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REVIEW OF PAST ON-ORBIT COLLISIONS AMONG CATALOGED OBJECTS AND EXAMINATION OF THE CATASTROPHIC FRAGMENTATION CONCEPT

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By mid 2013, four accidental hypervelocity collisions among cataloged objects have been recorded in low Earth orbit. Three were debris-intact impacts, generating very few cataloged fragments (< 10, in total), while one involved the collision between two intact spacecraft, one of which maneuverable, with the consequent production of > 2000 cataloged fragments. In order to evaluate the past, current and future average collision rates, the results of debris evolution simulations carried out in 1999-2000 were carefully re-analyzed and the corresponding collision rates, among objects > 10 cm, were estimated from 1980 to 2040. The value predicted for mid 2013, 0.240 events per year, was further validated by analyzing the current unclassified debris catalog and assessing its qualitative and quantitative incompleteness. It was also found that the intact-intact average collision rate is approximately 30% of the total, while debris-debris impacts account for < 2%, the majority of the events involving debris-intact collisions. The potential benefits of a wide adoption of collision avoidance practices for maneuverable spacecraft was analyzed as well. If applied to 50% of the current operational spacecraft below 2000 km, it would lead to an 11% reduction of the overall collision rate and to a 16% reduction of the intact-intact collision rate. The model estimates from 1980 to mid 2013 were then used to compute the probability of collision occurrence as a function of the time interval considered. It was found that the number of accidental collisions observed so far is in extremely good agreement with the model predictions, corresponding to the maximum likelihood of the probability distributions. Moreover, even the proportion between debris-intact and intact-intact events reflects well what should be expected. Concerning the projections up to 2040, the probability of avoiding further collisions is < 1%, while there is a probability of more than 50% of having 8 additional collisions, or more. Focusing the attention on the intact-intact events, the probability of avoiding another intact-intact collision is around 8%. At least 1 further collision will have therefore a probability to occur higher than 90%, 2 or more collisions will have a probability higher than 70%, and 3 or more collisions will have a probability higher than 45%, even though the broad adoption of collision avoidance for maneuverable spacecraft might reduce these figures. Finally, the concept of catastrophic collision was re-analyzed, taking into account the observational record and the basic assumptions usually adopted by the long-term debris evolution models. Potential sources of collision fragments over- and underestimation were identified and discussed, coming to the preliminary conclusion that after one century the number of collision fragments currently predicted by the evolutionary models might be overestimated.

I. INTRODUCTION

The intentional and accidental collisions involving artificial satellites in recent years have captured worldwide attention well outside the borders of the orbital debris community, raising a growing interest in topics like sustainable space activities, possible exponential growth of the fragments able to destroy intact spacecraft and rocket bodies, and active debris removal. The increasing awareness and concern led to a number of policy, research and operational initiatives at United Nations, international and national levels.

It is certainly a fact that during the last three decades, in spite of a progressively broader adoption of mitigation measures, the number of objects tracked around the Earth has grown by a factor 4.5. Part of this increase (~ 1/4) was due to the improving sensitivity of the space surveillance sensors, but most of it (~ 3/4) represented a real proliferation of objects, of which approximately 50% were generated in just two catastrophic collisions, one intentional and one accidental. It is also true, from a mathematical point of view, that the debris population in Low Earth Orbit (LEO) above 700 km is intrinsically instable, due to collisional dynamics and to the relative inefficacy of air drag in removing intact objects and fragments[1]. However, from a practical point of view, the evaluation of the time scale(s) characterizing the expected pace of debris growth is of fundamental importance to factor in the operational impact, the technological advances, the economic consequences, and the need of remediation measures.

Apart from the uncertainty of future launch traffic and space technology, the predictions of the current long-term evolutionary models are strongly affected by a number of critical assumptions concerning the definition of catastrophic collision, the fragmentation threshold, the collision geometry, and the mass, area and velocity distributions of the fragments. Any change in this set of hypotheses might have significant consequences on the time scale(s) of debris growth and this explains the current renewed interest in satellite breakup tests carried out on the ground. Even if the numbers involved are still too low, some insight can also be derived by revisiting the documented collisions already occurred in orbit. For instance, it is intriguing to remark that among the four accidental collisions recorded so far among cataloged objects, only one was truly catastrophic, but involved a maneuverable spacecraft, so it was, at least in principle, avoidable. This paper addresses the definition and expected relative frequency of catastrophic collisions and other hidden uncertainties of long-term evolutionary model forecasts.

II. ON-ORBIT ACCIDENTAL COLLISIONS

As of July 2013, four accidental hypervelocity collisions in space involving cataloged objects have been recorded[2]. In the following, each event is listed in chronological order[3,4]:

COSMOS 1934 Spacecraft (1991)

Object 1: Cosmos 1934 – Mass: 800 kg
Object 2: Cataloged debris 13475 – Mass: ~ 0.6 kg
Impact date: 23 December 1991
Impact altitude: 980 km
Impact velocity: 14.3 km/s
Energy-to-mass ratio: 7.66×10^4 J/kg
New cataloged debris generated: 2

CERISE Spacecraft (1996)

Object 1: Cerise (spacecraft) – Mass: 50 kg
Object 2: Cataloged debris 18208 – Mass: ~ 4.5 kg
Impact date: 24 July 1996
Impact altitude: 685 km
Impact velocity: 14.8 km/s
Energy-to-mass ratio: 8.30×10^6 J/kg
New cataloged debris generated: 1

THOR BURNER 2A Rocket Body (2005)

Object 1: DMSP 5B F5 Thor Burner 2A – Mass: 50 kg
Object 2: Cataloged debris 26207 – Mass: ~ 2.1 kg
Impact date: 17 January 2005
Impact altitude: 885 km
Impact velocity: 5.7 km/s
Energy-to-mass ratio: 6.28×10^5 J/kg
New cataloged debris generated: 6

COSMOS 2251 & IRIDIUM 33 Spacecraft (2009)

Object 1: Cosmos 2251 – Mass: 900 kg
Object 2: Iridium 33 – Mass: 560 kg
Impact date: 10 February 2009
Impact altitude: 789 km
Impact velocity: 11.6 km/s
Energy-to-mass ratio: 1.59×10^7 J/kg
New cataloged debris generated: 2199

All the events were characterized by an energy-to-mass ratio greater than 40,000 J/kg in the center-of-momentum frame, so were potentially able to completely destroy the bodies involved in the collisions, leading to the generation of many fragments[5]. However, 3 accidental collisions out of 4 created less than 10 additional cataloged debris in total, probably because the impacts occurred relatively far away from the centers of mass and/or involved loose structures or appendages, as the gravity gradient boom cut in the event involving the Cerise spacecraft.

Only one accidental collision with a truly catastrophic debris production has occurred so far, i.e. the sole involving the impact of two intact objects, the Iridium 33 and Cosmos 2251 spacecraft[4]. It was also the only accidental collision involving a maneuverable spacecraft (Iridium 33), as well as an abandoned satellite (Cosmos 2251), so it might have been avoided with an effective collision avoidance service in place.

III. ON-ORBIT COLLISION RATE

In 1999-2000, a detailed analysis was carried out for the European Space Agency (ESA), in order to investigate the orbital debris long-term evolution with an updated initial population (CODRM-99)[6] and an improved version of the Semi-Deterministic Model for Space Debris Mitigation assessment (SDM 2.0)[7,8]. Nearly 15 years after the reference epoch of 1 January 1999, the initial population of debris larger than 10 cm, built using the unclassified US catalog, but also including additional simulated objects, to take into account classified missions and to be consistent with a catalog incompleteness close to 90% in between 10 and 15 cm, 50% in between 15 and 20 cm, and 10% in between 20 and 50 cm, proved to be quite accurate, and so was its evolution, in the following 15 years, as simulated by SDM 2.0 with the traffic model adopted at that time[6,7,8].

Even though the analysis was focused on the long-term evolution and the relative effectiveness of various mitigation measures, the short-term predictions, over the time span (~ 15 years) elapsed since the simulations were carried out, are very useful for an a posteriori check between modeled estimates and the actual environment. This is particularly true for the rate of occurrence of mutual collisions among objects larger than 10 cm, specifically in LEO, and its temporal evolution for a few decades around the present epoch.

Year	Mean collision rate (year^{-1})	Mean interval between collisions (years)
1980.0	0.053	18.9
1990.0	0.107	9.3
1999.0	0.160	6.3
2010.0	0.227	4.4
2013.5	0.240	4.2
2020.0	0.267	3.7
2030.0	0.320	3.1
2040.0	0.387	2.6

Table 1: Predicted mean collision rate in LEO among objects larger than 10 cm (initial simulation epoch: 1 January 1999; backward extrapolation to 1980).

Table 1 summarizes the results obtained in 2000[7] for the expected average collision rate evolution in LEO among objects larger than 10 cm. The initial epoch of the simulation was 1 January 1999 (1999.0), while the present epoch is the beginning of July 2013 (2013.5). Moreover, it was quite easy to extrapolate backward the results obtained, to 1990.0 and 1980.0. It is clear that during the last 30 years, in spite of the progressive adoption of some mitigation measures, the collision risk in LEO increased by a factor 4.5, nearly exactly matching the corresponding increase of cataloged objects recorded in the same period of time.

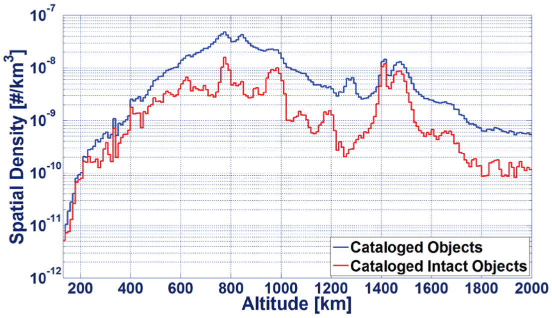

Fig. 1: LEO spatial density of unclassified cataloged objects and cataloged intact objects (spacecraft and rocket bodies), as of 8 July 2013.

In order to further check the results presented in Table 1, a totally independent estimate for the current collision rate was obtained in the following way. Figure 1 shows the present spatial density ρ in LEO of unclassified cataloged objects and cataloged intact bodies, i.e. spacecraft and rocket bodies. Using the same database, the spatial densities averaged over 10 altitude shells 200 km wide are presented in Figure 2. From the latter, average object fluxes in each altitude shell can be easily estimated by taking into account that in LEO the average relative velocity v_R among the cataloged objects is ≈ 10 km/s[9,10].

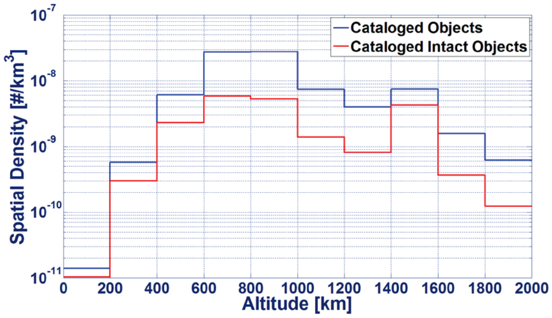

Fig. 2: LEO spatial density, averaged over 200 km altitude shells, of unclassified cataloged objects and cataloged intact objects (spacecraft and rocket bodies), as of 8 July 2013.

Two distinct populations of objects were therefore considered: intact objects, whose average mass was estimated to be ≈ 950 kg[11], and fragments, obtained by subtracting the intact objects from the cataloged ones. Assuming spherical shapes, the average radius of the fragments was assumed to be $r_D \approx 10$ cm, in agreement with simulated distributions[6,7], while for the intact bodies the following classical relationship was used[12]:

$$M = 62.013\, A^{1.13} \quad [1]$$

where M is the object mass, in kg, and A is the area, in m^2. This led to a mean intact object radius $r_I \approx 1.9$ m.

In each altitude shell, the expected average collision rate CR among the objects of the two populations was then estimated for the three possible combinations, i.e. intact-intact (I–I), debris-intact (D–I) and debris-debris (D–D), using the following relations[7]:

$$CR_{I-I} = 4\pi r_I^2 \frac{\rho_I v_R (\rho_I V - 1)}{2} \quad [2]$$

$$CR_{D-I} = \pi (r_D + r_I)^2 \rho_D v_R \rho_I V \quad [3]$$

$$CR_{D-D} = 4\pi r_D^2 \frac{\rho_D v_R (\rho_D V - 1)}{2} \quad [4]$$

where V is the volume of the considered altitude shell. By repeating the computation for each of the 10 altitude shells in LEO, using the appropriate values for the object spatial densities and shell volume, the total collision rates obtained summing up all the shell contributions are presented in Table 2.

The current average collision rate, estimated and presented in Table 2, is about 70% of the value predicted since 2000 and listed in Table 1, so the agreement is quite satisfactory if all the uncertainties, model assumptions and simplifications are taken into account. However, the picture offered by Table 2 is still underestimated for the following reasons:

1. There are several thousand objects tracked by the US surveillance network not included in the catalog, just because their nature and/or origin are unknown. According to the figures released by the Joint Space Operations Center, the overall incompleteness of the catalog is approximately 40%;
2. The unclassified catalog used to estimate the values presented in Table 2 does not include several hundred spacecraft, rocket bodies and mission related objects belonging to military and intelligence space missions carried out by the United States and some other allied countries. For instance, concerning the current operational spacecraft in LEO (523, as of 1 June 2013[13]), approximately 10% are not included in the public catalog.

Type of collision	Mean collision rate (year^{-1})	Mean interval between collisions (years)	Fraction of total collision rate (%)
I–I	0.0624	16.0	37.41
D–I	0.1028	9.7	61.63
D–D	0.0016	625	0.96
Total	0.1668	6.0	100

Table 2: Estimated mean collision rate in LEO among unclassified cataloged objects (8 July 2013).

Type of collision	Mean collision rate (year^{-1})	Mean interval between collisions (years)	Fraction of total collision rate (%)
I–I	0.0755	13.2	31.87
D–I	0.1583	6.3	66.82
D–D	0.0031	323	1.31
Total	0.2369	4.2	100

Table 3: Estimated mean collision rate in LEO among objects larger than 10 cm (mid 2013).

If these facts are taken into account, increasing by 40% the number of debris and by 10% the number of intact objects in LEO, the results of Table 2 should be modified as shown in Table 3. After this corrective action, the agreement between the estimated current collision rate, given in Table 3, and the value predicted since 2000, given in Table 2, becomes extremely good, but this is not surprising because, as already mentioned, the initial population of objects larger than 10 cm adopted on 1 January 1999 was truly realistic and the simulations carried out with SDM 2.0 matched very well the overall evolution of the debris environment observed in the following 15 years.

Looking at Tables 2 and 3, it is also worth mentioning the relative frequency of the different types of collisions. Debris-debris impacts should be quite unusual, around 1% of the total, while debris-intact collisions should account, on the average, for about 2/3 of the events. Of particular relevance is the expected rate of collision among intact objects, approximately 1/3 of the total, because the future evolution of the environment will be mainly driven by such incidents[14]. These results also confirm the relevance of debris conjunction assessment and collision avoidance maneuvers for the operational spacecraft in LEO, presently constituting about 17% of the intact objects residing below the altitude of 2000 km. However, even though very high implementation percentages might certainly lead to significant reductions in the intact-intact (up to ≈ 31%) and debris-intact (up to ≈ 17%) collision rates, no dramatic reversal of the situation would be possible without the active removal of large abandoned intact objects[11,15], as shown in Tables 4 and 5.

Type of collision	Mean collision rate (year^{-1})	Mean interval between collisions (years)	Fraction of total collision rate (%)
I–I	0.0632	15.8	29.94
D–I	0.1448	6.9	68.59
D–D	0.0031	323	1.47
Total	0.2111	4.7	100

Table 4: Estimated mean collision rate in LEO among objects larger than 10 cm if 50% of the operational spacecraft execute collision avoidance maneuvers (mid 2013).

Type of collision	Mean collision rate (year^{-1})	Mean interval between collisions (years)	Fraction of total collision rate (%)
I–I	0.0520	19.2	27.88
D–I	0.1314	7.6	70.46
D–D	0.0031	323	1.66
Total	0.1865	5.4	100

Table 5: Estimated mean collision rate in LEO among objects larger than 10 cm if 100% of the operational spacecraft execute collision avoidance maneuvers (mid 2013).

IV. COMPARISON BETWEEN COLLISION PREDICTIONS AND OBSERVATIONS

Having substantially validated the average collision rate predictions presented in Table 1 up to the present epoch (2013.5), such results have been used to estimate the expected number of collisions according to the probability theory. If $CR{\cdot}\Delta t$ is the mean number of collisions expected in the time interval Δt, the probability $P(k)$ of having exactly k collisions occurring during Δt can be estimated with the Poisson distribution[16]:

$$P(k) = \frac{(CR \cdot \Delta t)^k \, e^{-CR\cdot\Delta t}}{k!}\,. \qquad [5]$$

In Table 6, the probabilities found by integrating up to now the estimated collision rates since 1980, 1990 and 1999 are summarized. These predictions are in extremely good agreement with the observational evidence presented in Section II, with 4 accidental collisions recorded since 1980 (probability of 17.9%), 4 recorded since 1990 (probability of 19.5%) and 2 recorded since 1999.0 (probability of 23.1%). In each time interval, the observed number of collisions corresponds to the probability maximum of the applicable Poisson distribution. Even the observed ratio between intact-intact and debris-intact collisions (1/3) is compatible with the results outlined in Section III. Therefore, the observational data further support, at least so far, the extrapolated and predicted collision rates presented in Table 1.

Number of collisions k	Probability (%) since 1980.0 (33.5 yrs)	Probability (%) since 1990.0 (23.5 yrs)	Probability (%) since 1999.0 (14.5 yrs)
0	0.7	1.7	5.5
1	3.6	6.9	16.0
2	8.9	14.1	23.1
3	14.6	19.2	22.4
4	17.9	19.5	16.2
5	17.5	15.9	9.4
6	14.3	10.8	4.5
7	10.1	6.3	1.9
8	6.2	3.2	0.7
9	3.4	1.5	0.2

Table 6: Probability of occurrence of k collisions among objects larger than 10 cm in LEO, up to 2013.5, respectively since 1980.0, 1990.0 and 1999.0.

V. EXPECTED MID-TERM COLLISION ACTIVITY

Having further validated the average collision rate predictions, up to the present epoch, and backward extrapolations, down to 1980, thanks to the observed collision record, the forecasts shown in Table 1 may also be used to look at the next quarter of century, in order to figure out the expected evolution of the collision activity in LEO.

Table 7 shows the collision probabilities among objects larger than 10 cm in LEO, respectively from now (mid 2013) to 2030, and from now to 2040. It is evident that the probability to avoid further collisions in the time spans considered is quite small (≤ 1%); moreover, there is a probability around 50% of having 5 further collisions, or more, by 2030 and 8-9 collisions, o more, by 2040.

Number of collisions k	Probability (%) up to 2030.0 (next 16.5 yrs)	Probability (%) up to 2040.0 (next 26.5 yrs)
0	1.0	0.0
1	4.6	0.2
2	10.5	0.9
3	16.2	2.4
4	18.7	4.9
5	17.3	8.1
6	13.3	11.3
7	8.8	13.4
8	5.1	13.9
9	2.6	12.8
10	1.2	10.6
11	0.5	8.0
12	0.2	5.6
13	0.1	3.6
14	0.0	2.1
15	0.0	1.2
16	0.0	0.6
17	0.0	0.3
18	0.0	0.1

Table 7: Probability of occurrence of k collisions among objects larger than 10 cm in LEO, from now up to 2030.0 and 2040.0.

Concerning the much more dramatic intact-intact collisions, the probabilities of occurrence, presented in Table 8, have been estimated as well using the predicted collision rates listed in Table 1, but assuming a relative collision rate of 30%, compared to the total rate for objects larger than 10 cm. From now to 2030 there is a probability of 25% to avoid another intact-intact collision in LEO, but there is a probability of 35% to have 1 additional collision and a probability of 40% to have 2 collisions or more. If the temporal horizon is extended to 2040, just more than a quarter of century in the future, the probability to avoid an intact-intact collision decreases to around 8%. At least 1 further collision will have therefore a probability to occur higher than 90%, 2 or more collisions will have a probability higher than 70%, and 3 or more collisions will have a probability higher than 45%.

Number of collisions *k*	Probability (%) up to 2030.0 (next 16.5 yrs)	Probability (%) up to 2040.0 (next 26.5 yrs)
0	25.0	8.3
1	34.7	20.6
2	24.0	25.7
3	11.1	21.3
4	3.8	13.3
5	1.1	6.6
6	0.2	2.8
7	0.0	1.0
8	0.0	0.3
9	0.0	0.1
10	0.0	0.0

Table 8: Probability of occurrence of k collisions among intact objects in LEO, from now up to 2030.0 and 2040.0, assuming a relative collision rate of 30% compared to the total rate for objects larger than 10 cm.

These results show that, in spite of a progressively broader adoption of mitigation measures, as on-orbit explosion prevention and limited release of mission related objects, already included in the analysis leading to the predictions listed in Table 1[7,8], the mutual collisions in LEO among objects larger than 10 cm and among intact bodies will become more and more frequent in the coming decades. The possible widespread adoption of post-mission lifetime limitation for spacecraft and rocket bodies, following the 25 years disposal rule recommended by the Inter-Agency Space Debris Coordination Committee (IADC)[17], might certainly have beneficial long-term effects, but would not be able to significantly improve the situation in the coming quarter of century, due to the time scales involved. As shown in Section III, an important contribution to the collision probability reduction might come from the broad implementation of collision avoidance practices among the operators of maneuverable spacecraft, possibly cutting by almost 30% the average expected number of intact-intact collisions and by approximately 15% the average expected number of debris-intact collisions. However, even with these relevant contributions, the collision rates in LEO would be destined to increase anyway in the next quarter of century.

VI. CATASTROPHIC COLLISIONS

The concept of "catastrophic collision" is very important for the modeling community involved in the analysis of the long-term evolution of the orbital debris environment. It generally identifies an event involving the impact of two orbiting objects with an energy-to-mass ratio in the center-of-momentum frame higher than a given threshold, able to guarantee the complete fragmentation of the two bodies. Usually the critical threshold is assumed to be 40,000 J/kg, based on tests and analyses carried out in the past[5], but the actual situation might be more complex, due to basic structural differences between rocket bodies and spacecraft, and among spacecraft as well. The above mentioned definition also implicitly assumes a "nearly central" impact, i.e. a collision geometry able to guarantee a strong mechanical coupling between the objects, in order to effectively transform the original kinetic energy into internal mechanical and thermal stresses leading to the complete fragmentation of the impacting bodies.

The resulting fragment distribution is approximated by empirical equations, like the widely used NASA standard breakup model[18,19]:

$$N(L_c) = 0.1 M^{0.75} L_c^{-1.71} \qquad [6]$$

where $N(L_c)$ is the number of collision fragments of a given characteristic size L_c (m), or larger, and M (kg) depends on the type of collision. If a collision is catastrophic, i.e. the energy-to-mass ratio in the center-of-momentum frame is higher than the critical threshold, then

$$M = M_t + M_p \qquad [7]$$

where M_t and M_p represent, respectively, the target and projectile mass (by convention, the most massive body involved in the collision is called "target", while the smallest one is called "projectile"). On the contrary, for a non-catastrophic collision, i.e. when the energy-to-mass ratio in the center-of-momentum frame is lower than the critical threshold, the following relationship applies for the total mass (kg) to be fragmented:

$$M\,[\mathrm{kg}] = M_p\,[\mathrm{kg}] \cdot (v_{imp}\,[\mathrm{km/s}]/1\,[\mathrm{km/s}])^2 \qquad [8]$$

where v_{imp} (km/s) is the relative impact velocity. The NASA standard breakup model was empirically developed from 1980s on-orbit satellite breakup events and the Satellite Orbital Debris Characterization Impact Test (SOCIT) series, carried out on the ground in early 1990s. It adopts different area-to-mass distributions for rocket bodies and for spacecraft, but the same distributions for explosions and collisions[18,19,20].

Looking at the accidental collisions recorded so far in LEO, listed in Section II, all the events were potentially characterized by an energy-to-mass ratio in the center-of-momentum frame greater than 40,000 J/kg, so might (or should) have induced the "catastrophic" breakup of both projectile and target. However this occurred only in the case of the intact-intact collision, leading to the creation of 80% more cataloged objects than predicted by the NASA standard breakup model. In the previous three cases, the total number of new cataloged objects generated by the impacts (9) was two orders of magnitude less than the NASA breakup model predictions for catastrophic collisions (974), while the application of the non-catastrophic option would lead to absolute nonsense, with 1213 fragments larger than 10 cm.

The outcome of the accidental collisions recorded so far and the analyses presented in the previous sections suggest the following conclusions:

1. Contrary to what is stated elsewhere[2], the current spherical representations of the orbital objects for debris cross section estimation are quite accurate in predicting the correct collision rates among cataloged objects;
2. However, the object shapes, with loose structures or appendages, like solar panels, antennae and booms, have a critical influence on the outcome of collisions, transforming a potentially catastrophic event, with the creation of hundreds of fragments, in minor incidents, at least as far as the orbital debris environment is concerned (this, again, is in contrast to what is stated elsewhere[2]);
3. Therefore, the critical impact cross section leading to catastrophic collisions, in particular during the debris-intact events, might be significantly smaller than the overall impact cross section, possibly by more than a factor 2, on the average. This might also be true for the intact-intact events, even though the average scaling factors would probably be smaller.

If these conclusions are correct, the models used worldwide to simulate the long-term evolution of the orbital debris environment might correctly estimate the expected number of collisions among objects larger than 10 cm, but at the same time might significantly overestimate the expected number of catastrophic collisions, because the sole check on the event energy-to-mass ratio is not sufficient to predict the outcome of the impact without a knowledge of the target critical cross section, as clearly shown by the observational record.

Due to the fact that in the long-term simulations the catastrophic collision fragments act as feedback impactors, leading to further catastrophic collisions and dominating, after a few decades, the evolution of the environment[14], any uncertainty in the expected number of catastrophic collisions in LEO has important consequences on the prediction reliability of the long-term evolution models. Therefore, a statistically improved knowledge of the relationship between overall impact cross section and critical cross section for catastrophic collision would be of paramount importance. If, on the other hand, the catastrophic intact-intact events are less affected by such effective cross section reduction, being the far future environment dominated by the debris from intact-intact catastrophic collisions[14], the predictions of the long-term evolution models might remain qualitatively valid, with a reduction around 30% in the total number of collision fragments larger than 10 cm after one century[14].

Another aspect of the problem not usually addressed is that, from a debris generation point of view, a collision might be in principle "catastrophic", irrespective of the value of the energy-to-mass ratio. Even if such events have not yet occurred in space, it is easy to conceive situations with an energy-to-mass ratio significantly lower than 40,000 J/kg in which the impact would be anyway able to generate several hundred sizable fragments. Let consider, for example, a large spacecraft, with a total mass of 8 metric tons, made of different structural modules fixed together. The impact on the body of the spacecraft of a debris with a mass of 1 kg and a relative velocity of 10 km/s (quite typical in LEO) would provide an energy-to-mass ratio in the center-of-momentum frame of just 6248 J/kg, well below the commonly accepted critical threshold for a catastrophic fragmentation. By applying Eqs. [6] and [8] of the NASA breakup model, the resulting fragmented mass would be, in fact, just 100 kg (out of a total of 8001 kg), distributed in 162 debris larger than 10 cm. However, this simple modeling picture is clearly not realistic, because the impact of a 1 kg debris on a 1 metric ton module of the spacecraft will be probably "felt" by the structure of the module in a catastrophic way, with an effective energy-to-mass ratio of nearly 50,000 J/kg, while the other parts of the spacecraft, being mechanically decoupled from the point of view of the collision, will be left basically unscathed. Such revised "catastrophic" collision, by applying Eqs. [6] and [7] to the 1 metric ton module, would therefore result into the fragmentation of a mass of 1001 kg (out of 8001 kg), with the generation of 913 debris larger than 10 cm.

Concerning the consequences for the environment, catastrophic collisions should be therefore considered those able to generate several hundred debris larger than 10 cm, irrespective of the impact energy-to-mass ratio. In other words, non-compact spacecraft of large mass with a modular structure might be involved in catastrophic collisions even though the projectile masses were too low, and the impacts were not central, involving only one specific structural module.

Another important consequence of such state of affairs is a relatively higher probability of catastrophic collisions involving complex large mass spacecraft. As an example, let consider again the above mentioned 8000 kg spacecraft, placed in a sun-synchronous orbit at an altitude of about 770 km, where the average collision velocity with cataloged debris is about 13 km/s[10]. According to the MASTER-2009 model[21], the flux of debris with a mass of 3.79 kg or higher, able to catastrophically breakup the spacecraft with an overall energy-to-mass ratio of at least 40,000 J/kg, would be approximately 67% of the flux of debris with a mass of 0.47 kg or higher, capable to induce a catastrophic fragmentation event anyway by hitting a 1 metric ton structural module of the spacecraft. Therefore, the strict application of a fixed catastrophic fragmentation threshold to complex massive objects in the long-term debris evolution models might lead to an underestimation of the impact events able to produce several hundred fragments larger than 10 cm.

However, the relatively small numbers of abandoned objects of large mass in LEO and the long-term dominance of the fragments of intact-intact collisions lead to the conclusion that this cause of impact debris underestimation would not be able to significantly compensate the overestimation due to the critical cross section uncertainties previously discussed in this section.

VII. CONCLUSIONS

By mid 2013, four accidental hypervelocity collisions among cataloged objects have been recorded in space. Three were debris-intact impacts, generating very few cataloged fragments (less than 10, in total), while one involved the collision between two intact spacecraft, one of which functional and maneuverable, with the consequent production of more than 2000 cataloged fragments.

Thanks to a careful re-analysis of debris simulation results obtained in 1999-2000, it was possible to reconstruct the expected evolution of the average collision rate among objects larger than 10 cm from 1980 to 2040. The value predicted for mid 2013 was further validated by analyzing the current unclassified debris catalog and by assessing its qualitative and quantitative incompleteness. The results obtained were then used to compute the probability of collision occurrence as a function of the time interval considered, both in the past and in the future.

It was found that the number of accidental collisions observed so far in LEO is in extremely good agreement with the model predictions and also the proportion between debris-intact and intact-intact events reflects what should be expected in terms of probability distribution. The potential benefits, for collision rate reduction, of a wide adoption of collision avoidance practices, applied to maneuverable spacecraft, were also estimated. However, despite the growing adoption of mitigation measures, the collision rates in LEO will continue to increase in the next quarter of century, mainly due to past and current end-of-life disposal practices of spacecraft and upper stages.

Attention was then paid to a re-analysis of the “catastrophic collision” concept, very important for the modeling community involved in the simulation of the long-term evolution of the orbital debris environment. In fact, looking at the record of accidental collisions, all the events were potentially characterized by an energy-to-mass ratio in the center-of-momentum frame greater than the commonly adopted catastrophic breakup threshold. Nevertheless, the three debris-intact collisions did not produce a significant number of fragmentation debris, probably because the non-central impact geometry and/or the objects shapes, with loose structures or appendages, had a critical influence on the outcome of the collisions.

It was accordingly inferred that the critical impact cross section leading to catastrophic collisions, in particular for the debris-intact events, might be significantly smaller than the overall impact cross section. Consequently, the models used to simulate the long-term evolution of the orbital debris environment might correctly estimate the expected number of collisions among objects larger than 10 cm, but might also significantly overestimate the expected number of catastrophic collisions, in particular those involving debris-intact impacts.

On the other hand, a hypervelocity collision involving a non-compact spacecraft of large mass with a modular structure might lead to a catastrophic fragmentation even though the energy-to-mass ratio of the impact were significantly lower than the critical threshold, and the crash geometry were non-central, affecting only one specific structural module. In the long-term debris evolution models, this might lead to an underestimation of the impact events able to produce several hundred fragments larger than 10 cm. However, the preliminary conclusion was that this possible source of debris underestimation is not probably able to seriously compensate the overestimation resulting from the way the critical cross section for catastrophic collisions is usually evaluated in the models.

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IX. REFERENCES

1. Anselmo, L. The long-term evolution of the space debris environment, in: *Proc. of the Third European Conference on Space Debris*, ESA SP-473, Vol. 1, ESA Publications Division, Noordwijk, The Netherlands, 2001, pp. 333-340.
2. Wang, T. Analysis of debris from the collision of the Cosmos 2251 and the Iridium 33 satellites, *Science & Global Security*, 18 (2010) 87-118.
3. Johnson, N.L., et al. History of on-orbit satellite fragmentations, 14th Edition, NASA Johnson Space

Center, Houston, TX, USA, 2008.

4. Pardini, C., Anselmo, L. Physical properties and long-term evolution of the debris clouds produced by two catastrophic collisions in Earth orbit, *Advances in Space Research*, 48 (2011) 557-569.
5. McKnight, D.S. Collision and breakup models: Pedigree, regimes, and validation/verification, Briefing presented to the National Research Council Committee on Space Debris Workshop, Irvine, CA, USA, November 18, 1993.
6. Pardini, C. Model for the initial population, Study Note of Work Package 1, ESA/ESOC Contract on “Space Debris Mitigation: Extension of the SDM Tool”, Consorzio Pisa Ricerche, Pisa, Italy, January 17, 2000.
7. Anselmo, L., et al. Space debris mitigation: Extension of the SDM tool, Final Report of ESA/ESOC Contract No. 13037/98/D/IM, Consorzio Pisa Ricerche, Pisa, Italy, May 5, 2000.
8. Anselmo, L., et al. Effect of mitigation measures on the long-term evolution of the debris population, *Advances in Space Research*, 28 (2001) 1427-1436.
9. Pardini, C., Anselmo, L. Assessing the risk of orbital debris impact, *Space Debris*, 1 (1999) 59-80.
10. Pardini, C., Anselmo, L. Impact risk repercussions on the Iridium and Cosmo-Skymed constellations of two recent catastrophic collisions in space, in: *Progress in Propulsion Physics*, Volume 4, Advances in Aerospace Sciences, EUCASS Book Series, EDP Sciences & Torus Press, Moscow, 2013, pp. 749-762.
11. De Luca, L.T., et al. Active removal of large massive objects by hybrid propulsion module, in: *5th European Conference for Aero-Space Sciences (EUCASS 2013)*, ISBN 978-84-941531-0-5 (DVD), EUCASS, June 2013.
12. Johnson, N.L., McKnight, D.S. *Artificial Space Debris,* Orbit Books, Malabar, FL, USA, 1987.
13. Union of Concerned Scientists. UCS Satellite Database 6-1-13, http://www.ucsusa.org, June 2013.
14. Liou, J.-C. Collision activities in the future orbital debris environment, *Advances in Space Research*, 38 (2006) 2102-2106.
15. De Luca, L.T., et al. Active space debris removal by a hybrid propulsion module, *Acta Astronautica*, (2013) doi: 10.1016/j.actaastro.2013.04.025.
16. Dougherty, E.R. *Probability and Statistics for the Engineering, Computing, and Physical Sciences*, Prentice Hall, Englewood Cliffs, NJ, USA, 1990, pp. 152-157.
17. *IADC Space Debris Mitigation Guidelines*, Document IADC-02-01, rev. 1, Inter-Agency Space Debris Coordination Committee (IADC), 2007.
18. Johnson, N.L., et al. NASA's new breakup model of EVOLVE 4.0, *Advances in Space Research*, 28 (2001) 1377-1384.
19. Krisko, P.H. Proper implementation of the 1998 NASA breakup model, *Orbital Debris Quarterly News*, 15-4 (2011) 4-5.
20. Stansbery, E.G., et al. A comparison of three catastrophic on-orbit collisions, in: *Proc. of the 59th International Astronautical Congress*, Glasgow, Scotland, UK, Paper IAC-08-A6.1.07, 2008.
21. *Meteoroid and Space Debris Terrestrial Environment Reference* (MASTER-2009), ESA-SD-DVD-02, Release 1.0, Institute of Aerospace Systems, Technical University of Braunschweig, December 2010 (updated in November 2012).