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EFFECTS OF THE RORSAT NaK DROPS ON THE LONG TERM EVOLUTION OF THE SPACE DEBRIS POPULATION

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Abstract

Recently the Haystack radar observations led to the detection of a previously unrecognized space debris family, with circular orbits between 600 and 1000 km of altitude and inclinations around 65°. Due to their orbital and physical properties, such particles were tentatively identified by NASA as droplets of liquid sodium-potassium (NaK) coolant leaked from some of the nuclear powered radar ocean reconnaissance satellites launched by the former Soviet Union.

In this paper we investigate the effects of the observed NaK droplets on the long term evolution of the debris population around the Earth. Moreover, the outcome of a possible future accidental loss of sealing in the secondary cooling loop of two specific satellites is analyzed as well.

Because the NaK droplets are not able to induce catastrophic fragmentations of large targets, they do not alter significantly the future debris environment, as far as the possible onset of a collisional chain reaction is concerned. From this point of view, launch and mitigation policies, especially regarding satellite constellations in low Earth orbit, play the dominant role. On the other hand, the NaK droplets cause a significant and long-lasting increase of the rate of cratering events in the 850-1000 km altitude range.

The effects of a new leakage at the lower altitude of Cosmos 1900 would be significant, but short-lived. However, at the altitude of Cosmos 1932, where most of the RORSATs are stored, the adverse effects on the space environment would last for several decades, concealing for a while the long term growth of centimetric particles due to collisional processes.

Introduction

In the last few years the Haystack radar observations led to the detection of a previously unrecognized space debris population, with circular orbits between 600 and 1000 km of altitude (maximum concentration between 850 and 1000 km) and inclinations around 65° [1]. There are 50,000-70,000 such particles larger than 8 mm and a few hundreds larger than 3 cm. The radar signatures of these objects are characteristic of conductive spheres at every measured wavelength and their ballistic coefficients are consistent with mass densities around 1 g/cm^3. Due to their orbital and physical properties, these particles were tentatively identified by NASA's Johnson Space Center as droplets of liquid sodium-potassium (NaK) coolant leaked from one or more of the nuclear powered radar ocean reconnaissance satellites (RORSATs) launched by the former Soviet Union.

Following extensive analyses in the USA and Russia, that hypothesis is now strongly supported by most of the experts who have analyzed the experimental and theoretical evidence available. The origin of this unusual source of space debris can be traced back to the Cosmos 954 malfunction, that led, in January 1978, to the radioactive contamination of a sparsely inhabited area of Northern Canada. To prevent the occurrence of a similar mishap in the future, the Soviets redesigned the RORSATs, developing a way to eject the fuel core from the reactor at the end of the mission [2]. This would ensure the complete burning of the naked fuel core during an accidental reentry in the Earth's atmosphere, as effectively demonstrated five years later by Cosmos 1402.

But the design change affected also the nominal missions (16 up to the program termination in 1988). At the conclusion of each successful flight at low altitude, the nuclear reactor section was boosted up to an 800-900 km graveyard orbit - like before the Cosmos 954 accident - but with the important difference that the fuel core was ejected there in any case. The fuel core separation was accompanied by a loss of sealing in the primary reactor coolant loop, containing 13 kg of liquid NaK [3][4]. Therefore, a leakage of NaK droplets might have, and most probably did, occurred. The secondary reactor coolant loop, with 26 kg of liquid NaK, was designed to maintain, instead, its sealing [3][4].

The purpose of the study described in this paper is to investigate the effects, if any, of the observed NaK droplets on the long term evolution of the debris population around the Earth. The outcome of a possible accidental loss of sealing in the secondary cooling loop for two specific cases is analyzed as well.

Current environment

Besides the 8000-9000 objects larger than 10-20 cm tracked by the US Space Command sensors, the space around the Earth is populated by a very large number of uncatalogued debris, produced over the years and continually replenished by space activities. Millimetric and centimetric particles are particularly interesting because they can severely damage critical spacecraft sub-systems. Most of the experimental data available in that size range comes from dedicated campaigns of radar measurements carried out since 1990.

To understand the origin and distribution of the artificial debris in the 0.1-10 cm size range, a comprehensive analysis and modeling effort has been carried out at CNUCE. A dedicated software system, CLDSIM, was developed, implemented and continually upgraded to simulate the generation and orbital propagation of debris clouds produced by explosions and collisions, using several model and parameter options [5]. Recently, the possibility of simulating the leakage of NaK droplets was introduced as well.

Using CLDSIM, 140 spacecraft and upper stages fragmentations and 16 NaK liquid metal leaks from the post-Cosmos 954 RORSATs in orbit were independently simulated with the most appropriate models and parameters and the resulting debris clouds were propagated - including all the relevant perturbations - to a chosen reference epoch (January 1^{st}, 1997). At this point the population obtained was merged with a revised list of the US Space Command catalogued objects, propagated to the same epoch.

The resulting population, the 1997.0 CNUCE Orbital Debris Reference Model (CODRM-97), includes all the simulated particles larger than 0.9 mm that are still in orbit (more than 52 millions). The total mass obtained is 3431 metric tons, while the overall cross-sectional area is 37,569 m^2; 99.94% of the mass and 99.79% of the cross-sectional area are concentrated in the catalogued population.

Below 2000 km there are, on average, about 72,000 debris larger than 1 cm, including about 14,000 NaK drops. Fig. 1 shows the spatial density as a function of altitude (below 2000 km) for objects larger than 5 mm: the contribution of the RORSAT NaK droplets is evident.

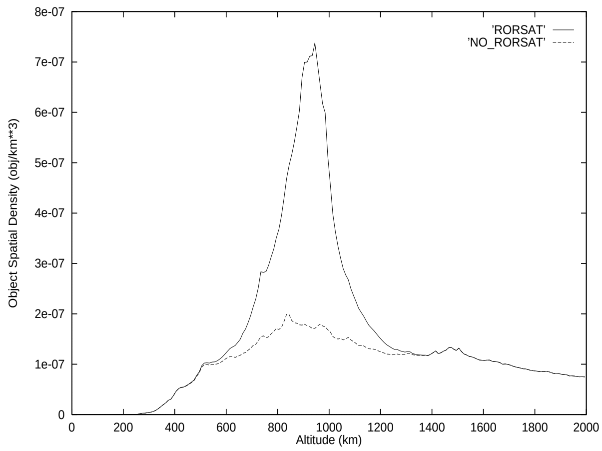

Fig. 1. CODRM-97: spatial density distribution of orbital debris larger than 0.5 cm, with and without the NaK RORSAT droplets.

CODRM-97, with and without the NaK drops contribution, was used to set the initial orbital debris environment for the simulations presented in this paper.

Traffic Model

To simulate for several decades the evolution of the debris population it is necessary to define an appropriate traffic model. Due to policy, financial and technological changes, it is practically impossible to foresee the evolving trend of the international space activities for fifty years or more: at most, a plausible forecast for the next 10 or 20 years can be extrapolated to the following decades.

The hypotheses adopted in this study are quite conservative. For the routine space activity we assumed a constant launch rate (78 per year), with an orbital distribution of payloads and upper stages in agreement with what was observed in the last five years. The payload mass was assumed to increase by only 5% over the next 50 years.

Several commercial constellations in low Earth orbit (LEO) were considered as well, in addition to the routine launch activity. In between 1997 and 2015, the insertion of the following constellations in LEO was assumed: Iridium, Globalstar, Odyssey, Orbcom, Ellipso, Concordia, Ico, Ecco, Teledesic, M-Star and Celestri. Three more constellations, similar to M-Star, were supposed to be launched between 2020 and 2040. The operational life of the constellations was set to range from 20 to 40 years, taking into account the deployment of new generations of spacecraft.

During their operational lifetime, the deorbiting of old satellites was assumed for 7 constellations out of 14; but at the end of the operational phase the remaining spacecraft were left in orbit. All rocket stages used to build the constellations (generally, depending on orbit and mass, more than one payload per rocket was assumed to be launched) were left in space in any case, but passivated in order to prevent explosions.

Our traffic model included also, starting in 1998, the assembly in orbit of the International Space Station. Such a facility, or a replacement, was supposed to stay aloft for the overall duration of the simulations (50 years), serviced by 8 dedicated flights per year.

Explosions and Collisions

Other important sources of space objects are explosions and collisions. The full details of the models used in our simulations are described in [6]. For the study presented here we adopted an explosion pattern (exploding objects, occurrence rates, calibration factors, orbits) based mainly, but not only, on the record of the last five years. The total average explosion rate adopted was 4 per year (2.1 high energy and 1.9 low energy events), decreasing to 3.5 per year by 2005 and to zero by 2010. Therefore, it was supposed that the generalized introduction of measures to prevent accidental and intentional explosions in space will take place in the near future.

To compute the effects of collisions with our model [6], we adopted, for the first time, two different catastrophic disruption thresholds for spacecraft and rocket bodies: 40,000 J/kg and 60,000 J/kg, respectively.

Simulations

To investigate the effects of the RORSAT NaK droplets on the long term evolution of the orbiting debris, we performed twenty 50-year simulations starting in 1997, 10 with ("RORSAT") and 10 without ("NO_RORSAT") the anomalous population of liquid particles. SDM, a powerful software tool developed in Pisa for the semi-deterministic study of the evolution of orbital debris [6], was used to obtain the results presented below. The model options and the input files were set according to the assumptions described in the previous sections. The area/mass relationship chosen for the debris was the classical one adopted by NASA, i.e.:

$$m = \begin{cases} 62.013\, A^{1.13} & \text{if } m \geq 8.04 \times 10^{-5}\text{kg} \\ 2030.33\, A^{1.5} & \text{if } m < 8.04 \times 10^{-5}\text{kg} \end{cases}$$

where m is the mass in kg and A is the area in m^2.

On average, after 50 years, the millimetric population in the RORSAT case resulted to be larger by about 7% with respect to the NO_RORSAT case. However, as shown in Fig. 2, due to the stochastic nature of explosions and collisions and the strong influence of single breakup events, the actual evolution of small particles is clearly predictable only to about a factor of two, and not much affected by the NaK droplets. In other words, the difference observed between single runs using the same initial conditions was much larger than the average difference between simulations including or not the NaK drops. This can also be seen in Fig. 3, where the cumulative number of collisions between objects larger than 1 cm km is shown.

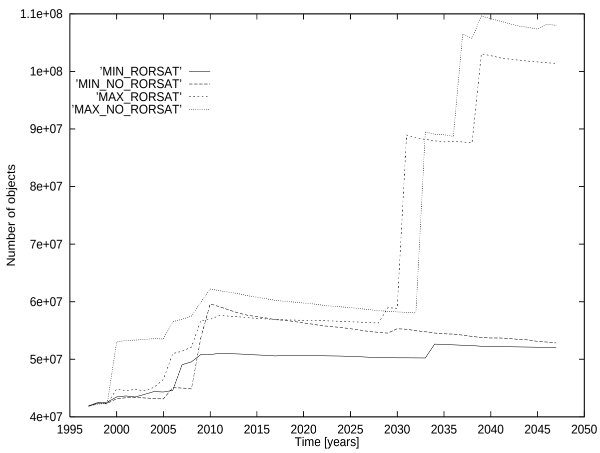

Fig. 2. Number of orbital debris larger than 0.9 mm. The maximum and minimum outcomes, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

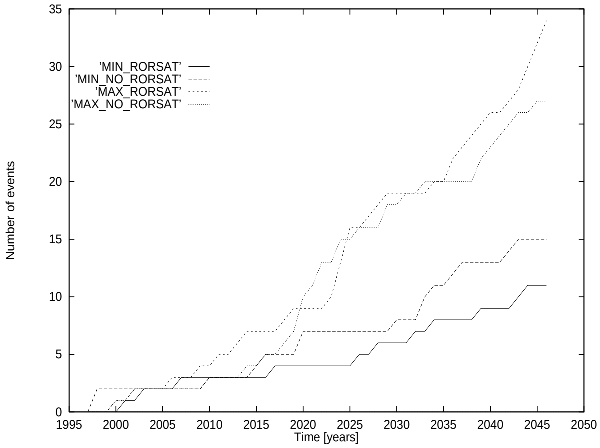

Fig. 3. Cumulative number of collisions involving space objects larger than 1 cm below 2000 km. The maximum and minimum outcomes, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

For debris larger than 1 cm, the RORSAT case gave an average total number, after 50 years, greater by 15% with respect to the NO_RORSAT case (Fig. 4). But, again, the effects of sporadic explosions and collisions can be more important and change significantly the final outcome.

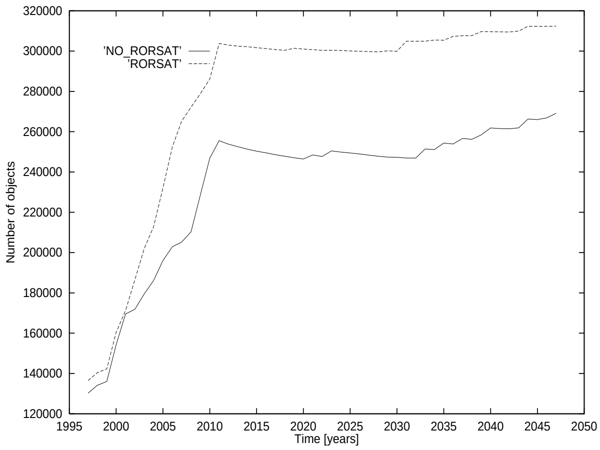

Fig. 4. Number of orbital debris larger than 1 cm. The averaged values, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

In our simulations the evolution of space objects larger than 10 cm is mainly driven by launches and explosions (much less by collisions). Before the explosion cut-off, in 2010, the growth rate is 500-600 objects per year; afterwards it is just a little bit more than 200 objects per year (Fig. 5). The NaK droplets, as expected, do not play any role here (the small difference apparent in Fig. 5 just reflects the residual stochastic effect of explosions): they are not able to break a large target up and therefore to generate a significant number of 10 cm fragments. For this reason the RORSAT drops cannot affect the circumterrestrial environment in such a way to trigger the onset of a collisional chain reaction [7],[8].

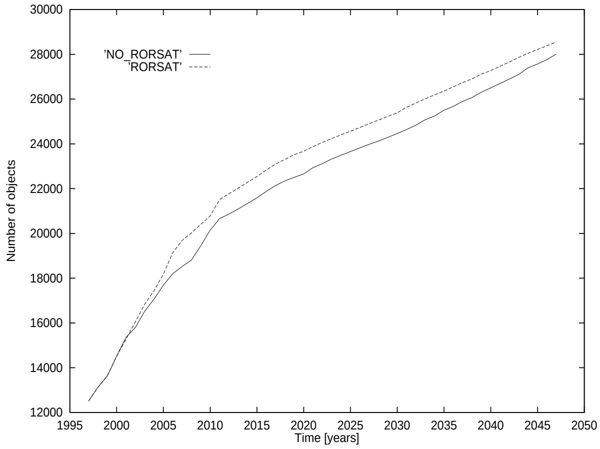

Fig. 5. Number of orbital debris larger than 10 cm. The averaged values, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

Fig. 6 shows, as a function of altitude, the critical density index [6] at the beginning (1997) and at the end (2047) of the simulation runs.

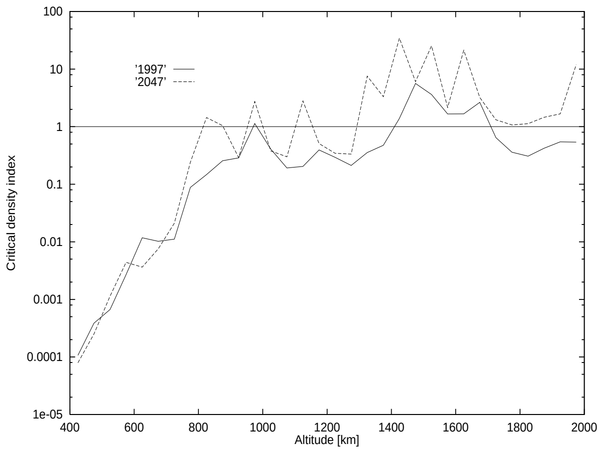

Fig. 6. Critical density index as a function of altitude at the beginning of the simulations (1997) and 50 years later (2047). The results are practically the same in the RORSAT and NO_RORSAT cases. The impact of the LEO satellite constellations after 50 years is clear.

Where the index 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, on the average, the objects removed by air drag. But where the index is larger than 1, a collisional chain reaction may occur in the long term, even though all launches and explosions were stopped at once.

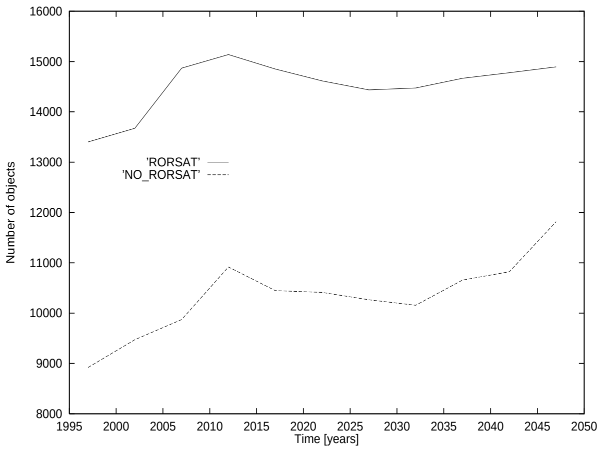

Fig. 7. Number of orbital debris larger than 1 cm in the 850-1000 km altitude range. The averaged values, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

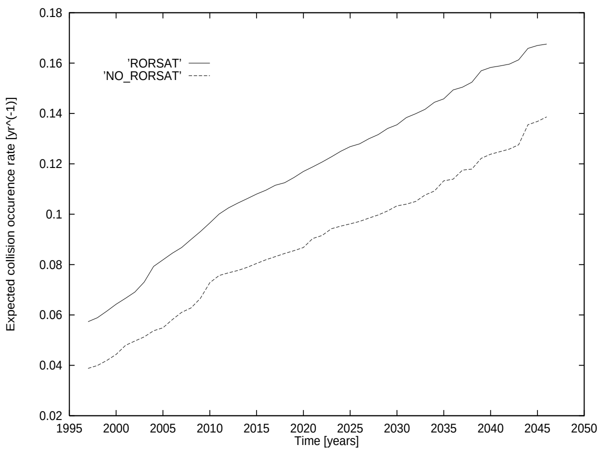

Fig. 8. Expected collision rate between objects larger than 1 cm in the 850-1000 km altitude range. The averaged values, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

At present there are two regions of the near–Earth space where the critical density index is larger than 1: between 950 and 1000 km and between 1400 and 1700 km. The worsening of the situation predicted 50 years in the future is mainly due to the satellite constellations in low Earth orbit and the routine space activity. The NaK drops, instead, in spite of their huge number and impressive contribution to the present debris population (see Fig. 1) do not affect significantly the overall evolution of the artificial particles larger than 1 mm in Earth orbit and have negligible long term effects.

On the other hand, these bodies represent a serious operational concern for spacecraft in the 850-1000 km altitude range. As shown in Figs. 7 and 8, the collision probability with centimetric particles has been significantly increased there, and will remain so for several decades in the future. 50 years in the future, the NaK drops will still be a prominent feature of the spatial density distribution of centimetric debris (Fig. 9).

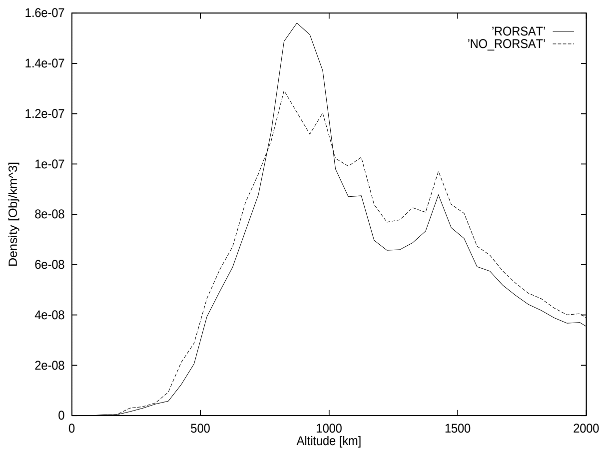

Fig. 9. Spatial density of orbital debris larger than 1 cm after 50 years (2047). The averaged values, out of 10 independent simulations, are shown for both the RORSAT and the NO_RORSAT cases.

New RORSAT Leaks

From the evolution of the debris population, modeled by SDM using CODRM-97 as initial conditions, it is possible to compute the probability of impact of a particle larger than 1 cm with the radiator pipes of the RORSATs still in orbit. This probability is about 5.6×10^{-5} per satellite and per year, corresponding to an 8% overall impact probability over a 50-year period. Therefore, the possibility that one of the RORSATs still in a graveyard orbit might be punctured by a centimetric debris, leaking into space the NaK metallic fluid contained in the secondary cooling circuit (26 kg), is far from remote.

For this reason we decided to include in our analysis such an accidental event. As test cases we considered the two most probable potential leakage sources: the satellites Cosmos 1900 and 1932 [3]. The main difference between the two cases is the much lower altitude of Cosmos 1900, due to problems arisen at the end of its operational life that prevented the insertion into the standard storage orbit.

In both cases it was assumed that the radiator puncture and the consequent leakage of 26 kg of NaK liquid occurred in 2025. The events were simulated with SDM assuming a size distribution for the released droplets of the form

$$N(d) = A \left(\frac{d_{max}}{d} \right)^{c} ,$$

where $N(d)$ is the number of objects with diameter larger than d, d_{max} is the diameter of the largest drops and the value of A is derived from mass conservation (for a given value of the total mass loss). The exponent c of the power law was calibrated following the radar measurements presented in [9] and the droplets were assumed to be released with a velocity of a few meters per second from the parent object.

As before, such events were unable to significantly affect the overall long term evolution of the debris population in Earth orbit, but the environmental impact in the altitude shells interested by the leaks were far from negligible.

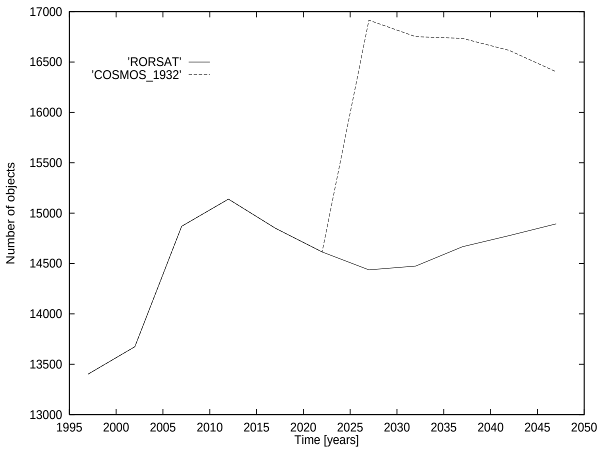

Fig. 10. Number of orbital debris larger than 1 cm in the 850-1000 km altitude range. The averaged values, out of 10 independent simulations, are shown for the RORSAT case, with and without an additional NaK leakage from the secondary cooling loop of Cosmos 1932 in 2025.

A leakage from Cosmos 1932, that is located in the altitude shell where most of the RORSATs are, would have long lasting effects, as shown in Figs. 10 and 11. In the 850–1000 km altitude range the number of centimetric particles could be increased by 15-20%, with a corresponding growth of the expected collision rate. At those altitudes air drag is not effective in removing space debris and the environment might remain upset for several decades.

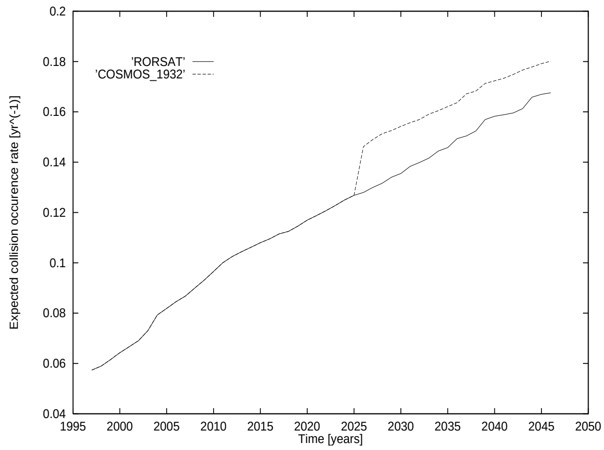

Fig. 11. Expected collision rate between objects larger than 1 cm in the 850-1000 km altitude range. The averaged values, out of 10 independent simulations, are shown for the RORSAT case, with and without an additional NaK leakage from the secondary cooling loop of Cosmos 1932 in 2025.

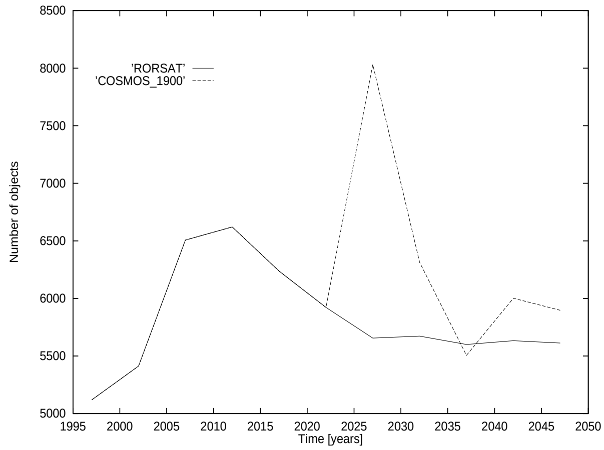

Fig. 12. Number of orbital debris larger than 1 cm in the 550-700 km altitude range. The averaged values, out of 10 independent simulations, are shown for the RORSAT case, with and without an additional NaK leakage from the secondary cooling loop of Cosmos 1900 in 2025.

At the altitude of Cosmos 1900 the picture would be quite different, as shown in Figs. 12 and 13. The immediate effect of a leakage would be significant (+40% at 1 cm), abruptly reversing a decreasing trend in the centimetric population following the end of in-orbit explosions in 2010. But in just a decade the air drag would be able to restore the previous conditions and afterwards the evolution of centimetric particles would be driven by collisional processes. The appearance of such collisional debris would be "masked" at the altitude of Cosmos 1932 for a long time (Fig. 10).

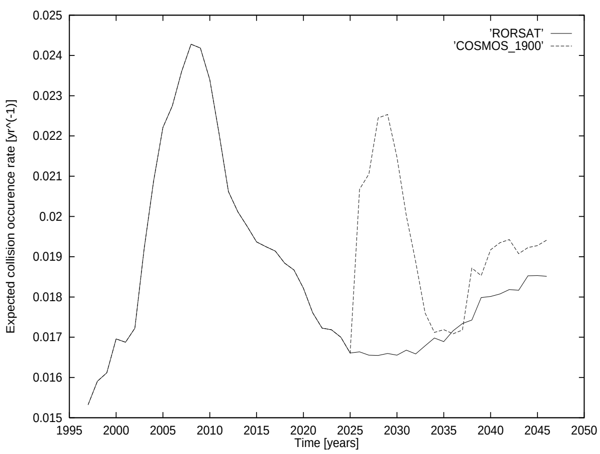

Fig. 13. Expected collision rate between objects larger than 1 cm in the 550-700 km altitude range. The averaged values, out of 10 independent simulations, are shown for the RORSAT case, with and without an additional NaK leakage from the secondary cooling loop of Cosmos 1900 in 2025.

Conclusions

We have performed extensive numerical simulations on the effects of the newly discovered population of RORSAT NaK drops on the evolution of orbital debris. In particular, we have compared the results of a number of simulations using an initial population including such droplets (CODRM-97) with those obtained by disregarding them.

Since the largest observed diameter of the drops is about 4.5 cm, in normal conditions they are not capable of producing catastrophic fragmentations of large targets and therefore do not alter significantly the future debris environment, as far as the possible onset of a collisional chain reaction is concerned. Launch and mitigation policies, especially regarding satellite constellations in low Earth orbit, play the dominant role.

On the other hand, the RORSAT NaK droplets cause a significant increase of the rate of cratering events (i.e., non-disruptive collisions) in the 850-1000 km altitude range, and therefore they give rise to an additional risk of serious damage for operational satellites. These unfavorable effects will be long-lasting, since the corresponding peak in the spatial density of objects larger than 1 cm will still be a prominent feature in Earth orbit several decades in the future.

Although the NaK coolant leakage may have been limited to a specific class of spacecraft which are no longer launched, the probability that a debris impact might puncture the radiator of one of the old RORSATs located in a graveyard orbit, inducing a new leak from the secondary cooling circuit, is far from negligible. Thus we have implemented in our software the possibility of simulating such low–energy sources of particles.

The effects of a new leakage at the low altitude of Cosmos 1900 would be significant, even though short-lived. But at the altitude of Cosmos 1932, where most RORSATs are stored, the adverse effects on the space environment would last for several decades, concealing for a while the long term growth of centimetric particles due to the collisional process.

Acknowledgments

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References

1. Sridharan R., W. Beavers, R. Lambour, E.M. Gaposchkin, J. Kansky and E. Stansbery, Remote Sensing and Characterization of Anomalous Debris, *Proceedings of the Second European Conference on Space Debris*, ESA SP-393, pp. 261-269, May 1997

2. Johnson N.L., *Soviet Space Programs 1980-1985*, Volume 66, AAS Science and Technology Series, Univelt Inc., San Diego, California, 1987

3. Grinberg E.I., B.V. Grigoryev, V.S. Nikolaev, N.A. Sokolov and A.I. Nazarenko, Interaction of Space Debris with Liquid Metal Circuit of RORSAT Satellites, *Proceedings of the Second European Conference on Space Debris*, ESA SP-393, pp. 273-277, May 1997

4. Inter-Agency Space Debris Coordination Commit-

tee, Minutes of Working Group 1 (Measurements), *Proceedings of the 14th IADC Meeting*, ESOC, Darmstadt, Germany, pp. WG1 1-8, March 20-21, 1997

5. Pardini C., Development of a Single Fragmentation Event Simulator (CLDSIM), *Study Note of Work Package 3600*, ESOC Contract No. 10034/92/D/IM(SC), Consorzio Pisa Ricerche, Pisa, Italy, September 1995

6. Rossi A., L. Anselmo, A. Cordelli, P. Farinella and C. Pardini, Modelling the Evolution of the Space Debris Population, *Planetary and Space Science*, in press; preprint available from http://apollo.cnuce.cnr.it/~rossi/publications/pub_ale.html

7. Kessler, D.J., and B.G. Cour–Palais, Collision frequency of artificial satellites: The creation of a debris belt, *J. Geophys. Res.*, Vol. 83, pp. 2,637–2,646, 1978

8. Farinella, P., and A. Cordelli, The proliferation of orbiting fragments: A simple mathematical model, *Science and Global Security 2*, pp. 365–378, 1991

9. Stansbery G., M. Matney, A. Bade and T. Settecerri, Debris Families Observed by the Haystack Orbital Debris Radar, *paper IAA.-96-IAA.6.3.01*, 47^{th} International Astronautical Federation (IAF) Congress, Beijing, China, October 7-11, 1996