LONG TERM EVOLUTION OF EARTH ORBITING DEBRIS

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Abstract. The space environment is presently dominated by man-made debris, for particles larger than 1 mg. A comprehensive survey of the debris population from 1 mg to the larger sizes in view of the recent data from radar and optical observations, and from the analysis of materials retrived from space is given.

A brief description of the major source and sink mechanisms acting on the debris population is given, along with a very short introduction to the two models for the long term evolution developed by the group in Pisa in the last years.

The results of the long term evolution analysis are presented in some detail. A likely scenario of the future space activities leads to a large growth of mm-size particles due to several catastrophic collisions. The simulation highlights the necessity of more realistic explosion models, since the current ones overestimate the 10 cm-sized fragments.

An enlarged version of this paper can be found at the CNUCE Spaceflight Dynamics Group Web site: *http://apollo.cnuce.cnr.it/~rossi/homerossi.html.*

1. The Space Debris Environment

In near–Earth space there are two major regions where orbital debris is of concern: Low Earth Orbits (LEOs), below about 2000 km, and Geosynchronous Orbits (GEOs), at an altitude of about 36 000 km. The issues are in principle the same in the two regions, nevertheless they require different approaches and solutions. In this paper my discussion will be focused mainly on LEOs.

As of November 1, 1995 the US Space Command (USSPACECOM) listed 7929 objects in the Two Line Elements (TLE) catalogue. These objects broke down to 5747 objects in Low Earth Orbit (LEO) (orbital period < 225 minutes), 601 objects in Geosynchronous Earth Orbit (GEO) (period about 24 h, altitude around 36 000 km), 134 objects in Medium Earth Orbit (MEO) (orbiting between LEO and GEO) and 1447 objects in other

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kind of orbits (highly elliptical and transfer orbits, moving between LEO and other regions of space). Of the total number of items in the catalogue 2298 were spacecraft (only about 350 operational), 1506 rocket bodies and 4125 fragmentation debris (Office, 1995).

To maintain the catalogue the USSPACECOM collects observational data from a worldwide array of sensors which form the Space Surveillance Network (SSN). The SSN sensors can be divided into two main categories: radar and optical. Radars are typically used for LEO observations while optical instruments are used for deep space observations, since their sensitivity falls off less rapidly with range ($\propto$ to power -2 instead of -4). The limiting size of the catalogued objects is a function of the altitude but we can assume it to be $10 \times 10\,\mathrm{cm}^2$ radar cross section in LEO and about $1\,\mathrm{m}^2$ at geosynchronous altitude. Due to limitations in the coverage of SSN, the catalogue is probably incomplete for large fragments in highly elliptical orbits of low inclinations and in Molniya orbits. Finally, the catalogue purposedly excludes US military satellites.

In summary, it can be stated that the TLE objects represent well, even if not completely, the space environment for sizes larger than 10 – 15 cm. These objects account for about 99.93% of the total mass in Earth orbit (about 3500 tons), but only for 0.02% in number, if we go down to the 1 mm size range.

Above 1 mm in diameter the particles are mainly man-made debris (below about 1 mm the natural meteoroid population still dominates the particle flux) originating from a large number of fragmentations of orbiting objects. Following the first of such events, the explosion of the Transit 4A Rocket Body of June 29, 1961 (whose fragmentation debris are still tracked), a total of 133 breakups have been recorded by the US until January 1, 1996. (Johnson and Loftus, 1996) (Note that the Russian sources catalogued 176 events – these discrepancies are under investigation by the respective space agencies). Three of these events are known to be deliberate hypervelocity impacts, performed to test antisatellite weapons by the US (P-78 Solwind destroyed by a homing vehicle, US 19 and US 19 Rocket Body sent against each other). One event, Kosmos 1275, is strongly suspected to be the first and, up to now, the only accidental collision between a spacecraft and a piece of debris. Recent radar measurements showed a number of fragmentation debris coming from Kosmos 1275, whose mass distribution matches better the mass distribution of a collision-induced breakup than that of a high-intensity explosion-induced breakup.

All the other breakup events were caused by explosions, either deliberate or accidental.

Most of the fragments are too small to be routinely tracked by the SSN; their number and orbital distribution must be estimated by means of optical and, mainly, radar observation and from the examination of materials returned from space. The Haystack radar (located near Boston, USA) is the main source of observations of small debris. During space debris observations, its large dish antenna is pointed in a fixed direction and the objects flying through the radar beam are detected; it is capable of detecting 1-cm objects orbiting at 1000-km altitude. The flux of debris recorded during several hours of observation in the above described *beam-park mode* provides data samples which form the basis for statistical models of the debris environment.

Data samples concerning 1-mm particles (and below) are provided by surfaces returned from space which experienced the debris environment for some time. These returned materials include the Long Duration Exposure Facility (LDEF), a spacecraft released by the Space Shuttle in 1985 at an altitude around 460 km and retrieved in 1991, one of the Hubble Space Telescope (HST) solar panels (which spent 3.2 years in orbit at a mean altitude $h \approx 550\,\mathrm{km}$) and the Eureka platform which stayed 326 days at $h \approx 500\,\mathrm{km}$ (the three spacecraft were all at an inclination $i = 28^\circ\!.5$). All these devices where brought back to Earth by the Space Shuttle, which is itself a valuable source of information about the LEO debris environment.

The analysis of pits and craters provides *in situ* measurements of the small debris flux. In general it is very difficult to determine the exact nature of the projectile responsible for a crater on a retrieved surface because the high energy of the impact melts and vaporizes the particles and the composite materials of the target mix with those of the projectiles. For example on the HST panel about 150 craters have been detected but more than 2/3 of them are of unknown origin; on the LDEF front and side surfaces 14% of the impacts were identified as due to orbital debris and 55% of the impacts were classified as of "unidentified origin", even if they were supposed to come from man-made debris.

From this point of view a good "collecting surface" is the Space Shuttle and in particular its windows. Since the first launch, 59 windows had to be substituted due to impact craters; the largest crater ever revealed on a Shuttle window is a 1.2 cm diameter crater on STS-59, caused by a paint flake. Detailed analyses of the impacts on STS-73 can be found in (Bernard and Christiansen, 1995). Currently the Space Shuttle suffers an increasing number of craters per day of flight, with the average value being 1.1 crater/day of flight.

As stated above the retrieved surfaces (from different orbits and altitudes) provide data points to calibrate the statistical models of the small debris population; the data from STS-73, for example, showed that the NASA BUMPER model underestimates the debris flux by about a factor 3, while it is in good agreement with the observed meteoroid flux. The statistical estimates indicate that about 110 000 particles between 1 and 10 cm and 35 000 000 particles between 1 mm and 1 cm are present in orbit.

The observed debris environment can be "reconstructed" by simulating all the past fragmentation events and propagating the fragment orbits to a common reference epoch, using "ad hoc" models to reproduce the mass and the ejecta velocity distribution of the fragments produced in a breakup event. This kind of population model requires large software codes and a significant amount of computer time to propagate the orbit of a huge number of particles (Pardini *et al.*, 1995). In order to produce an inital population for our models of the long term evolution of Earth orbiting debris, at CNUCE we made this kind of effort, modelling all the fragmentation events from 1961 to January 1, 1994. The resulting population named CNUCE 1994.0 Orbital Debris Reference Model (ODRM) (Version 5.1) consisted of the 7 375 467 simulated fragments from 1 mg to 300 g and the 7091 objects included in the TLE catalogue at the epoch of reference, for the objects larger than 300 g. Plotting all the objects in an eccentricity – inclination (or semimajor axis – eccentricity, semimajor axis – inclination) diagram and watching at the distribution of objects in the orbital element space the two population of spacecraft and fragmentation debris are easily detectable. The TLE objects are clearly grouped in "families" or constellations corresponding to different mission designs and launching bases; the fragmentation debris are distributed around the orbit of the fragmented parent objects, but also populate other regions of the orbital element space, devoid of spacecraft (in particular eccentric orbits), due to the Δv imparted by the breakup event.

The population of the CNUCE ODRM, having been generated by simulating only breakup events, does not contain a large population of objects, which was discovered by the Haystack Radar observations in the crowded region between 800 and 1000 km, with an inclination of 65°. This population, with a very steep mass distribution ($\simeq 10^5$, 10^3 and 10^2 objects having sizes $\simeq$ 1 mm, 1 cm and 10 cm, respectively) has a very distinct property: the objects have an almost specular reflectivity when observed by radar. For this reason, they are supposed to be drops of the liquid coolant of the nuclear reactors on board the RORSAT satellites, leaked outside the spacecraft. The phenomenon is of concern due to the abundance of these satellites and because the leakage happens in a region of space which is already the most crowded one. The problem is still under investigation by the Space Agencies to identify with certainty the source of this new debris family.

For a complete picture of the debris environment, which matches closely the Haystack observations, it is necessary to consider also the exhaust particles ejected by Solid Rocket Motors (SRMs), typically used to transfer spacecraft from LEO to GEO. These particles are mainly aluminum oxide dust with characteristic sizes less than 0.01 cm, but cm-sized particles of by-product material (propellant slag condensate, incompletely burned fuel, etc.) can also be found. There have been approximately 720 SRMs firings during the history of the space programs. The large retrograde velocity ($\simeq 3\,$km/s), the low mass of the dust and the low altitude parking orbits used in current mission profiles, result into a short orbital lifetime of the smaller particles, while the cm-size debris should survive longer (some of the chunks may also be released long after the completion of the burn, i.e. in higher orbits).

The last group of debris to be accounted for are created by the gradual disintegration of spacecraft surfaces as a result of exposure to the space environment (paint flaking, plastic and metal erosion). Usually these are very small debris particles, even if several orbital objects (e.g. COBE, COSMOS 1484) have been observed to periodically shed material in larger pieces (e.g. thermal blankets and insulation).

2. Long Term Evolution of the Debris Population

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 drag) and the relative speeds are dominated by mutual inclinations, which are much larger than typical orbital eccentricities and unevenly distributed.

The physical models for the source and sinks mechanisms affecting the orbital debris population have been combined to produce two complex computer models for the simulation of the long term evolution of the debris population (Rossi *et al.*, 1995a). One of them, called STAT, is the logical unfolding of the model described in (Rossi *et al.*, 1994). A division in discrete bins of semimajor axis (from 6378.14 to 46 378.14 km), eccentricity (from 0 to 1) and mass (from 1 mg to 10 000 kg) is introduced. The variables used represent the number of objects contained in each bin; the time evolution is performed by means of a set of finite-difference equations which take into account launches, retrievals, explosions, collisions and orbital propagation.

The other code, called SDM, while using the same physical models of STAT, is based on a completely different approach. In SDM the aim is to follow, as much as possible, the actual orbital evolution of the objects orbiting between 0 and 40 000 km of altitude. For this reason all the larger objects are individually propagated using a fast semi-analytical Debris Cloud Propagator (Rossi *et al.*, 1995a); of course, due to the very large number of small objects involved, a user-defined sampling was introduced for them.

Both the codes presently use the 1994.0 ODRM 5.1 as the initial conditions. The two codes allow the simulation of many different future scenarios with a large versatility in the choice of the physical parameters of the models. The agreement between the results of the two codes in a number of test runs has confirmed the reliability of their predictions.

3. Results for the Long Term Evolution

The results discussed in this section have been obtained by simulating a reasonable scenario for the future traffic in low Earth orbit.

The explosion rate has been maintained similar to the present one, only taking into account the preventive measures already undertaken; e.g. the Ariane IV 3rd Stages, which are now vented of the residual fuel after the burn, are not supposed to explode any longer after the year 1996, and similar hypotheses have been made about other upper stages which used to explode in the past. No new sources of explosions have been included. This leads to an average number of 4 explosions/year.

The launch rate has been supposed to decrease by 0.5% per year until 2002 and then to remain constant; superimposed to this trend of "standard" launches I supposed the launch of 5 large constellations of satellites: IRIDIUM (66 satellites), GLOBALSTAR (48 satellites), ODYSSEY (12 satellites), ORBCOM (18 satellites), ELLIPSAT (24 satellites). In the launch of the constellations debris prevention measures are assumed (e.g. no upper stages are left in orbit and the old satellites are deorbited when they are replaced). Moreover the launch and construction of 2 large orbiting stations have been simulated during the investigated 100-year time span (the planned International Space Station starting in 1997 and a possible replacement starting in year 2030). The way in which satellite constellations and large structures are simulated by the model is described in (Rossi *et al.*, 1995a).

The collisional events were simulated assuming a catastrophic fragmentation threshold Q^* of 45 000 J/kg; the empirical formula used to relate the area and the mass of the objects is that used by the NASA/JSC EVOLVE code (Reinhardt *et al.*, 1993).

Figures 1 and 2 show, respectively, the number of objects larger than 1 mg and 10 cm; in both the plots three lines are drawn: the central one is the mean value over 10 runs with different random number generator seeds (the code uses random number generators for the statistical treatment of "stochastic" events such as explosions and collisions) and the other two correspond to the lowest and the highest results out of 10, at the end of

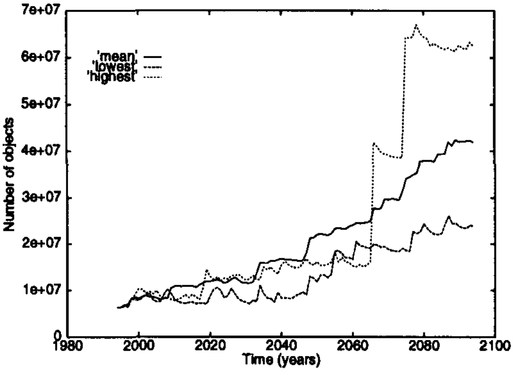

Figure 1. Number of objects larger than 1 mg vs. time. The solid line gives the mean over 10 different runs, the small-dashed line gives the highest values out of the 10 runs and the dashed line gives the lowest ones at the end of the simulation time span.

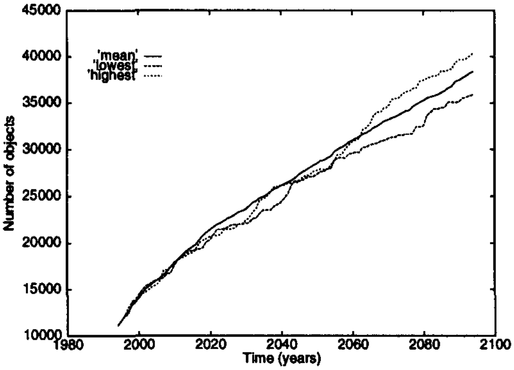

Figure 2. The same as Figure 1, but for objects larger than 10 cm.

the 100-yr time span. The difference between the upper and lower curves gives the "intrinsic" variability of the model predictions.

The evolution of the small particle environment is dominated by the occurrence of several (around 10 in 100 years) collisions between large objects, leading to complete target breakups, which produce millions of mm-size particles. The objects larger than 10 cm are instead created mainly by explosions and therefore their variability around the mean is less pronounced. The growth rate of the objects larger than 10 cm is around 270 per year; this value is close to the observed one. It is worth stressing that in all the simulated explosions we rescaled the actual exploding mass in order to fit the number of large fragments tracked after the breakup; the rescaled masses are in most cases around 10% to 30% of the actual mass of the exploding spacecraft. This highlights the fact that a fundamental uncertainty about the dynamics of explosions still remains and probably most explosions affect only a part of the spacecraft/rocket structure, leaving the remainder almost unaltered or at most divided into a few large fragments. Performing the 100-year simulation without rescaling the exploding masses would lead to a growth rate, for objects larger than 10 cm, $\simeq$ 1000 per year.

The flux of objects larger than 10 cm in LEO presently shows two major peaks between 750 and 1000 km and around 1500 km. After 100 year the growth in these region is particularly strong, going from $5\times10^{-6}\,\mathrm{yr}^{-1}\mathrm{m}^{-2}$ to $1.5\times10^{-5}\,\mathrm{yr}^{-1}\mathrm{m}^{-2}$ and from $3\times10^{-6}\,\mathrm{yr}^{-1}\mathrm{m}^{-2}$ to $8\times10^{-6}\,\mathrm{yr}^{-1}\mathrm{m}^{-2}$, respectively, with the second peak moving toward lower altitudes ($\sim$ 1400 km). In these regions the density of objects is already "critical" (Kessler, 1991), (Rossi *at al.*, 1995b), i.e. above the value which is capable of producing, even in the hypotesis of a complete stop of all space activities, the onset of a destructive collisional chain reaction in the future. The critical density, after 100 years, is reached also around 800 km and in the regions between 1300 and 1400 km. The flux of particles larger than 1 mg increases, almost uniformly with height, by one order of magnitude after 100 years, showing peaks around 300, 800 and 1800 km.

The scenario simulated here can be considered as a "conservative" one, since no new explosion sources have been introduced, while some of the explosion sources of the past have been supposed to disappear entirely in the future. Further policy measures to limit the debris growth can be devised. The effectiveness of some of them has been analyzed in (Rossi *et al.*, 1994) and (Rossi *at al.*, 1995b).

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