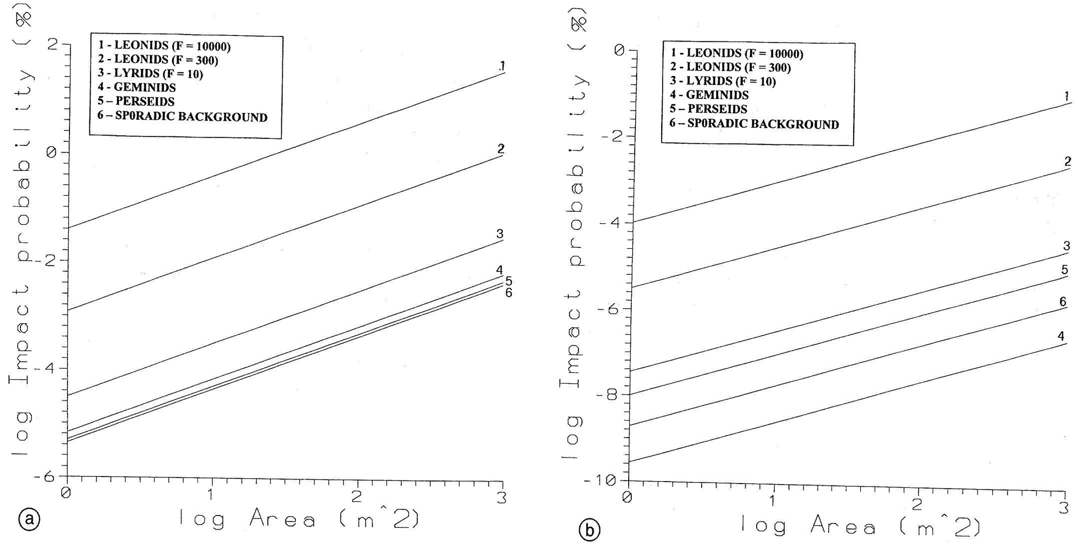

Fig. 7a,b. Impact probabilities *versus* the exposed satel-lite area (in m^2) with a 1-h exposure for meteoroids of different streams (Leonids, Perseids, Geminids and Lyrids) and sporadic background, with masses greater than: a) 10^{-8} kg; b) m_{eq} of CSDS (Critical Space Debris Sphere) (Foschini and Cevolani, 1997). In all cases the considered exposure time is 1 h. The data were recorded at the Bologna-Lecce FS radar system.

5. Conclusions

The problem of enhanced (outburst or storm) activity of meteoroid streams is analysed in relation to the effects of the meteoroid populations on spacecraft. According to Jenniskens (1995), meteor outbursts or storms occur at a rate of more than 1 event a year and only 35 of these events from 17 streams have been enough documented over the past two centuries to give useful information. Even if the meteor storm is one of the most poorly understood phenomena in our solar system both observationally and theoretically, this phenomenon is now thought to be as the most hazardous to Earth-orbiting satellites. In the past, the role of high velocity meteoroids has been ignored or underestimated, but the effects of fast meteoroids have to be carefully evaluated mainly for oriented or collimated detectors of spacecraft, and in general, for instruments having a high velocity dependence such as those utilized for plasma dust experiments. Some meteoroid streams dominated by submillimeter particles are thought to be able to erode satellite surfaces so weakening external structures or to cause electromagnetic shocks because of their extremely high flux occurring during storm conditions. By considering that particles associated with meteor storms are highly directional, the penetrating flux of meteoroids, the charge production and the plasma current are important factors to be taken into account when analysing this hazard (McDonnell *et al.*, 1997). In addition, during a meteor storm it is necessary to determine the optimum attitude to orient space platforms and their fragile elements (*e.g.*, solar arrays) in order to minimise damages (Levin *et al.*, 1997). Foschini and Cevolani (1997) have recently shown that the impact probability deduced by radar measurements generally increases by a factor 2 with respect to the findings of Beech and Brown (1994) obtained by visual observations of the same meteoroid streams. If meteoroids larger than CSDS (Critical Space Debris Sphere) are considered, the impact probabilities become 2-3 order higher when compared with the results of the same authors. A salient aspect is that radar data (Foschini and Cevolani, 1997) give impact probability values generally higher than those deduced from visual data (Beech and Brown, 1993, 1994; Beech *et al.*, 1995).

Modern radar techniques make it possible to detect meteors with initial mass usually higher than 10^{-8} kg and in addition, to determine the flux of meteoroids in a wider mass range (10^{-8}-10^{2} kg) (Foschini, 1997). A radar facility such as the Tracking and Imaging Radar (TIRA) of FGAN in Germany, is potentially able to track 2 cm sized space debris in LEO and 30-40 cm in GEO, and meteoroids with an initial mass of 10^{-9}-10^{-10} kg (Mehrholz, personal communication). Radar techniques will be thus able to provide more precise fluxes of Leonids in the coming years when storm meteoroids could potentially inflict serious damages to spacecraft (Beech *et al.*, 1995).

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