MODELLING THE EVOLUTION OF THE SPACE DEBRIS POPULATION: RECENT RESEARCH WORK IN PISA

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ABSTRACT

Since the beginning of the 90's the Pisa-based space debris research group has studied the long term evolution of the debris population. We briefly describe the models developed in the last four years, outlining the innovations introduced in this field of study. Three new powerful software tools have been developed under an ESOC contract and then upgraded and exploited in the framework of an agreement with the Italian Space Agency (ASI). With these tools a number of research results have been obtained. In the paper we summarize the main findings of our work, with particular emphasis on the parameter sensitivity analysis.

1. INTRODUCTION

The space debris research group at the CNUCE Institute of CNR and the Department of Mathematics of the University of Pisa started working on issues related to the evolution of the space debris population at the end of the 80's. The models developed in the first stage of our work were based on a set of first order nonlinear differential equations taking into account the main source and sink mechanisms acting on the debris population (Refs. 1 to 3). On the basis of this experience, in 1992 our group was selected by ESOC to carry out research and software development work under a contract named "Study on the Long Term Evolution of the Space Debris Population".

In the framework of this contract, three complex computer programs were developed. Two of them, named SDM (Semi Deterministic Model) and STAT (STochastic Analog Tool) are comprehensive codes for a realistic simulation of the time evolution of the space debris population over a vast range of masses and orbits, under various source and sink mechanisms; they were based upon very different modelling approaches, in order to allow for detailed comparisons and to assess the robustness of the simulation results. The third code, called CLDSIM (CLoud Debris SIMulator), is aimed at predicting the outcomes of single fragmentation events, caused either by collisions or explosions; it was used mainly to simulate all the known fragmentation events occurred in the past, in order to provide a reliable initial population of objects with mass greater than 1 mg for the long term evolution runs to be performed with SDM and STAT.

In the following section we will briefly describe these codes with a particular emphasis on the main innovations we introduced with them in the space debris modelling field (for an extensive description of them see Ref. 4). Then we will summarize the main results obtained in the past few years with the programs.

2. LONG TERM EVOLUTION CODES

Although based on different concepts, the two codes for the long term evolution, STAT and SDM, contain the same physical models for the source and sink mechanisms.

STAT is the logical unfolding of the models described in Refs. 1 and 3. A division in discrete bins of semi-major 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

Proceedings of the Second European Conference on Space Debris, ESOC, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997)

carried out by means of a set of finite-difference equations, which take into account launches, retrievals, explosions, collisions and orbital propagation:

$$\frac{dn_i}{dt} = (\text{launches})_i - (\text{retrievals})_i + \sum_j \left\{ (\text{explosions})_{j \to i} + (\text{propagation})_{j \to i} \right\} + \sum_{jk} (\text{collisions})_{(jk) \to i}$$

n_i being the number of objects in the i^{th} semimajor axis–eccentricity–mass bin. The action of STAT is not merely the numerical integration of such differential equations; in fact, if this were the case, we should have introduced quantities like the average number of explosions/collisions at every time step and, due to the very low occurrence rate of this kind of events, these quantities (which may be much less than unity) would have had a poor physical meaning. In order to avoid such problems, we have introduced as fundamental quantities not the *rates* of explosions/collisions, but their *occurrence probabilities* at each time step; then an integer number is extracted from a Poisson distribution whose mean is just the probability of the event.

It is worth stressing that, differently from Ref. 3, in STAT we introduced semimajor axis–eccentricity bins (instead of altitude shells), in order to correctly take into account orbits with any possible eccentricity; moreover, the time evolution is obtained with a rigid displacement, in the semimajor axis–eccentricity two-dimensional space, of the rectangle representing a bin and not only with a mean orbital decay of the representative point (Ref. 4). This innovative concept was later adopted and extended, to take into account also the inclination, by other authors (Ref. 5).

SDM is instead closer to the philosophy underlying EVOLVE (Ref. 6); in fact it aims to follow, as much as possible, the actual orbital evolution of the objects between 0 and 40000 km of altitude. The main concept is that the population of debris is divided into two main classes: *historical population* and *running population*. The former represents all the objects larger than 1 mg present in space at the beginning of the simulation; this group of objects was propagated only once for the desired time span (e.g. 100 years) and then stored in terms of objects density, as a function of altitude, time and mass bin. The second one is composed by everything that goes into space after the beginning of the simulation: launched objects, explosion and collision fragments. Among these particles the largest ones are individually propagated using a fast Debris Cloud Propagator (DCP); DCP carries out the time evolution of a large number of particles with an analytical method taking into account the influence of air drag (with a time dependent atmospheric density). Since the number of small debris can become very large, a user-defined sampling method is introduced for them so that only a subset of orbits is propagated. The *background population* obtained adding the *historical* and *running* objects densities, is instead used to compute the collision probability at each step.

The codes are suitable for the same applications, but the CPU time required by SDM depends on the number of objects simulated during a run, so it increases year after year (when the population is growing). On the other hand, the CPU time required by STAT is almost constant for each time interval and is independent of the total number of objects. For a 100-year simulation, the computation times of STAT and SDM are comparable (with SDM being slightly faster), but for longer time spans STAT becomes more efficient.

In the design phase, a particular attention was devoted to developing highly modular codes. This allowed us to easily introduce a large number of options for the main physical processes. In particular, STAT and SDM contain six area vs. mass relations, three velocity models for the collision ejecta, two models for the mass distribution after a collision (one of them depending on the ratio of the impact energy to a selectable *fragmentation threshold*), two models for the mass distribution after a high-intensity explosion and one for low-intensity explosions; likewise it is easy to add new models if required (Ref. 7). This feature allowed us to perform a detailed sensitivity analysis to investigate the dependence of the evolution upon the main physical parameters. The two codes make use of a very versatile traffic model, which can simulate in a straightforward way the *routine* space activity, the launch of constellations of satellites and the building of large structures in space (Ref. 4). For all the launches we take into account the mass and orbital elements of the payload and upper stage; in particular the upper stage can be deorbited or not, and in the latter case we can place it either on the same orbit as the payload or in a transfer orbit. For the constellations we also specify the number of satellites composing them, along with their planned lifetime. All these features clearly lead to many different scenarios for the future traffic; this has also been an innovation in the modelling field and stimulated similar efforts by other groups (e.g. Ref. 8).

The models developed for STAT and SDM were also used inside CLDSIM. With CLDSIM it is possible to simulate an explosion or a collision and to propagate the cloud of resulting debris either with DCP or with a more accurate orbital predictor (FOP) taking into account all the relevant perturbations (Earth gravity field harmonics, radiation pressure with eclipses and luni-solar perturbations in addition to air drag). With this tool we have simulated all the past fragmentation events in order to obtain a reliable initial population for the long term evolution runs (Ref. 9).

3. SUMMARY OF THE MAIN RESULTS

During the developing phase and after the completion of the models a large amount of research work has been conducted. In the following we will outline the main results obtained so far.

Before starting the long term propagations of the whole debris population, we analyzed the effects of single fragmentation events and the evolution of the resulting clouds of debris (Ref. 10). An interesting result of this work was that high intensity explosions in circular orbits could inject significant amounts of small debris in high eccentricity orbits. Due to this, we may expect more particles in high eccentricity trajectories than those produced only by fragmentation events occurred in GTO and Molniya type orbits.

Applying the single event simulator to 117 catalogued fragmentation events, occurred from 1961 to the end of 1993, and propagating with FOP the resulting debris clouds to the reference epoch of January 1, 1994, we reconstructed the uncatalogued part of the current debris population (Ref. 11). Together with the objects contained in the Two-Line Elements catalogue, it forms the CNUCE 1994.0 Orbital Debris Reference Model 5.1. Another Reference Model (5.1.R) includes the NaK droplets produced by the Soviet RORSATs, following the distribution given in Ref. 12. Both provide the initial conditions for the long term simulations.

The first simulations were devoted to the study of the effects of possible mitigation measures on the growth of the space debris (Ref. 13).

Initially we defined a business-as-usual (BAU) scenario, with launches and explosions occurring at the same average pace of the last 5 years. Then we considered three alternative scenarios: (*i*) all explosions eliminated after year 2000 (NEX); (*ii*) in addition to this, all upper stages deorbited and no operational debris released, again after 2000 (NEAD); (*iii*) in addition to this, all payloads in LEO and Molniya orbits deorbited after 10 years of operational life, if launched after 2030 (NEAD_LIF).

In the BAU case a much larger number of small objects (< 10 cm) is produced after 100 years, mainly due to a significant number of catastrophic collisions. Stopping all the explosions in the year 2000, the number of fragments large enough to shatter a spacecraft is severely reduced; mainly for this, in the last three cases the final population of small objects is lower. For objects larger than 1 m explosions may be a source comparable to launches, so the elimination of the former significantly reduces the final population of this size, consisting at this point mainly of spacecraft and upper stages. Of course, the deorbiting of upper stages and spacecraft at the end of the operational life improves the situation further. The sharp reduction of large objects in the last three scenarios also reduces the total cross–sectional area in orbit, resulting in a prominent decrease of the collision rate.

Apart from the interesting information about the effectiveness of different space policies, these preliminary studies showed that there is a fundamental uncertainty about the outcomes of explosions. Probably, most explosions involve only a part of the spacecraft/rocket structure, leaving the remainder almost unaffected, or at most divided into a few large fragments. In fact, using the commonly accepted explosion models, an explosion rate like that of the past several years leads to a growth rate of trackable objects (larger than about 10 cm) of more than 1000 objects/year; to obtain a rate close to the observations (about 200 objects/year) it is necessary to rescale the exploding masses. We found that the rescaled mass is in most cases the 10 – 30% of the actual mass of the exploding spacecraft. It is remarkable that the possibility of simulating all the events with different models throughout the time span of the runs allowed us to implicitly test and validate the models themselves, comparing the results with the observations.

In order to gain a better understanding of the future evolution, we defined the so-called ***critical density index***. Extending a concept first introduced by Kessler (Ref. 14), the critical density index is defined, for each altitude shell, as the ratio between the mean

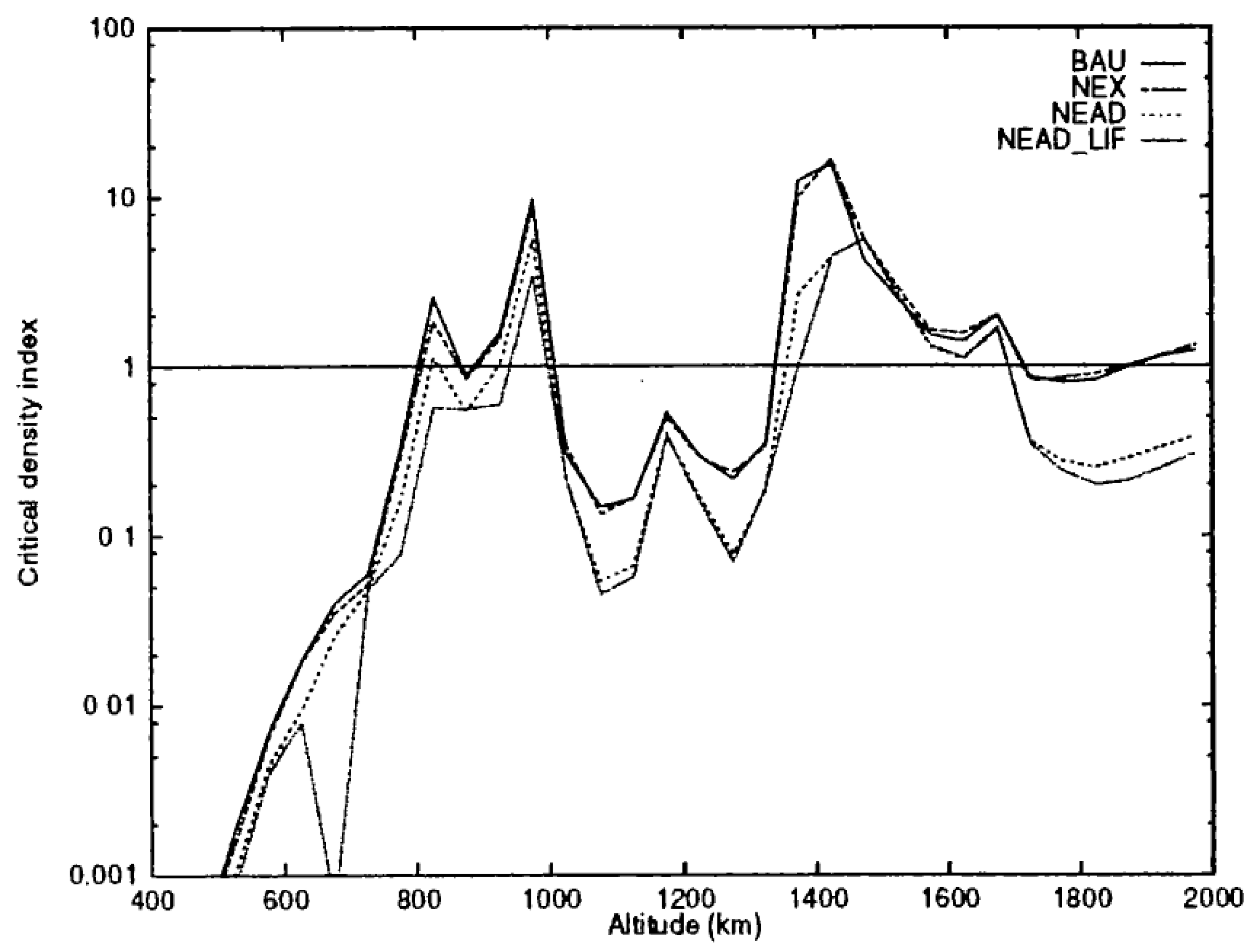

Figure 1. Critical density index in the year 2094 for the BAU (solid line), NEX (dashed line), NEAD (dotted line) and NEAD_LIF (dash-dotted line) scenarios.

number of objects left by collisions and able to produce new catastrophic impacts and the mean number of such objects that might be removed by the air drag in the same shell during the same time (Ref. 11). If this ratio is lower than 1, the density in the chosen altitude shell is still lower than the critical density, for which collisional processes alone are able to replace all the objects removed by the drag. But where the index is larger than 1, a collisional chain reaction may occur in the long term, even if all launches and explosions were stopped at once. At the starting epoch of the simulation, the year 1994, the density is above the critical value in two regions: a small one close to 1000 km and a larger one between about 1400 and 1700 km of altitude. Fig. 1 shows the critical density index after 100 years for the four scenarios described above; while the situation becomes worse in the BAU and NEX scenarios, the remaining two cases leave the overall picture practically unchanged, confirming that the debris limitation measures studied improve the situation, although they do not solve the problem entirely.

Starting from these conclusions, we have defined a revised, more realistic BAU scenario. The explosion rate has been maintained similar to the current one, only taking into account the preventive measures already undertaken (e.g., the Ariane IV third stages, which are now vented of the residual fuel after burnout, are not supposed to explode any longer after 1996, and similar hypotheses have been made about other upper stages which used to explode in the past). No new source of explosions has been included, leading to an average rate of 4 explosions/year. The routine launch rate has been supposed to decrease by 0.5% per year until 2002 and then to remain constant; superimposed to this trend, we simulated the launch of 5 large constellations of satellites: IRIDIUM (66 satellites), GLOBALSTAR (48 satellites), ODYSSEY (12 satellites), ORBCOM (18 satellites), and ELLIPSAT (24 satellites). Assembling the constellations, debris prevention measures have been assumed (e.g. no upper stage left in orbit and the satellites deorbited whenever replaced). Moreover, the building of two large orbiting stations has been simulated during the investigated 100-year time span (the planned International Space Station starting in 1997 and a possible replacement starting in 2030). The collisional events were simulated adopting the fragmentation model described in Ref. 3, assuming a catastrophic fragmentation threshold at a specific impact energy of 45000 J/kg. As initial population, both the 5.1 and 5.1.R CNUCE models were used.

The results obtained with this scenario show that, in terms of the number of objects, the environment is dominated by mm-sized particles, created in huge quantities by collisions between massive objects. The stochastic nature of these events is illustrated in Fig. 2, where the solid line represents the number of objects larger than 1 mg, averaged over 10 runs with different random number generator seeds, while the small-dashed and dashed lines represent, respectively, the lowest and highest results, out of the ten runs performed with population 5.1. The difference between the highest and lowest curve somehow represents the intrinsic stochastic variability of the evolution process. The same feature is less marked for particles larger than 1 cm, since their rate of production is less affected by collisional events. Finally the objects larger than 10 cm are mainly generated by explosions and launches. Fig. 2 also shows the debris evolution, again averaged over 10 runs, using the initial population 5.1.R (dotted line).

Since a perfect knowledge of the initial population is not available, especially for mm-sized particles, we have performed some simulations to assess the dependence of the future environment upon the initial conditions (Ref. 15). We have used again, as reference population the 5.1 CNUCE model. This was given in input to SDM, after computing the corresponding number densities in a set of 800 50-km wide altitude shells and 10 logarithmic mass bins. Then we produced some *random clones* of the initial population by multiplying the densities for all the 10 mass bins and 800 shells by a random number in between 0 and 3. Other *multiplicative clones* were obtained by multiplying the densities of some mass bins, in a selected

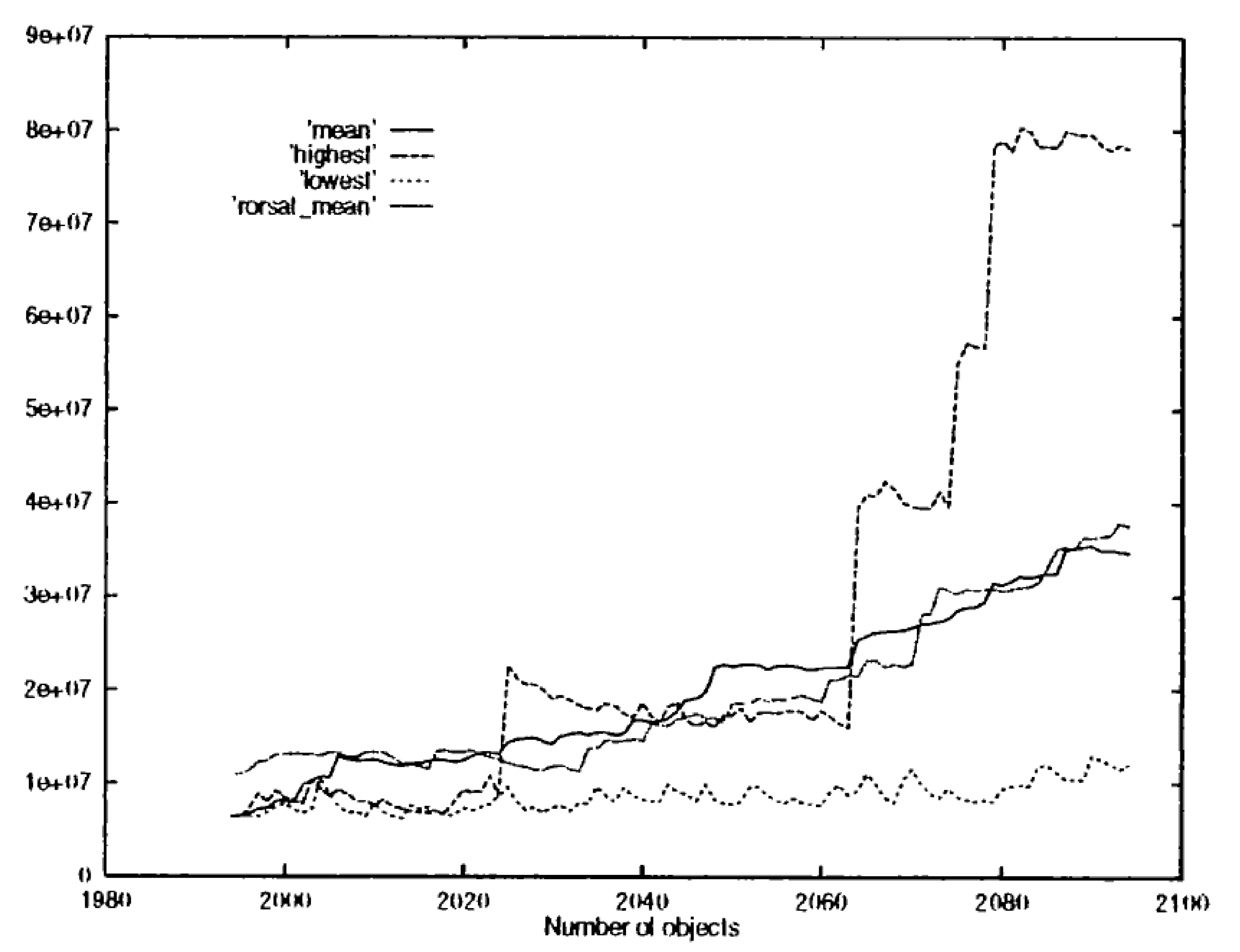

Figure 2. Number of objects of mass larger than 1 mg vs. time. The solid line gives the mean over 10 different runs, whereas the dashed and small dashed lines correspond to the highest and lowest values at the end of the simulations, respectively. The dotted line shows the average value for the case where the RORSAT's NaK droplets are included in the initial population.

altitude range, by a specified factor, in between 0.8 and 1.5, to introduce systematic differences among the initial populations.

The conclusions drawn from this study have been that the debris population can be divided into two main classes, as far as the long term evolution is concerned: objects larger and smaller than approximately 10 cm. The evolution of the former is mainly driven by explosions, so that differences in the initial populations propagate almost linearly with time, provided we are far enough from the *catastrophic* growth regime (this is true in the next century with our parameter choices). On the other hand, the evolution of the smaller objects is mainly affected by catastrophic collisions; therefore typical non-linear stochastic effects are dominant here. As a consequence, even small initial differences can be highly amplified (or, on the contrary, reversed) during the subsequent collisional evolution. The weak or missing correlation between the final and initial populations of small objects means that their evolution is strongly *chaotic*, in particular in the altitude ranges where a high concentration of objects larger than 10 cm causes comparatively frequent catastrophic collisions.

From these results we can also conclude that, for long-term predictions, it is very important to determine well the current population in its large-mass portion, because its future evolution is strongly correlated to the initial conditions, and moreover it provides the targets for future catastrophic collisions, which dominate the evolution of small particles. These, on the other hand, evolve in a stochastic fashion, so their future abundance has an *intrinsic* uncertainty unrelated to the current population in the same size range.

Then, we have tried to test how different model options can affect the long-term evolution. The revised BAU case, described above, has been compared with other simulations in which alternative models have been used for: the debris area/mass relationship, the fragment mass distribution, the fragmentation threshold and the ejecta velocity model following collisional breakup.

As far as the area/mass relation is concerned, using five different models we have obtained comparable results, well within a factor 2. Also the use of different models for the velocity of the ejecta after a collision did not produce a significant systematic variation in the number of particles over the time span considered.

In our nominal collisional model the mass distribution of the fragments is based on a power law, whose exponent depends on the impact energy; this means that in highly energetic events a much larger number of mm-sized particles are produced with respect to models, like the one adopted in the EVOLVE code, in which the exponent has a fixed value. After a 100-year simulation, we have verified that with the nominal relationship the number of objects larger than 1 mm is higher than in the constant exponent case by a factor 1.6; the number of particles larger than 1 cm is instead smaller by 30%.

Using an energy dependent relationship, it has also been possible to test the influence of the strength parameter of satellites and rocket bodies, namely the typical specific energy required for breaking them up. The results of a few laboratory experiments have indicated a probable value in the range 30,000 – 45,000 J/kg. We have explored the range from 4,500 J/kg to 45,000 J/kg; the thresholds inside the experimental range mentioned above lead to similar evolutions, apart from statistical fluctuations. On the other hand, a value lower by one order of magnitude (4,500 J/kg) leads to a much larger number of catastrophic collisions, which create a higher number of small particles. In between, the other thresholds show similar behaviors. While for the mm-sized particles, due to the stochastic character of the evolution (despite the 10-run average) a few very large fragmentations produce a huge number of objects in the 10,000 J/kg case, the abundance of objects larger than 1 cm is comparable for the 10,000, 20,000 and 30,000 J/kg cases, as shown in Fig. 3.

Another study performed has been devoted to the effect of the launch, in the next decades, of a number of LEO satellite constellations (Ref. 16). These will

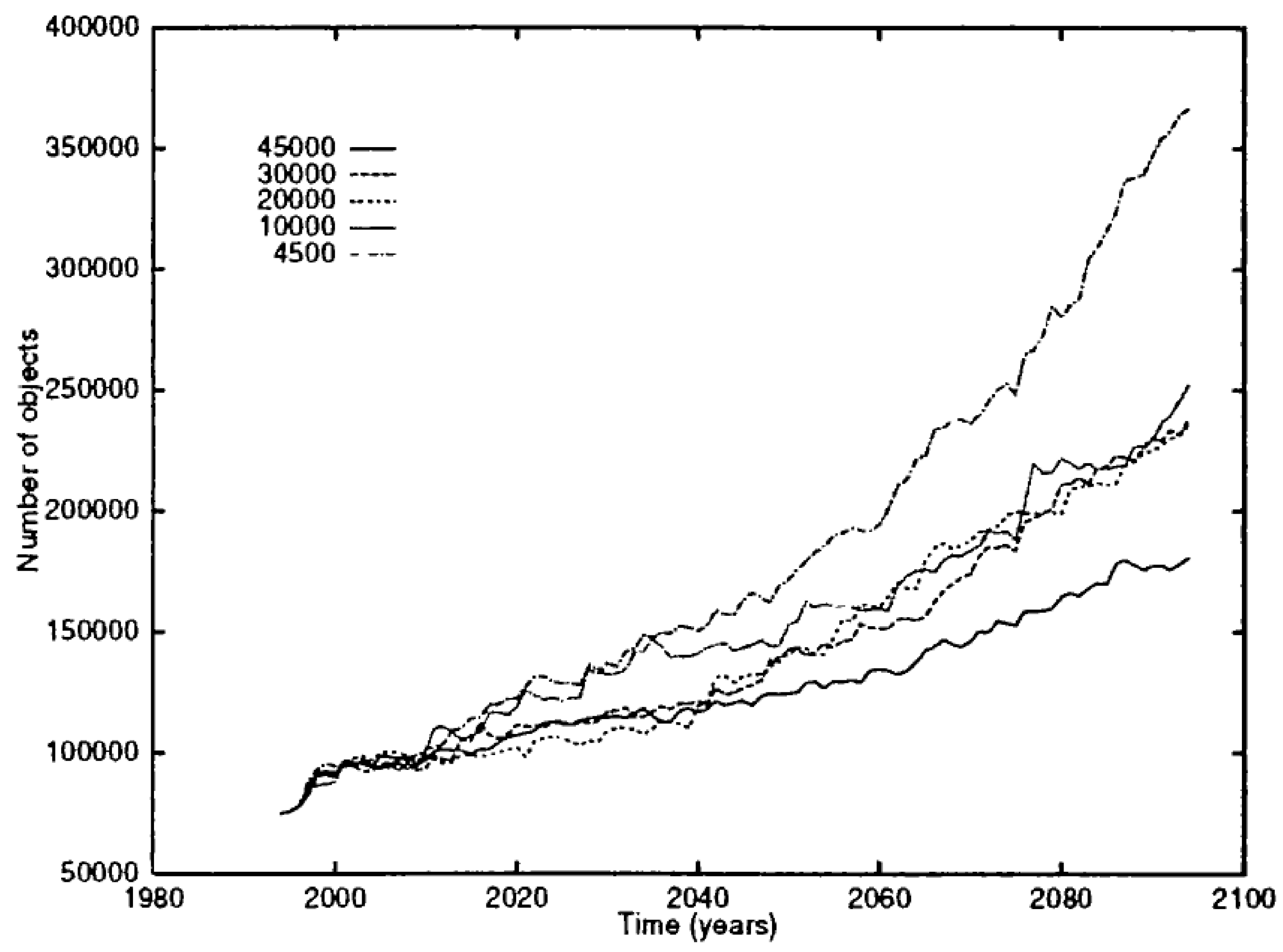

Figure 3. Number of objects larger than 1 cm vs. time, with the fragmentation threshold set to 45000 (*reference*, solid line), 30000 (dashed line), 20000 (small-dashed line), 10000 (dotted line) and 4500 J/kg (dash-dotted line). All curves refer to averages over 10 runs.

represent a considerable increase in the orbiting population. In this context, it is important to model appropriately the *debris prevention policies* of the launching organizations: the upper stages of the rockets used to launch the constellations can be left in orbit or deorbited, and the same holds for the satellites at the end of their operative life (so that the total population of the constellation remains constant throughout its planned lifetime). In the case that the upper stages are left in orbit there is also the possibility of new explosions, if some residual fuel is left in the tanks. In the revised BAU case, described above, all the debris prevention measures were assumed to have been taken; the other cases included a scenario where no constellation is launched and two others were the prevention measures are not adopted (in the *worst* case we also assumed one additional explosion per year, caused by the upper stages left in orbit). Our conclusion was that, if the debris prevention measures are adopted, the LEO population evolution is not much affected by the launch of the simulated constellations. There is a growth in the flux of objects in the already crowded LEO altitude bands and a correspondingly higher collision probability, but, over the investigated 100-year time span, the evolution is similar in the cases with and without the constellations. On the other hand, the non-adoption of the mitigation measures causes the earlier onset of collisional events, especially if the upper stages left in orbit are not passivated and, therefore, remain prone to explode.

5. ACKNOWLEDGMENTS

SDM, STAT and CLDSIM were developed under the ESA/ESOC contract No. 10034/92/D/IM(SC) with the Consorzio Pisa Ricerche. L.A., C.P. and A.R. contributed to this paper in the framework of the cooperation agreement between CNUCE/CNR and ASI.

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