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Impact probabilities of meteoroid streams with artificial satellites: An assessment

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Summary. — Impact probabilities of artificial satellites with meteoroid streams were calculated using data collected with the CNR forward scatter (FS) bistatic radar over the Bologna-Lecce baseline (about 700 km). Results show that impact probabilities are 2 times higher than other previously calculated values. Nevertheless, although catastrophic impacts are still rare even in the case of meteor storm conditions, it is expected that high meteoroid fluxes can erode satellites surfaces and weaken their external structures.

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1. – The environment around the Earth

Since the beginning of the space era (Sputnik-1 launch date, October 4, 1957), thousands of artificial satellites have been placed in the Earth orbit by several nations. Only about 6% of these satellites are now active and the remaining are upper stages of rocket motors and debris associated with the launch or break-up of payloads or rockets. Debris are generated by typical explosion events induced by residual fuel. The severe damages of the Solwind satellite and the fragmentation of the Kosmos-1275 lead to believe that space debris may be responsible of catastrophic impacts [1]. Quite recently (July 24, 1996), a space debris collided with CERISE microsatellite, but this time without causing serious damages [2].

Satellite fragmentation increases the probability of collision between satellites, generating an exponential mechanism that creates a debris belt around the Earth [3, 4]. The area and mass distribution depend on the intensity of the explosion, whereas atmospheric drag and luni-solar perturbations cause changes in the velocity of debris, affecting in this way the lifetime and the orbital evolution of the debris population [5].

Ground-based radars, optical and infrared sensors of the US Space Command tracked so far more than 21000 space objects, of which more than 7000 are still in orbit [1]. The minimum size of trackable object is about 0.1 m for a low Earth orbit and about 1 m for the geostationary orbit. Other useful data came from the post-flight analysis of some artificial satellites retrieved from space, such as LDEF [6] and

EURECA [7]. The optical survey of impact features on EURECA satellite led to consider meteoroids as the main source of impactors, even if these data must be handled with caution because for more than 50% of analyzed craters, the impactor type remained unknown.

In general, natural meteoroids do not represent a danger for artificial satellites and even for space platform, because of the low impact probability. If, for example, we draw attention to the Geminid meteor shower that has very high mean echo hourly rates during the maximum activity, we obtain an impact probability of about $7\cdot 10^{-3}$% for the *International Space Station Alpha* (when assuming an exposed area of 1000 m^2). If, on the other hand, we consider the annual mean activity, the impact probabilities decrease to $4\cdot 10^{-3}$%. Nevertheless, some showers increase periodically their activity and there are periods where shower activity can reach the highest values and generate a meteor storm. A meteor storm can be generated by any active comet, because it produces a compact dust trail of limited lifetime, stretching predominantly behind it as a result of solar radiation pressure [8, 9]. In the case of a meteor storm, the meteoroid flux increases very much and consequently the risk of satellite impacts with meteoroids can become dramatically high [10]. Furthermore, although some meteoroid showers are dominated by submillimeter particles, and then individual impacts cannot damage the spacecraft, the extremely high flux occurring during storm conditions and possibly associated with high geocentric velocity (up to 71 km/s), can erode satellite surfaces, or cause electromagnetic shock effects (as in the case of the ESA's Giotto spacecraft and the Olympus geostationary telecommunication satellite).

Leonids are the the meteoroid stream able to produce the most exceptional observed storms. The highest meteor rate recorded as yet was 40 meteors per second and was due to the 1966 Leonids [8, 9]. This shower is linked with the comet P/Tempel-Tuttle parent body: the retrograde motion of this comet with its high geocentric velocity was responsible for the strongest meteor displays, even though the spatial particle density was not particularly high. The comet period is 33 years and past observations suggest that a storm can occur a year or two after the comet crossed the perihelion, when activity rises by about 300–10 000 times [10]. Even if the next perihelion crossing of P/Tempel-Tuttle is expexted to occur on February 28, 1998, radar observations during the last years already showed an increasing activity [11, 12]. A ZHR (Zenithal Hourly Rate) of about 100 000 is hypothesized for November 17.60, 1999, by Kresak [9], whereas a lower hourly rate is suggested on the same date by Wu and Williams [13]. During the last meteor storm in 1966, there were only about one thousand artificial satellites in orbit around the Earth, but now the space is very crowded and, consequently, severe damages to artificial satellites should be expected.

2. – Analysis of the risk

Space platform impact channels are substantially four and include the space debris, the meteoroid sporadic background, the annual meteor showers and the meteor storms. We intend to explore here the impact probability associated to meteoroid streams, both in the case of annual shower and of storm conditions. During the last years, several studies were carried out on main meteor showers by using the CNR bistatic FS Bologna-Lecce radar that spans a 6000 km^2 area (see, *e.g.* [11, 12, 14-16]). From 1993, improved instruments made it possible to detect meteors with electron line

TABLE I.

Shower	Record days	Mean echo hourly rate
Lyrids	April 20-21, 1994	187
Perseids	August 12-13, 1993	165
Perseids	August 12-13, 1994	299
Leonids	November 17, 1994	229
Leonids	November 17, 1995	255
Geminids	December 13-14, 1994	407

density $q \geqslant 10^{12}$ el/m, corresponding to meteoroids with initial mass of about 10^{-8} kg [15]. In table I the mean echo hourly rates of meteor shower radar data are reported.

In order to calculate the impact probability, we need to know first the flux density Φ ($\mathrm{km}^{-2}\,\mathrm{h}^{-1}$) of meteoroids in a specific mass range; and second the cross-sectioned area of the artificial satellite A and the exposure time t to the meteoroid flux. From the flux density of meteoroids it is possible to obtain the spatial number density [17, 18]

$$n = \frac{\Phi}{3600\,V}\,(\mathrm{km}^{-3})\,, \tag{1}$$

where V is the meteoroid geocentric velocity expressed in km/s. Since during a meteor storm the spatial number density can increase strongly, we can introduce the storm enhacement factor F [10], assuming that

$$n_{\mathrm{storm}} = n_{\mathrm{normal}}\,F\,. \tag{2}$$

Now it is possible to define the *impact rate* on a particular spacecraft as the number dI of impacts with the satellite during the time dt [3]:

$$\frac{\mathrm{d}I}{\mathrm{d}t} = nFVA\,, \tag{3}$$

Otherwise, we can consider the *impact probability* [10]

$$I = n_{\mathrm{c}}FVAt\cdot 10^{-13}, \tag{4}$$

where n_{c} is the spatial number density of meteoroids contained, under normal conditions, in a volume of space equivalent to that of a cube with 1000 km sides; V is the mean velocity of meteoroids (km/s); A is the space platform surface (m^2) and t is the exposure time (s).

Then, to compare the damages that a meteor storm may inflict to an artificial satellite, 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. The equivalent mass m_{eq} of a meteoroid that has the same kinetic energy as this typical space debris is

$$m_{\mathrm{eq}} = \frac{\pi}{6}\left(\frac{V_{\mathrm{s}}}{V}\right)^2 \delta_{\mathrm{s}}\,D^3(\mathrm{kg})\,, \tag{5}$$

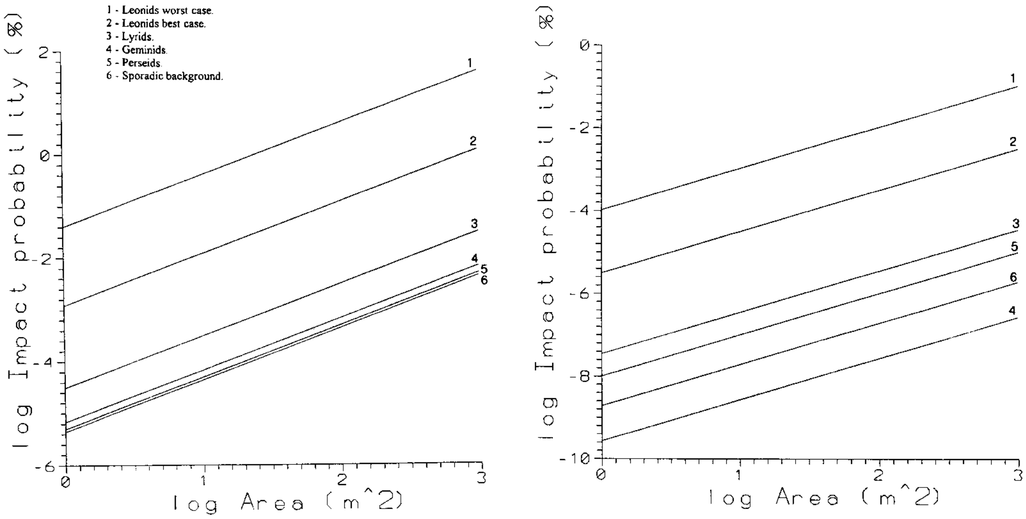
Table II.

Shower	V (km/s)	eq. 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	$1.0 \cdot 10^{-4}$

where D is the sample space debris diameter (m), δ_s is its density (for aluminium $\delta_s = 2710$ kg/m^3) and V_s is its velocity (m/s); V is the meteoroid velocity (m/s). On substituting values for the sample aluminium sphere, eq. (5) can be written as $m_{eq} = k/V^2$, where $k \cong 1.42 \times 10^5$ (kg m^2 s^{-2}).

Actually, the shield design specifications call for impact protection up to this sample aluminium sphere that is called *Critical Space-Debris Sphere* (CSDS): a shield must absorb any impact from space debris up to and including the CSDS. Hence, we can calculate the impact probabilities for equivalent meteoroid larger than the CSDS (table II).

Now, by using the method developed by Foschini [19], we can calculate the flux density for equivalent meteoroids larger than the CSDS and then determine the impact probabilities and impact rates utilizing eqs. (3) and (4). Results are shown in fig. 1.



(A) (B)

Fig. 1. – Impact probabilities for meteoroids with masses greater than 10^{-8} kg (A) and with masses greater than CSDS (B).

3. – Conclusion

In 1994, Beech and Brown [10] calculated the impact probability by using data from visual observations. Now, radar data collected with the CNR Bologna-Lecce meteor radar enabled us to make a more accurate analysis, though with expected improvements. Our results show that the impact probability generally increases by about a factor 2 with respect to Beech and Brown results, but the impact probability of meteoroids larger than CSDS, although showing very low values, is 2-3 orders higher when compared with the findings of the same authors. The results suggest indeed that main damages could derive by the erosion of surfaces, and then by the weakening of the satellite structures, owing to high fluxes of microparticles. Antennas and solar arrays are more exposed to this threat because the shielding could be ineffective at all. In fact, since the risk of satellite impacts with meteoroids increases dramatically under meteor storm conditions, we must pay attention to the fact that spacecraft shielding against objects larger than 10^{-2} m is not technically feasible.

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