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Effects of the deployment and disposal of mega-constellations on human spaceflight operations in low LEO

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ABSTRACT

The substantial space traffic changes occurred since the 2010s are having measurable repercussions even at the altitudes used for human spaceflight. These changes were mainly driven by the deployment of thousands of small satellites and cubesats below 600 km.

After having evaluated how the situation evolved, from 2008 to 2021, at the altitudes of the International and Chinese space stations, and discussed the main aspects of the problem that may have an operational impact, the attention was focused on what might be expected in the 2020s, whether the current deployment plans for mega-constellations will be realized in whole or in part.

Finally, the rationale for the introduction of a “human spaceflight protected region”, with the associated space traffic management recommendations, is presented and discussed.

1. Introduction

In recent years there was a huge increase in the launch rate of small satellites and cubesats in the lowest part of low Earth orbit (LEO), i.e. below 600 km, boosting the number of potentially risky objects to be tracked and monitored. But the most dramatic development currently going on is the deployment of large satellite constellations, with almost 10,000 spacecraft planned only in low LEO in the coming years. Even though any failed satellite of the planned low LEO mega-constellations will decay from orbit in less than a few years, it is realistic to expect a relatively high number of failures, considering the experimental nature of spacecraft tested in space, and in great numbers, for the first time.

The low LEO region will also be significantly affected by the evolution of space activities above 600 km. In fact, several mega-constellations are planned at higher altitudes as well. In order to mitigate the long-term accumulation of objects and the production of new collisional debris in high LEO, the end-of-life disposal of constellation satellites in orbits able to guarantee a relatively fast reentry in the atmosphere is foreseen. This procedure, highly recommended for the orbital debris long-term mitigation in the whole LEO protected region, may however present some temporary drawback in low LEO. In fact, during the operation of mega-constellations in high LEO, a significant number of disposed satellites will cross at any time the low LEO region as well, in a dynamic balance between new end-of-life disposals and atmospheric reentries.

Also worth mentioning are the constellation satellites which, destined for higher operational altitudes, for example 550 km, are initially launched and tested below 320 km. Slowly raising their orbits, with very low thrust and nearly continuous propulsion, these satellites cross the low LEO region and are difficult for third parties to track and avoid.

The consequences of these developments for human spaceflight operations might be far from negligible. In fact, since the last Apollo mission to the Moon, in December 1972, all human spaceflights were carried out in low LEO. In addition to the International Space Station, the large Tiangong space station, to be completed by China in 2022, and the scheduled Indian and private crewed missions will use this region of space as well. This is because circular orbits below 550 km are particularly attractive for human spaceflight, as a convenient energetic gateway to more remote destinations, for the radiation shielding effect of the magnetosphere, and for the relatively easy compensation of atmospheric drag by propulsion, without of course forgetting the favorable logistics and safety aspects. A better attention to this important region of space is therefore well deserved, in order to leave open all future options of human presence outside the Earth.

The purpose of this paper is precisely to highlight what could be the consequences of the spectacular increase in low LEO traffic on human spaceflight, both from the operations and safety points of view. The attention is focused on the two main crewed facilities operating at the beginning of the 2020s, that is the International Space Station (ISS) and the new Chinese Space Station (CSS), whose current orbital parameters, adopted for our analysis, are summarized in Table 1.

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Table 1
Current average orbits of the main crewed facilities (the orbits are assumed circular, and their mean altitude and inclination are measured with respect to the Earth's equator).

Crewed Facility	Mean Altitude (km)	Inclination (°)
CSS	380	41.5
ISS	410	51.6

2. Environmental impact of the new space launch pattern

At the beginning of 2007, the LEO environment was suddenly deeply modified by the intentional destruction of the Fengyun 1C meteorological spacecraft with an anti-satellite impactor fired from the ground. The test generated more than 3400 fragments cataloged by the US Space Surveillance Network (SSN), making it the worst breakup recorded in orbit so far.

Since it is now clear to everyone that similar tests must be avoided in the future, the year 2008 can therefore represent a good starting point for evaluating the current evolution of the debris environment in LEO, both due to unwanted events, such as accidental explosions and collisions, and to how space activities have changed in the meantime. In 2014, in fact, the payload launch pattern began to change, with a progressively increasing number of micro and nanosatellites and the debut, at the end of the decade, of the so-called mega-constellations.

These changes were particularly significant in low LEO, i.e. below 600 km (Fig. 1). Focusing the attention on the current altitudes of ISS and CSS (Table 1), the orbital debris evolution occurred since 2008 is summarized in Figs. 2–6 and was quite similar in both cases. Overall, the density of cataloged objects remained relatively stable for several years since 2008, but began to rise rapidly in 2017 around the orbit of ISS, and from 2019 around the lower orbit of CSS (Fig. 2).

This significant increase – by a factor of three from mid-2008 to mid-2021 – is almost entirely attributable to the launch of new satellites (Fig. 4). The spatial density of abandoned rocket bodies, on the other hand, remained small and relatively stable (Fig. 5), further evidence of the fact that the growing number of satellites was not placed in orbit with a corresponding number of launches, but with many launches involving dozens of small spacecraft at a time.

Finally, as regards the actual cataloged debris pieces, that is breakup fragments plus mission related objects, from 2008 to 2017 they actually decreased, due to the accelerated decay rate of fragments produced

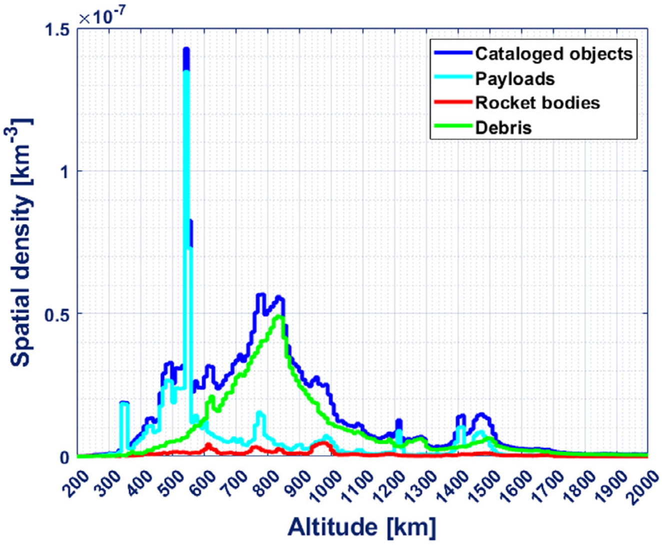

Fig. 1. Object spatial density in LEO, as of 28 June 2021.

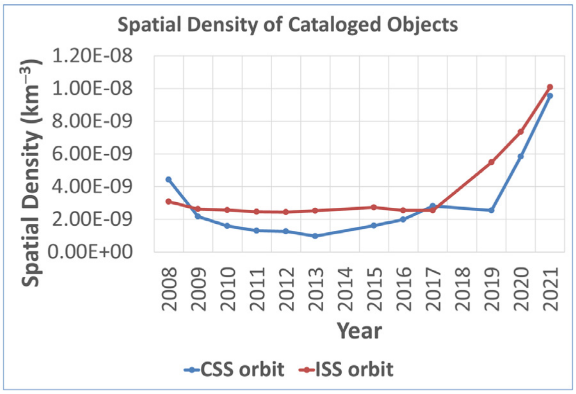

Fig. 2. Evolution of the mean spatial density of cataloged objects at the current altitudes of CSS and ISS.

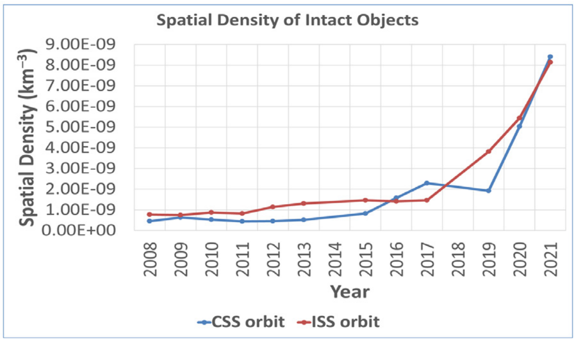

Fig. 3. Evolution of the mean spatial density of intact objects, i.e. payloads + rocket bodies, at the current altitudes of CSS and ISS.

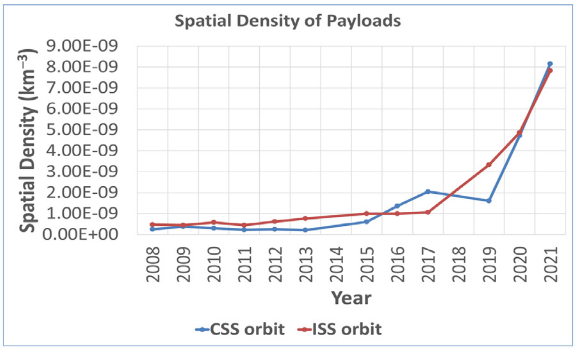

Fig. 4. Evolution of the mean spatial density of payloads at the current altitudes of CSS and ISS.

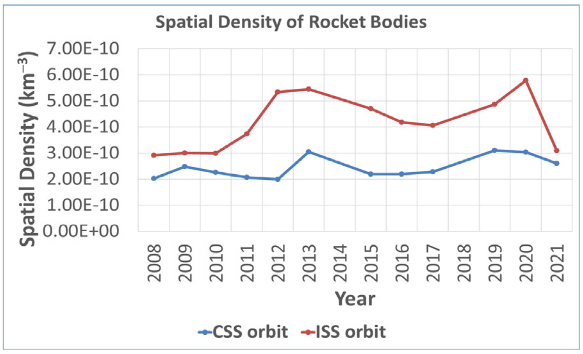

Fig. 5. Evolution of the mean spatial density of rocket bodies at the current altitudes of CSS and ISS.

Table 2
ISS average orbit: mean cross-sectional area flux and velocities of cataloged objects in mid-2013.

Cataloged Object Type	Mean Relative Velocity (km/s)	Mean Collisional Velocity (km/s)	Mean Cross Sectional Area Flux (m^{-2} yr^{-1})
Catalog	8.48	10.30	4.8×10^{-7}
Payloads*	8.06	9.72	1.6×10^{-7}
Rocket Bodies	9.00	10.08	1.2×10^{-7}
Debris Pieces	9.36	10.63	2.0×10^{-7}

* Payloads include the Active Satellites.

Table 3
ISS average orbit: mean cross-sectional area flux and velocities of cataloged objects in mid-2021.

Cataloged Object Type	Mean Relative Velocity (km/s)	Mean Collisional Velocity (km/s)	Mean Cross Sectional Area Flux (m^{-2} yr^{-1})
Catalog	6.59	9.82	2.1×10^{-6}
Payloads*	6.15	9.41	1.5×10^{-6}
Active Satellites	5.60	8.80	1.2×10^{-6}
Rocket Bodies	8.61	10.04	8.4×10^{-8}
Debris Pieces	8.42	10.86	4.8×10^{-7}

* Payloads include the Active Satellites.

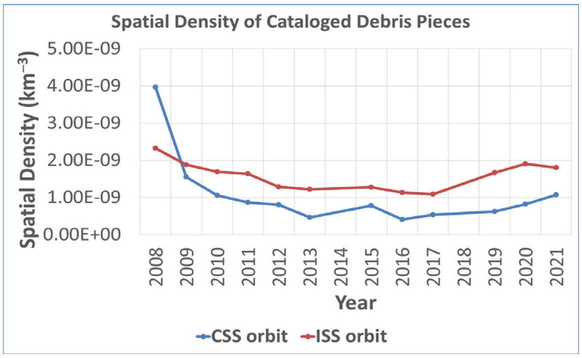

Fig. 6. Evolution of the mean spatial density of cataloged debris pieces at the current altitudes of CSS and ISS.

by fragmentations occurred at higher altitudes earlier in the period, induced by the progression of Solar Cycle 24. Since 2017, even though the minimum of solar activity was rather low, the debris density rebound was very slow, leading to values in mid-2021 lower than in mid-2008 (Fig. 6).

In conclusion, at the current altitudes of the two space stations, the average density of cataloged debris pieces and abandoned upper stages remained basically stable from 2008 to 2021, that is even through the sharp change in satellite launch pattern occurred during the latter half of the period. Nearly all the density increase recorded was therefore due to new spacecraft, many of them with no on-board propulsion, or with limited collision avoidance capabilities [1]. And this trend will be even more pronounced in the next decade [2,3].

3. Estimate of the added conjunction analysis burden

In order to obtain a coarse quantitative estimate of the added conjunction analysis burden caused by the environmental changes occurred around the orbits of ISS and CSS, a specific analysis was carried out using the Space Debris Impact Risk Analysis Tool (SDIRAT), developed at ISTI/CNR [4,5]. The attention was focused on two epochs: mid-2013, i.e. before the onset of the new satellite launch pattern, and mid-2021. The results obtained are summarized in Tables 2–5. (Being the flux of objects proportional to their relative velocity, the average collision velocity is higher than the relative one, since the faster the potential impactors are, the more they contribute to the incident flux [4].)

At the altitude and inclination of the ISS, the mean cross-sectional area flux of cataloged objects increased more than four times, from mid-2013 to mid-2021, mainly driven by a nearly tenfold boost in the flux of payloads (Tables 2 and 3).

The mean flux of rocket bodies dropped instead by 30%, while the flux of cataloged debris pieces, the main component back in 2013, only grew 2.4 times in the meantime, accounting now for less than a quarter of the total. In 2013, payloads (33%), rocket bodies (25%) and cataloged debris pieces (42%) contributed to the mean cross-sectional area flux with comparable values, while now, in 2021, payloads are dominant (73%), with a large contribution from active satellites (57%), followed by cataloged debris pieces (23%) and rocket bodies (4%).

The population change is also reflected in the evolution of the mean relative velocity of cataloged objects vs. the ISS. Overall it decreased by more than 20%, again due mainly to the large number of new payloads, many of which launched near the height of the station with a distribution of orbits such as to reduce the average relative speed.

Obviously, it is not immediate to translate a growth in average object flow into a corresponding increase in the number of evasive maneuvers necessary to guarantee the safety of the ISS. For example, there may be a large number of satellites just above or below the ISS that do not present a significant collision risk, the orbits being well known and possibly controlled. What matters, specifically, are the objects that cross the station's orbit, a consequence not only of traffic and possible breakups, but also of solar activity, which determines the decay rate of objects flying higher without orbit maintenance. Moreover, the frequency of collision avoidance maneuvers is influenced by the applicable flight rules, by operational constraints and by the accuracy of conjunction assessments [6].

Between 1999 and 2020 the ISS carried out 28 collision avoidance maneuvers and in one further case it was a NASA satellite – the Global Precipitation Measurement (GPM) spacecraft – that maneuvered to prevent a high risk conjunction in 2017 [6,7]. The maneuver rate was clearly correlated with solar activity and the number of tracked objects crossing the station's orbit, peaking during the last solar maxima of cycles 23 and 24 [6].

Currently the tracked crossing objects are more than 1200, just 10% more than in 2013–2014, during the solar maximum of Solar Cycle 24, and in 2020 there were three collision avoidance maneuvers, after four years of solar activity minimum marked only by that one of the GPM spacecraft [6]. As solar activity is growing again, it is very likely to expect, between 2022 and 2026, a significant increase of the number of tracked crossing objects, coming from the large "reservoir" created

Table 4
CSS average orbit: mean cross-sectional area flux and velocities of cataloged objects in mid-2013.

Cataloged Object Type	Mean Relative Velocity (km/s)	Mean Collisional Velocity (km/s)	Mean Cross Sectional Area Flux (m^{-2} yr^{-1})
Catalog	7.80	9.38	3.9×10^{-7}
Payloads*	6.45	8.07	1.1×10^{-7}
Rocket Bodies	7.97	8.88	1.0×10^{-7}
Debris Pieces	8.27	9.34	1.7×10^{-7}

* Payloads include the Active Satellites.

Table 5
CSS average orbit: mean cross-sectional area flux and velocities of cataloged objects in mid-2021.

Cataloged Object Type	Mean Relative Velocity (km/s)	Mean Collisional Velocity (km/s)	Mean Cross Sectional Area Flux (m^{-2} yr^{-1})
Catalog	6.59	8.66	2.0×10^{-6}
Payloads*	6.36	8.38	1.6×10^{-6}
Active Satellites	6.00	7.97	1.4×10^{-6}
Rocket Bodies	8.62	9.48	7.1×10^{-8}
Debris Pieces	8.21	9.84	2.8×10^{-7}

* Payloads include the Active Satellites.

above the station by old and new launches. This will inevitably lead to a heightened burden on the whole conjunction analysis process.

The first element of the new Chinese Space Station was launched in 2021, therefore its operational history is only now beginning. Tables 4 and 5 then present how the situation has changed for an orbit with its height and inclination, from mid-2013 to mid-2021. The mean cross-sectional area flux of cataloged objects increased more than five times, again mainly driven by a nearly 15 times boost in the flux of payloads. Also in this case the mean flux of rocket bodies dropped instead by about 30%, while the flux of cataloged debris pieces, the main component back in 2013, only grew by 65% in the meantime, accounting now for less than 15% of the total.

As for the ISS orbit, in 2013, payloads (29%), rocket bodies (26%) and cataloged debris pieces (45%) contributed to the mean cross-sectional area flux with comparable values, while now, in 2021, payloads are widely dominant (82%), with a large contribution from active satellites (72%), followed by cataloged debris pieces (14%) and rocket bodies (4%). Same as for the ISS orbit, the mean relative velocity of cataloged objects decreased, this time by about 15%, again due mainly to the growing relative contribution of new payloads and their orbital distribution.

Concerning the unclassified cataloged objects crossing the CSS orbit, in mid-2021 they were already more than 800 and are likely to grow significantly as Solar Cycle 25 progresses towards its peak of activity, currently expected between October 2024 and July 2025. In any case, as shown by the number of crossing objects and by the mean cross-sectional area flux given in Tables 3 and 5, the burden on conjunction analysis anticipated for the CSS is equivalent to that for the ISS, despite the lower height and inclination of the former.

4. Impact of new constellations and nanosatellites

The deployment of mega-constellations and the launch of thousands of nanosatellites during the 2020s will have a profound impact on the low LEO landscape. First of all, many mega-constellation spacecraft and most nanosatellites will be placed in orbits below 600 km, in order to be automatically compliant with space debris lifetime guidelines in case of failure or inability to maneuver. By 2030, these developments alone might lead to at least 10,000 satellites packed between the altitude of the International Space Station and 600 km [8].

Secondly, spacecraft reaching the end of their operational life will be deorbited, again for reducing their residual lifetime and freeing up space for new satellites. However, this will involve not only the spacecraft below 600 km, but also those deployed in LEO at greater heights, always to comply with the space debris mitigation requirements [8]. And since in most cases this will be achieved by lowering the perigee of the orbit below the altitudes of the ISS and CSS, but leaving the initial apogee in the vicinity of the operational altitude, it is obvious to conclude that this process will produce and maintain a considerable number of objects crossing the heights of the two space stations.

Therefore, in the coming years, two new components will add to the tracked objects crossing the altitudes of the ISS and CSS: the disposed satellites in elliptical orbits with perigee below and apogee above the operational altitude range of the space stations, and the failed or non-maneuverable satellites decaying from nearly circular orbits just above the stations. For the mega-constellations, following the analysis presented in [9], the contribution of these two components can be roughly estimated in the following way, where the first addendum in the right-hand side of the equation represents the average number of satellites deorbited in elliptical orbits at any time, and the second one expresses the average number of failed satellites decaying at any time through the altitude ranges of the space stations:

$$N_C = (N_A \, / \, L_T) \cdot T_C + N_A \cdot F_R \cdot T_F \qquad (1)$$

In this equation N_C is the average number of constellation satellites crossing the altitude of either the ISS or the CSS at any time, N_A is the total number of active constellation satellites to be maintained above the stations, L_T is the average operational lifetime of the satellites, T_C is the average time needed so that the apogee of the deorbited spacecraft falls below the operational altitude range of the ISS or CSS, F_R is the average failure rate of the satellites, and T_F is the mean time spent by the decaying satellites at the heights of the stations. N_A, L_T and F_R depend on the design of the planned constellations and constituent satellites, while T_C and T_F are also a function of thermospheric drag and, therefore, of solar activity, being minimum at solar cycle maximum and maximum at solar cycle minimum.

Assuming quite conservative values for N_A and L_T, and reasonable mean values for F_R, T_C and T_F [8–10], that is N_A = 10,000, L_T = 5 years, T_C = 0.5 years, F_R = 2% per year and T_F = 0.15 years, we obtain $N_C \approx 1000 + 30 \approx 1030$, to which we must add the downward flux of non-maneuverable small satellites launched in the meantime. Therefore, in the most optimistic scenario conceivable, during the 2020s we could expect a further increase in the number of objects crossing the heights of the two space stations approximately up to 1100, practically doubling the current value. However, an increase of one order of magnitude might be possible as well, if all the plans presented so far were realized [8,9].

According to our SDIRAT simulations, in 2021 we should expect, on average, around 6 close approaches of cataloged objects per year within 1 km of either the ISS or CSS, and an a priori collision probability, excluding any conjunction analysis and avoidance maneuver, of about 1%

per year, or less. These numbers are clearly still low and manageable, that is not such as to disrupt the normal operations and activities onboard the orbital outposts. A doubling of these figures would probably be still acceptable, but an increase of one order of magnitude would certainly be a problem for the orderly and efficient running of a human space program in low LEO.

A significant improvement of tracking accuracy and the application of artificial intelligence to the problem of conjunction analysis might certainly greatly increase the efficiency of the process, dramatically reducing false alarms and the workload of human operators. But a too large growth of the objects to be monitored might partly offset, if not completely cancel, any progress in the efficiency of conjunction analysis and collision avoidance that may have been made in the meantime. This due to new launches, deorbiting and failures, but also to the improving sensitivity of sensors, which will track more and more objects in the 1–10 cm range. Moreover, if the number and frequency of evasive maneuvers exceeded a certain threshold, even assuming that a good fraction of them might be carried out by the satellites that cross the orbits of the stations, the consequences for human activities in orbit could become no longer acceptable.

5. Conclusion

In the mid-2000s, Michael Yakovlev, from the Russian delegation, proposed to the Inter-Agency Space Debris Coordination Committee (IADC) the creation of a special “human spaceflight protected region” below 550 km. The proposal was motivated by the prediction, which turned out to be very accurate, of a dramatic increase in the launch rate of small satellites in such volume of space. Unfortunately, the suggestion did not receive, at that time, the attention it deserved and there have been no further developments in this regard.

Today, human space activities in low LEO are broadening in scope, duration, stakeholders and independent players. At the same time, several mega-constellations of satellites are being deployed or planned, just above or below the altitudes of the International and Chinese space stations, and the number of nanosatellites, many of them non-maneuverable, is skyrocketing. Even though the traffic and the debris environment have clearly worsened in this region of space during the last decade, the operations of the ISS and CSS can still be managed without particularly adverse effects. But the situation is rapidly changing and negative consequences might materialize over the next decade with an impact that is anything but negligible. It is therefore absolutely necessary to act now to ensure the safety, operation and sustainability of human spaceflight in low LEO.

The new measures to be endorsed and applied should transcend the pure aspect of space debris mitigation, focusing instead on space traffic management. At a minimum they should include the following:

(1) The definition of an altitude range, for instance between 350 and 450 km, to be considered as “human spaceflight protected region”.
(2) Unmanned spacecraft deployments should be avoided in this region, but, if absolutely necessary, the satellites must be reliable and maneuverable.
(3) The use of non-maneuverable satellites (as most of cubesats) should be restricted to orbits fully below this region.
(4) The satellites disposed from above should be controlled and maneuverable at least until their decaying orbits stop crossing the protected region.
(5) The operators of the satellites crossing the protected region should maintain a stable communication channel and a standardized information flow with the human spaceflight mission control centers, in order to manage the conjunction assessment process and address the eventual alerts.
(6) In case of high risk conjunctions, the avoidance maneuvers shall be carried out, as a rule, by the unmanned spacecraft.

Apart from the exact definition of the human spaceflight protected region, which must in any case be able to accommodate, in the near future, also Indian and private missions, most of the requirements listed above – specifically No. 2, 4, 5 and 6 – might be, and probably will be, implemented by the mega-constellation operators, like in the case of Starlink vs. ISS. An extension of the appropriate best practices to other operators, and including the CSS as well, besides being very desirable is also quite probable.

The application of the third recommendation might be met, instead, with greater resistance. In fact, the use of cubesats by a multitude of users is widespread and booming, and these nanosatellites can comply with current space debris mitigation guidelines, limiting the orbital lifetime to less than 25 years [11,12], up to 600 km even without propulsion. Below 350 km, on the other hand, their mission lifetime would be severely limited, going from no more than a couple of months around solar activity maximum and no more than 11 months during the minimum of the solar cycle. However, it is also clear than to think of continuing to place, pretending nothing happened, several thousand small and non-maneuverable objects between 450 and 600 km, which would then gradually rain down, without any control, on the region occupied by human space missions, is not the right thing to do. And the sooner this matter is dealt with, the better.

Declarations of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Carmen Pardini: Software, Formal analysis, Data curation, Writing – review & editing, Project administration. **Luciano Anselmo:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

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