Part 6

SATELLITE AND STELLAR SYSTEMS

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

Dynamics of Populations of Planetary Systems
Proceedings IAU Colloquium No. 197, 2005
Z. Knežević and A. Milani, eds.

DOI: 10.1017/S1743921304008956

Population models of space debris

Alessandro Rossi
ISTI/CNR, Via Moruzzi 1, 56127 Pisa, Italy
email: Alessandro.Rossi@isti.cnr.it

Abstract. More than 300 000 artificial debris particles with diameter larger than 1 cm are orbiting the Earth. The space debris population is similar to the asteroid belt, since it is subject to a process of high-velocity mutual collisions that affects the long-term evolution of its size distribution. The near–Earth space can be divided in three major regions where orbital debris is of concern: Low Earth Orbits (LEOs), below about 2000 km, Geosynchronous Orbits (GEOs), at an altitude of about 36000 km and the Medium Earth Orbits (MEOs) in between. The issues are in principle the same in the three regions, nevertheless they require different approaches and solutions. The space debris are composed by several different populations according to their source and their orbital region. A description of the nature and dynamics of the different populations in the low, medium and high orbital regimes is given. The impact risk posed by these debris is then briefly outlined.

The long term evolution of the whole debris population can be studied with computer models allowing the simulation of all the known source and sinks mechanisms. One of these codes is described and the evolution of the debris environment, over the next 100 years, under different traffic scenarios is shown, pointing out the possible measures to mitigate the growth of the orbital debris population.

Keywords. Space vehicles, celestial mechanics, n-body simulations

1. Introduction

When in October 1957 the first artificial satellite, Sputnik 1, was launched by the USSR, nobody could even imagine that after less than 50 years we would be facing an environmental problem in the near-Earth space. A few years later, on June 29, 1961 the first known break–up in orbit, the explosion of the *Transit 4A* rocket body happened. From then on, the repetition of these two events (launches of new satellites and break-up of in orbit spacecraft) contributed to build up a huge population of objects that are now polluting, perhaps in an irreversible way, the space around us. Many years later, on July 24, 1996, the danger posed by the space debris to all the human activities in space has been clearly showed by the first recorded accidental collision between an operational satellite and a piece of debris: the French micro-satellite *Cerise* has been hit, at the relative velocity of 14.77 km/s, by a fragment, of about 10 cm^2, coming from the explosion of an Ariane rocket upper stage, that happened ten years before (Alby *et al.* 1997). Though still very unlikely from a statistical point of view, collisions with space debris represent now a threat for all the space missions, especially the manned ones, and are deemed to become the most important source of debris in a not too distant future.

2. The space debris population

The near–Earth space can be roughly divided in three main regions. The Low Earth Orbit (LEO) region, below about 2 000 km, is where most of the orbiting objects of any size can be found. Due to the high objects density and the large impact velocities (larger than 9 km/s on average (Rossi & Farinella 1992)) it is in this region where the space debris issue is presently most urgent and where it has been historically more studied.

The Medium Earth Orbit (MEO) between 2 000 km and about 36 000 km is emerging as a new issue in the space debris studies, since it is the home of the so-called navigation constellations, i.e., the constellations of satellites, like the Global Positioning System (GPS), used to locate with high accuracy the position of a receiver on the ground. The vital role that this navigation services is acquiring in the air and terrestrial transportation make these constellations and the region of space they occupy correspondingly important.

The geostationary ring can be defined roughly as a toroidal region of space close to the equatorial plane at about 36 000 km of altitude. A satellite placed in the Geosynchronous Orbit (GEO) region will orbit the Earth in about one sidereal day, remaining almost fixed with respect to a given ground station. For this reason most of the telecommunication satellites are launched in the geostationary ring; hence its uniqueness and importance.

In Fig. 1, the spatial density of objects with diameters larger than 1 mm, 1 cm and 10 cm in Earth Orbit is plotted. The peaks of density corresponding to LEO, MEO and GEO are immediately apparent from the figure. In particular it should be noted that there are mainly two regions of the near Earth space where the debris "pollution" is particularly high: one around 900 km and one around 1400 km.

The space debris issues in the three regions are in principle the same, nevertheless the orbital dynamics and the existing population are different and therefore they require different approaches and solutions.

From the mm–sized particles up to the largest satellites, tens of meters across, the population of objects of artificial origin orbiting in near–Earth space spans many orders of magnitude in size and mass. Below about 1 μm in diameter the natural meteoroid population still dominates the particle flux, whereas above this threshold artificial space debris accounts for the majority of the solid bodies present in the near–Earth environment.

This huge ensemble of particles includes many different populations produced by various mechanisms. In the following a brief review of these populations is given.

Since the Sputnik I about 5 000 payloads have been launched. Among these objects, some 3 000 have re–entered in the atmosphere. The others (about 2 000) are still orbiting and represent most of the large (> 1 m) objects in orbit. It should be remembered that every launch often implies that more than one object is injected into Earth orbit since, beyond the payload(s), we have the upper stages of the rocket and the so-called mission related debris (e.g., sensors caps, yo-yo masses used to slow down the spacecraft spin, etc).

All the un-classified spacecraft currently in orbit are cataloged by the United States Space Command in the so called Two–Line Element (TLE) catalog. In this catalog about 10 000 objects are listed along with their current orbital parameters. The limiting size of the objects included in the catalog (due to limitations in sensors power and in observation and data processing procedures) is about 5 to 10 cm in LEO and about 0.5 - 1 m in GEO. The orbits of the TLE catalog objects are maintained thanks to the observations performed by the Space Surveillance Network. The network is composed by 25 sensors, both radars (providing the vast majority of information) and optical sensors. Only about 6% of the objects in the catalog are operative satellites. Approximately 24% is composed by non-operative spacecraft; around 17% by the upper stages of the rockets used to place the satellite in orbit. Then about 13% is composed by mission related debris. Finally some 40% are debris generated mostly by about 170 explosions and 2 collisions which have involved rocket upper stages or spacecraft in orbit (Bendish *et al.* 2004). About 99% of the mass in orbit is due to the large objects included in the catalog. In Fig. 2 (left panel) the cataloged objects are plotted in the semi-major axis versus inclination

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

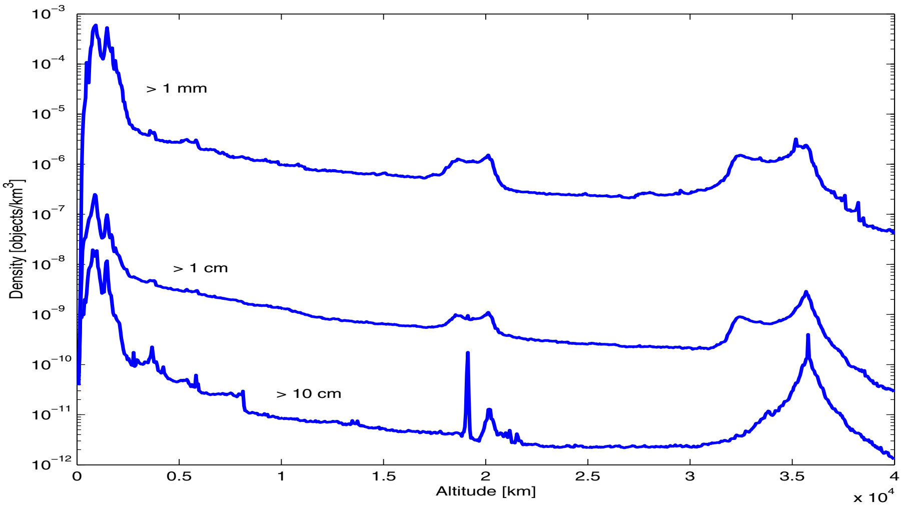

Figure 1. Density of objects as a function of altitude for three different size thresholds: objects with diameter larger than 1 mm, 1 cm and 10 cm.

space. This representation clearly highlights some features in the distribution of objects in space with the spacecraft (and the resulting debris) being clearly grouped in "families" or constellations, according to their different purposes and to the different launching bases: e.g., we can distinguish the US GPS (Global Positioning System) satellites and their Russian analogues GLONASS ($a \simeq 26,000$ km, $i \simeq 55°$ and $i \simeq 63°$, respectively), the Russian communication satellites in Molniya–type orbits ($a \simeq 26,000$ km, $e \simeq 0.7$, $i \simeq 63°$), the geosynchronous satellites ($a \simeq 42,000$ km, $e \simeq 0$, $15° \geqslant i \geqslant 0°$), the satellites in Sun-synchronous orbits ($i \simeq 100°$) , the satellites in polar orbits ($i \simeq 90°$), some families of Russian COSMOS satellites between $i \simeq 60°$ and $i \simeq 80°$, the LEO satellites launched from the Kennedy Space Center (at $i \simeq 27°$) and the families of objects in geosynchronous transfer orbits (GTO) (mostly upper stages) launched from Kourou (ESA Ariane rockets, $i \simeq 7°$), from the Kennedy Space Center ($i \simeq 27°$) and from Baikonour ($i \simeq 48°$).

To get data on the smaller objects not included in the catalog, different sensors, or the same sensors but operated in a different way, are needed. Radar campaigns have been carried out to detect objects of 1 cm and below in LEO by putting the radar in a "beam park" mode, where the radar stares in a fixed direction and the debris randomly passing through the field of view are detected. This allows a counting of the number of objects, i.e., the determination of the objects flux and density, but only a rough determination of their orbits.

These radar campaigns gave an explanation of the prominent peak of density of objects around 900 km of altitude (see Fig. 1). It is mainly due to the presence in this altitude band of a large number of sodium-potassium liquid metal droplets leaked outside a number of Russian ocean surveillance satellites (RORSAT) (Foster *et al.* 2003). This liquid was used as a coolant for the nuclear reactor which generated the power on board and was dispersed in space after the core of the reactor was ejected from the spacecraft in order to prevent possible risks due to its reentry into the Earth atmosphere. About 70 000 drops with diameter between 0.5 mm and about 5.5 cm have been estimated to orbit the observed region.

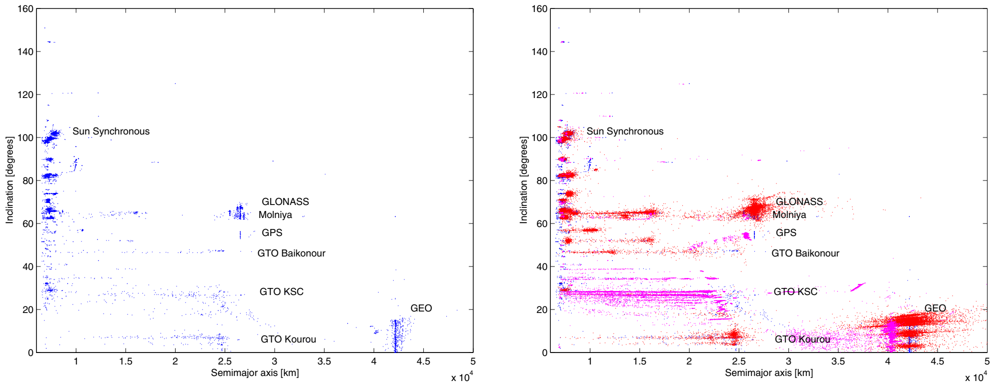

Figure 2. Distribution in the semimajor axis - inclination space of the cataloged objects (left) and of the whole population of objects larger than 1 cm inside MASTER 2001 (right)

The Haystack observations were instrumental also to point out the importance of another unexpected source of space debris, the aluminum oxide particles coming from the burns of the rocket motors with solid propellant. During these burns a large number of sub-millimeter sized particles are ejected. As a matter of fact the solid rocket motor (SRM) exhaust are probably the main contributors to the debris population between $10\,\mu$ and $100\,\mu$. Between $100\,\mu$ and 1 cm the SRM exhaust are again one of the main components of the population, together with fragments and paint flakes that detached from spacecraft surfaces exposed to the space environment effects. In some cases (particularly toward the end of the burn) also slugs of this propellant are released from the SRM, which are of centimetric dimensions (Jackson *et al.* 1997); particularly at low inclinations, where the SRM firings have been more frequent, these slag particles could be responsible for a significant portion of the centimetric debris and even dominate the 1 cm population below about 400 km and above 2 500 km of altitude.

Another previously unknown debris population, around 2900 km of altitude, consisting of the so-called *West Ford Needles* has been detected by radar surveys. Using the powerful Goldstone radar, Goldstein *et al.* (1998) found the remnants of the copper dipoles, 1.77 cm long, which were released in space in 1961 and 1963 by the American satellites Midas 3 and Midas 6, for telecommunication experiments. They were conceived to reenter the atmosphere in about 5 years, but apparently some of them stuck together after the release so lowering their area over mass ratio and therefore augmenting their orbital lifetime. According to the Goldstone observations, a population of about 40 000 such clusters is orbiting between 2400 and 3100 km of altitude.

With circular orbits and an altitude of 20 181 km and 19 100 km respectively, the American GPS and the Russian GLONASS are the two currently deployed navigation constellations. Along with the Russian telecommunication spacecraft in Molnyia orbits, they are the most sensible objects orbiting the MEO region and can be clearly distinguished in Fig. 1 and Fig. 2. According to the MASTER 2001 population model (see later), in the MEO region there are about 60 000 objects larger than 1 cm that are possibly crossing the orbits of the navigation constellations. Actually most of the objects in MEO are clustered about the Molnyia orbits and have therefore a minimal interaction with the navigation constellations. But, even if we exclude the objects close to Molnyia orbits, about 16 000 objects with diameter larger than 1 cm have orbits potentially crossing the navigation constellations. In particular, the GPS orbit appears within reach of several thousand objects, due to the non-zero eccentricity of most of the debris in the

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

MEO zone. The risk of an impact in this region and its possible consequences on the navigation constellations is investigated in Rossi *et al.* (2003).

Notwithstanding its paramount importance, the picture of the debris environment in the GEO region is still very uncertain, mainly due to the physical distance which prevent its mapping by radars. The peculiarities of the GEO region are mainly the absence of any natural decay mechanism, such as air drag (see Sec. 4) and the fact that each satellite in geostationary orbit is assigned an "orbital slot" of about 0.1° of width in longitude. For these reasons, though huge in physical terms, the useful space in the GEO region is actually operationally limited since an orbital slot not freed by a "dead" satellite (or a debris) is not any more usable by other spacecraft. Moreover any debris created in the region will stay there almost for ever. Note that, during their operative lifetime, the satellites are periodically maneuvered to keep them inside the slot, counteracting the perturbations that would tend to change their orbital parameters. In particular perturbations due to the Sun, the Moon and the Earth oblateness would induce a precessional motion of the orbital plane inclination, inducing an oscillation of i of 15°, with a period of about 53 years. Then the solar radiation pressure would induce small periodic variations in e. Therefore, once the satellite is no more operational its inclination and eccentricity will tend to deviate from the nominal zero values. This means that they will start crossing the operational orbits with relative velocities of several hundreds of m/s, much higher than those common for operative coorbiting GEO satellites. Dedicated optical observation campaigns are performed to characterize the environment in this orbital region. The European Space Agency has installed for this purpose a 1 m Schmidt telescope in the Canary Islands. The limiting detection size in GEO for this telescope is about 20 – 30 cm. Since 1999 routine observations have been performed leading to unexpected and worrying results (Flury *et al.* 2000; Schildknecht *et al.* 2004). About 1040 objects have been detected near GEO. Only 340 are active satellites, while the rest are debris, mostly uncataloged objects. The source of this objects remains still uncertain since only two explosions have been recorded in GEO and these two events cannot account for all the observed debris. Probably ten more unrecorded fragmentation events must have happened in GEO (Bendish *et al.* 2004). Of course the number of non-trackable objects, smaller than the telescope detection threshold, should be much larger than 1000. A large uncertainty remains obviously in the geostationary region and international efforts are under way to fill this important gap.

The ground based observations are then supplemented by the data, mainly about mm and sub-mm particles, obtained from the analysis of the surfaces of spacecraft returned to Earth after some time spent in orbit (e.g. the Long Duration Exposure Facility (LDEF), a satellite released and then retrieved by the Space Shuttle, the Hubble Space Telescope solar panels, the Space Shuttle external surface itself, etc) and from impact sensors on board a few satellites.

The observations and in-situ data allow to calibrate the models of the space environment. There are models produced mainly by fitting the observational data to derive values of the flux of debris as a function of the altitude and on a given orbit (Liou *et al.* 2002). Another kind of models reconstruct the environment by reproducing all the known source and sink mechanisms (such as the atmospheric drag) with ad-hoc computer models. One of these last models has been developed by the European Space Agency and is called MASTER 2001 (Bendish *et al.* 2004). Figs. 1 – 2 have been produced by using the MASTER 2001 population of objects.

The right panel of Fig. 2 shows the distribution of the objects larger than 1 cm from the MASTER 2001 population. The families of orbits, described in the left panel of the same figure, are still recognizable. Nonetheless they are now covered by large clouds of smaller objects. Note the spread of the orbital elements (mostly in semi-major axis, since it is very expensive to impart changes in inclination) due to the energy imparted to the fragments in case of breakups. The long stripes of objects at the inclination of the different GTOs are mainly due to the release of the slag by the SRM of the upper stages. Also noticeable, with respect to the situation in the left panel, is the large number of objects in the GEO vicinity due both to slag from upper stage burns and to the large number of uncataloged fragments.

The current estimate, derived from the observations and the simulated populations, is that the total number of non–trackable particles of 1 cm and greater is around 350 000, while those larger than 1 mm could be more than 3×10^8.

3. Risk of collision for orbiting spacecraft

The overcrowding of the space around the Earth makes collisions a serious threat and, as pointed out by the *Cerise* event, a reality. Also the Space Shuttle has already performed several maneuvers to avoid pieces of junk which might have crossed its path.

The average impact velocity for orbiting bodies in LEO, of about 9.7 km/s (Rossi & Farinella 1992), means that even centimeter sized particles are delivering a large kinetic energy on the target. If the mass of the projectile exceeds about 1/1000 of the target's mass, then the target can be completely shuttered producing a cloud of fragmentation debris (see Sec. 4); this corresponds to a threshold for the impact specific energy (i.e the ratio between the projectile kinetic energy and the target mass) of the order of some 10^4 J/kg. Below this value a localized crater–like damage occurs.

To highlight the collision risk, another interesting way of representing the space debris population is shown in Fig. 3, following Valsecchi *et al.* (1999). In this representation, the space debris population is plotted as a function of the square of the impact velocity, U^2 (in units of the target orbital velocity, i.e., about 7 km/s in LEO), of every object with respect to a selected target in a given circular orbit. In the left panel of Fig. 3 the population of the cataloged objects of Fig. 2, is plotted with respect to a target in an equatorial ($i = 0°$) circular orbit with semi-major axis $a_{ref} = 6\,828$ km. The different families of objects are still recognizable, but now the additional information about the impact velocity against the selected target is available. Moreover, all the objects found on the left of the line tagged "Tangency condition" are not crossing the target orbit, and therefore are not potential projectiles. Note also how, in the same 2-dimensional plot, the information about the eccentricity and the inclination of the projectile orbit, with respect to the target one, is included. In the right panel the same population is plotted with respect to a target in a circular orbit with the same a but with $i = 52°$ (i.e., an orbit similar to the one of the International Space Station (ISS)). Note how the the projectile population spreads and mixes and especially how the impact velocities can become significantly larger since the relative inclination between the target and the projectile orbit has to be taken into account. Therefore also almost head-on collision at very high velocity can take place. This target centered risk analysis, based on Öpik's studies of impacts in the Solar System (Öpik 1976), has been applied to the case of multi-plane satellite constellations in LEO (Rossi *et al.* 1999) and MEO (Rossi *et al.* 2003) and to the ISS (Valsecchi & Rossi 2002), showing the dependence of the collision risk to the complex dynamics of these systems. The results of these studies cannot be reported here and the interested reader can refer to the cited papers.

To protect the space assets against impacts with small debris ($\leqslant$ 1 cm) multi-wall bumper shields have been devised and installed on some modules of the ISS. Yet for larger debris the shields are not enough to prevent the penetration of the target or

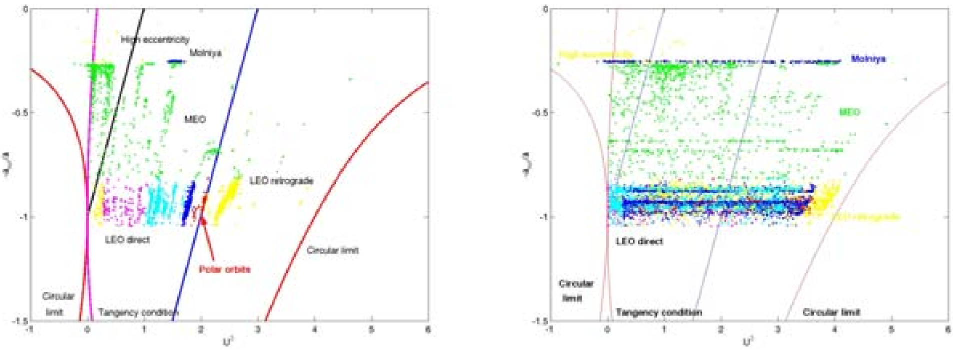

Figure 3. Representation of the TLE catalog population in the space U^2 vs $E = -a_{target}/a_{projectile}$, with respect to a target in a circular orbit at 450 km of altitude. In the left panel the target orbit has equatorial inclination $i = 0°$, while in the right panel the target has $i = 52°$. For a thorough explanation of the lines drawn in the plot, refer to Valsecchi *et al.* (1999). Note that the admissible region is included between the two circular limits and that the objects possibly crossing the orbit of the target lie to the right of the tangency condition. The objects to the right of the inclined line starting from the target position have higher probability of hitting the target on the front; on the left of this line impacts from the back predominate (the more so as we approach the tangency condition). Finally, the straight line from $(1.5, -1.5)$ to $(3, 0)$ is the locus of orbits with inclination equal to 90° with respect to the selected reference plane.

even its complete fragmentation; in this case an avoidance maneuver, if the projectile is trackable from the ground, is the only solution to save the Station module. Note moreover that, as specified in the previous section, most of the debris between 1 and 10 cm are not cataloged. In addition, most of the operational satellites cannot carry the heavy bumper shields so they can rely only on avoidance maneuvers or on their "good luck" to survive the harsh debris environment.

4. Long–term evolution of the debris population

As a matter of fact, the low–orbiting Earth debris population is similar to the asteroid belt, since it is subject to a process of high–velocity mutual collisions that affects the long-term evolution of its size distribution. However, the situation is more complex than for the asteroids, because here the source and sink mechanisms are (partially) subject to human control (e.g. launches, explosions and retrievals), the number density of objects is a sensitive function of the altitude (and so is the sink mechanism due to atmospheric drag) and the relative speeds are dominated by mutual inclinations, which are much larger than typical orbital eccentricities and unevenly distributed (whereas among the asteroids eccentricities and sine of inclinations have similar, fairly broad distributions, with average values ≈ 0.15).

In the end of the '70s Donald Kessler (Kessler & Cour–Palais 1978) first pointed out the possibility that a process of mutual collisions between the objects presently in orbit could lead to the creation of a debris belt surrounding our planet and jeopardizing, if not preventing, all the space activities. Mathematical models and large numerical codes have been developed to simulate the interplay of all the physical processes involved in the evolution of the debris population. In these codes the main source and sink mechanisms of debris that have to be modelled are:

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

• the launches: being the only source that adds mass to the population in orbit it is of great importance to be able to predict, in a reliable way, the future space traffic. On the other hand, it is extremely difficult to make a reliable forecast since the traffic will depend on several technical, economical and political factors. The best way to deal with this problem is to produce models able to simulate, in an efficient way, different traffic scenarios and to compare the results of the various cases to identify significant trends.

• the explosions: the fragmentations due to explosions of on-orbit spacecraft represent the major source of cataloged objects. After an explosion, a single object produces a swarm of fragments with a mass distribution that approximately matches exponential laws.

• the collisions: although only one accidental collision has been recorded up to now, the collisions are going to represent the most important source of debris for the long term evolution of the space environment. The energy involved in a collision at about 10 km/s is huge, of the order of 10^3 Joules even for a centimetric projectile. The mass distribution of the fragments follows a power law:

$$N(>m) \propto m^{-b}$$

where b is a suitable positive exponent (<1 to be consistent with a finite total mass). This mass distribution means that more small fragments are produced with respect to an explosion. In our model the exponent b has typically an energy-dependent value (Petit & Farinella 1993). The few laboratory experiments, with non-classified results, make it very difficult to estimate, in a fully reliable way, the outcome of a hypervelocity collision (i.e. a collision where the impact velocity is larger than the velocity of sound inside the materials, typically around 5 km/s) between space objects. This remains one of the most important uncertainties in modelling the space debris evolution.

• as described in Sec. 2, other non-fragmentation debris sources played an important role in determining the present population of orbiting debris. The SRM slag production has to be modelled as well to have a good picture of the future debris environment, whereas the RORSAT drops should not represent a significant source of debris in the future.

On the other side there are the sink mechanisms, that is the processes that tend to remove objects from the orbit. Several natural perturbations act on an orbiting spacecraft, altering its motion from a pure two body orbit:

• gravitational perturbations, due to the non-spherical shape of the Earth and to a third body, i.e. the Moon or the Sun. These perturbations do not affect the semi-major axis of an orbiting object (i.e. do not change the orbital energy), therefore they are not efficient in removing debris form space. Actually, lunisolar perturbation, coupled with non-gravitational perturbations, may play a role in speeding the orbital decay of certain classes of highly eccentric orbits.

• non-gravitational perturbations such as the solar radiation pressure and the atmospheric drag (Milani *et al.* 1987). The latter is the most important one since it subtracts energy from an orbiting object causing its decay into the atmosphere; it represents, therefore, the main sink process. Unfortunately the atmosphere density is decreasing exponentially with the altitude, so that this perturbation is efficient only up to about 800 km above the surface of the Earth. Above this level the air drag takes several hundreds of years to remove a typical satellite from orbit.

Another "non-natural" way to remove objects from space is represented by the de-orbiting of the spacecraft after they completed their mission; we will discuss this issue in the following.

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

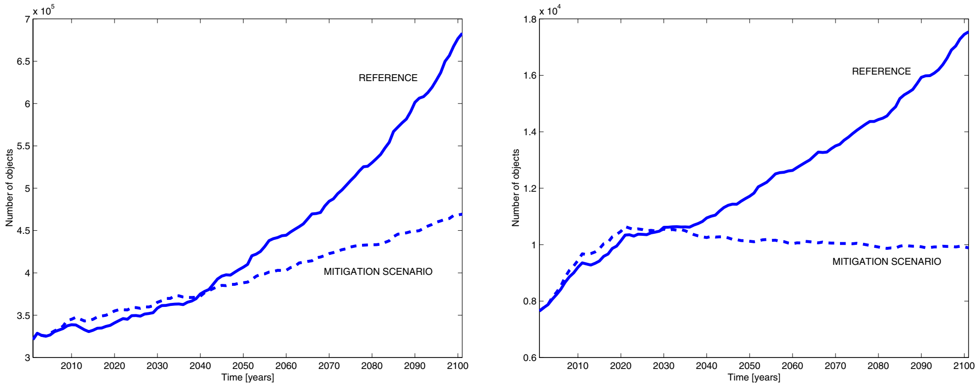

Figure 4. Number of objects larger than 1 cm between 0 and 40 000 km (left) and number of objects larger than 10 cm in LEO (right), with two different simulation scenarios.

The Semi Deterministic Model (SDM) is a software package for the simulation of the long term evolution of the debris population developed in Pisa since the early '90s. In SDM, along with a modelling of all the above mentioned source and sink mechanisms, the actual orbital evolution of all the larger objects is followed by means of an *ad-hoc* fast orbit propagator (Rossi *et al.* 1998). SDM can simulate many complex scenarios allowing to test the influence on the evolution of different fragmentation models, launch traffic, explosion patterns and mitigation measures.

In particular SDM has been used in the last years to study the effect on the environment of the measures proposed at international level to control and, if possible, reduce the number of debris in Earth orbit. The main international committee established to study and face the space debris issue is the Inter-Agency Debris Coordination Committee (IADC) that periodically gathers the representatives of all the main space agencies to share the results of the researches on the different aspects of the field. The most favored *mitigation measures* include:

• change the design of the spacecraft in order to prevent the release of mission related debris;

• prevent on-orbit explosions: this includes venting the upper stages of the residual fuel to avoid over-pressurization and discharging any power system on board after the end of the operational life;

• de-orbit all the upper stages and the satellites at the end-of-life (EOL), sending them to a fiery reentry into the atmosphere. The preferable solution would be, of course, to send them to an immediate reentry at EOL. Nonetheless, depending on the operational orbit, it has been shown how the required maneuver might be too expensive in terms of fuel consumption (Rossi 2002). Therefore an alternative solution may be a delayed reentry, where the spacecraft is de-orbited to an orbit that will naturally decay, under the effect of air drag, within a fixed amount of years (a common accepted value is 25 years). If the operational orbit is still such that this cannot be realistically accomplished (e.g. in the case of the GEO satellites), the spacecraft should be sent to a "graveyard" orbit, i.e. into a zone of space where no other operative spacecraft are orbiting (Rossi 2002).

Fig. 4 summarizes the results of a typical long term evolution study performed by SDM. For the sake of simplicity only two scenarios are shown, out of the several recently studied ones (Rossi *et al.* 2004). The scenario tagged REFERENCE is the so-called business-as-usual evolution. Namely, it is characterized by a launch activity deduced from the traffic

https://doi.org/10.1017/S1743921304008956 Published online by Cambridge University Press

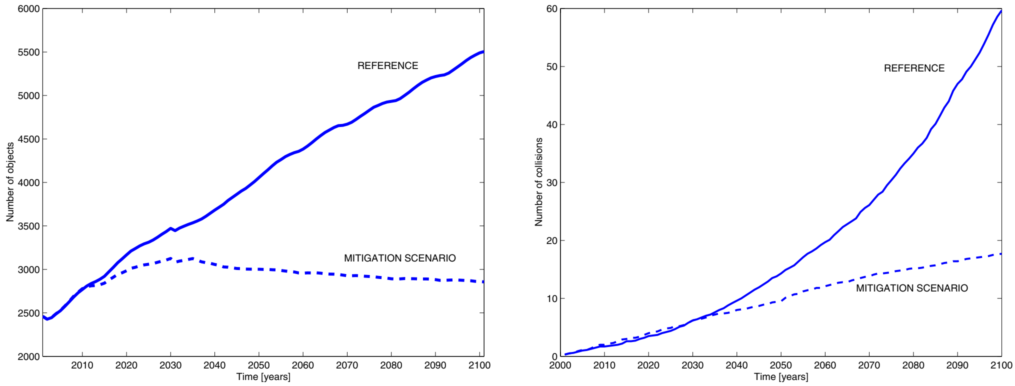

Figure 5. Number of objects larger than 1 m in LEO (left) and cumulative number of catastrophic collisions (right) with two different simulation scenarios.

observed over the last five years (1999-2003), adjusted by taking into account the phasing out of obsolete launchers and the introduction of new rocket families, with different hardware and mission characteristics. Mission related objects are released according to the current practices and no de-orbiting or re-orbiting of spacecraft and upper stages is performed at the EOL. The explosion statistics is based over the last 5 years (1999-2003) events, with an average of 2.4 explosions/year. Nonetheless, the introduction of mitigation measures on several classes of old and new upper stages systems (e.g., passivation of upper stages after burn), the existence, in orbit, of a large number of old upper stages prone to explode for at least a few decades, the progressive introduction, over the coming 5-25 years, of explosion prevention measures on the systems currently in use are taken into account. All these assumptions lead to a complete stop of explosions after 2030. As far as the production of slag is concerned, a minimum use of SRM is envisaged, based on current and planned practices. Two solid rocket motor firings are simulated for each GPS mission (perigee and apogee burns) and one of them is considered as well for each Chinese rocket Long March 3 GEO injection.

The left panel of Fig. 4 shows the number of objects larger than 1 cm as a function of time, between 0 and 40 000 km of altitude. In the REFERENCE scenario an almost linear growth is observed in the first 20-30 years. This growth is sustained by the remaining on-orbit explosions and by a progressively larger number of collisions. After 2030, collisions remain the only substantial source of centimetre sized objects and a more than linear pace takes place, leading to a number of objects, after 100 years, more than twice the initial population.

The right panel of Fig. 4 shows the number of objects larger than 10 cm in LEO. The initial growth rate levels off after 2020 due the cessation of most of the on-orbit explosions and the growth rate never returns to the values experienced in the first 10-20 years, even though the absolute increase is still about a factor 2 in one century for the REFERENCE scenario.

The population of the objects larger than 1 metre is dominated by the intact spacecraft and upper stages and the linear trend observed in the REFERENCE case is just the result of the net accumulation due to new launches in the considered time span (Fig. 5, left panel).

The picture changes considerably if some mitigation measures are introduced.

In the simulated mitigated scenario first the MRO are no more released starting from the year 2020, then the re-orbiting of spacecraft at EOL is performed. In particular, the GEO satellites are re-orbited at EOL to a circular orbit about 300 km above GEO (according to the IADC recommendation). Starting from the year 2010, all the spacecraft with perigee altitude $h_p < 1400$ km, or in high eccentricity orbits crossing the LEO region, are maneuvered to orbits with a residual lifetime $T_{res} = 25$ years. The spacecraft with $h_p \geqslant 1400$ km are re-orbited in a super-LEO storage zone above 2000 km (with a width of 100 km).

In Fig. 4 and Fig. 5 the effect of the mitigation measures are shown in comparison with the REFERENCE case. The measures seem to be able to maintain approximately stable the growth of centimetre sized debris, with a moderate linear trend. Moreover, the adoption of a combination of re-orbiting and de-orbiting at the EOL is able to stabilize the population of objects larger than 10 cm and 1 m in LEO, and even lead to slightly decreasing trends. These conclusions are supported by the cumulative number of catastrophic collisions in LEO (Figure 5, right panel). It is worth remembering that, due to the typical impact velocities in LEO, the fragmentation of a satellites requires a projectile larger than about 10 cm. In the REFERENCE scenario there is a progressive rise of the yearly number of catastrophic collisions, but in the mitigation scenario the collision rate remains approximately constant, with a difference of a factor 3 between the two cases.

These results suggest that the use of disposal orbits might be the solution to adopt in the near future to stabilize the debris environment and to guarantee the continued exploitation of the circumterrestrial space. Nonetheless it is again worth stressing that the compliance to the recommendations of international committees, such as the IADC, and the actual implementation of these measures sometimes may collide with technical, political or economical reasons that can slow down and reduce their efficiency. As an example, in the last few years only about 10 % of the GEO satellites have followed the de-orbiting procedures recommended by the IADC. In fact the operators often tend to privilege the immediate return of a few more months of operations, performed with the fuel that should be used for the de-orbiting maneuvers, as opposed to the long term benefit of all the space environment.

5. Acknowledgements

The studies on the long term evolution of the debris population and the development of the SDM software have been performed under ESA funding.

References

Alby, F., Lansard, E. & Michal, T. 1997, *Second European Conference on Space Debris*, Proceedings ESA SP-393 (Darmstadt), 589

Bendisch, J., Bunte, K., Klinkrad, H., Krag, H., Martin, C., Sdunnus, H., Walker, R. & Wegener, P. 2004, *Advances in Space Research* 34, 959

Flury, W., Massart, A., Schildknecht, T., Hugentobler, U., Kuusela, J. & Sodnik, Z. 2000, ESA Bulletin 104, 92

Schildknecht, T., Musci, R., Ploner, M., Beutler, G., Flury, W., Kuusela, J., de Leon Cruz, J. & de Fatima Dominguez Palmerod, L. 2004, *Advances Space Res.* 34, 901

Foster, J., Krisko, P., Matney, M. & Stansbery, E. 2003, *54^{th} International Astronautical Congress*, Paper IAC-03-IAA.5.2.02 (Brehmen, Germany)

Goldstein R.M., Goldstein S.J. & Kessler D.J. 1998, *Planet. Space Sci.* 46, 1007

Jackson, A., P. Eichler, Potter, R., Reynolds A. & Johnson, N. 1997, *Second European Conference on Space Debris*, Proceedings ESA SP-393 (Darmstadt), p. 279

Kessler D.J. & Cour–Palais B.G. 1978, *J. Geophys. Res.* 83, 2637

Liou, J.-C., Matney M.J., Anz-Meador P.D., Kessler D., Jansen M. & Theall R. 2002, *NASA/TP-2002-210780*

Milani A., Nobili A. & Farinella P. 1987, *Non gravitational perturbations and satellite geodesy*, Adam Hilger Ltd., Bristol and Boston.

Öpik, E.J. 1976 *Interplanetary Encounters*, Elsevier, New York, USA

Petit, J.–M. & Farinella, P. 1993, *Cel. Mech. Dyn. Astron.* 57, 1

Rossi A. & Farinella P. 1992, *ESA Journal* 16, 339

Rossi, A., Cordelli A. Farinella P. & Anselmo L. 1994, *J. Geophys. Res.* 99, No. E11, 23 195

Rossi, A., Anselmo L., Cordelli A., Farinella P. & Pardini C. 1998, *Planet. Space Sci.* 46, 1583

Rossi, A., Valsecchi, G.B. & Farinella, P. 1999, *Nature*, 399, 743

Rossi, A. 2002 *Journal of Spacecraft and Rockets* 39, No. 4, 540

Rossi A., Valsecchi G.B. & and Perozzi E. 2003, *13th AAS/AIAA Spaceflight Mechanics Meeting*, Paper AAS 03-185 (Ponce, Puerto Rico).

Rossi, A., Anselmo L., Pardini C., Valsecchi G.B. & Jehn R. 2004, *55th International Astronautical Congress*, Paper IAC-04-IAA.5.12.1.06 (Vancouver, Canada)

Valsecchi G.B., Rossi A. & Farinella P. 1999, *Space Debris* 1, 143

Valsecchi G.B. & A. Rossi 2002, *Cel. Mech. Dyn. Astron.* 83, 63