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Long-term dynamical evolution of high area-to-mass ratio debris released into high earth orbits

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ABSTRACT

The long-term dynamical evolution of objects with extremely high area-to-mass ratios released in synchronous and semi-synchronous Earth orbits was simulated with a numerical propagator including all the relevant perturbations. In fact, as suggested by optical observations in the geosynchronous regime and orbital analysis of breakup fragments in low Earth orbit, artificial debris characterized by average area-to-mass ratios hundreds or thousands of times greater than those of intact satellites or rocket bodies might be produced much more frequently than previously supposed. The results obtained show that even objects with average area-to-mass ratios of tens of m^2/kg may remain in space for several decades, or more, with very wide eccentricity excursions and orbit pole precessions, but maintaining a mean motion close to the original one, either synchronous or semi-synchronous.

1. Introduction

Optical observations have led to the discovery of a population of faint uncataloged objects, with mean motions of about 1 revolution per day and orbital eccentricities as high as 0.8 [1–3]. The discovery of such objects was initially quite surprising, but an obvious explanation for their origin was immediately proposed. In fact, direct solar radiation pressure may significantly affect the eccentricity with small effects on the total energy of the orbit and, therefore, on the semi-major axis or mean motion. However, this perturbation would be adequately effective only on objects with sufficiently high area-to-mass ratios (A/M).

The existence of a substantial amount of orbital debris larger than 10 cm with $A/M \geq 1\,m^2/kg$, resulting from breakups or surface degradation, had not been previously anticipated, but a statistical orbital decay analysis of the A/M distribution for the debris of the Fengyun-1C breakup, that occurred on 11 January 2007, has shown (Fig. 1) that about 5% of the cataloged fragments had $A/M \geq 1\,m^2/kg$ and slightly more than 1% had $A/M \geq 10\,m^2/kg$ (up to $90\,m^2/kg$) [4]. Very similar results were obtained with a statistical decay analysis of the Cosmos 2251 fragments produced after the collision, on 10 February 2009, with Iridium 33 (Fig. 2). However, a larger fraction of high A/M objects was obtained in the Iridium 33 case, leading to a faster debris decay and reentry: 26% of the cataloged fragments had $A/M \geq 1\,m^2/kg$ and 5% had $A/M \geq 10\,m^2/kg$ (Fig. 3). Therefore, the generation of orbital debris larger than 10 cm and with average A/M hundreds or thousands of times greater than those of intact satellites might be more common than previously supposed. Such objects are likely to be a consequence of fragmentation events, both at high and low energy, involving, for instance, spacecraft and rocket bodies with multi-layered insulation (MLI) blankets [5] and other low density composite materials.

In low Earth orbit, below 1000 km, the orbital lifetime of such high A/M fragments would be relatively short compared to that of typical cataloged debris, due to the action of atmospheric drag. Even at higher altitudes the lifetime of high A/M objects would generally be shorter

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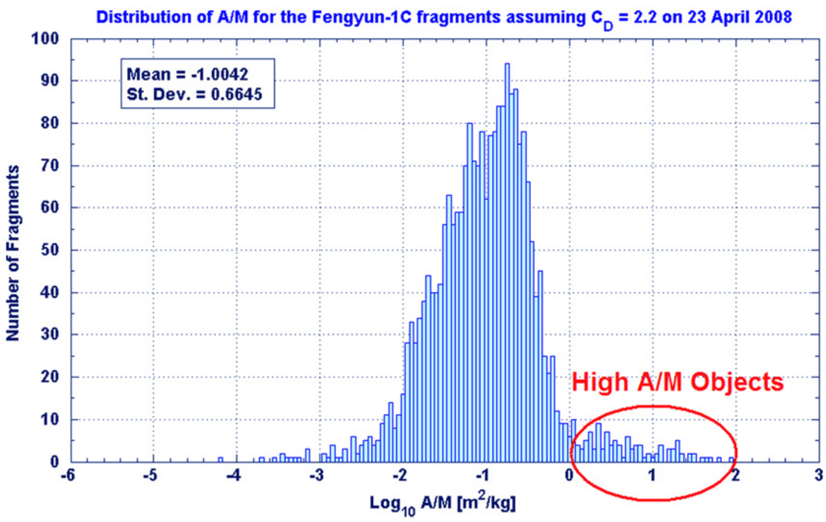

Fig. 1. A/M distribution of the Fengyun-1C fragments inferred from a statistical orbital decay analysis.

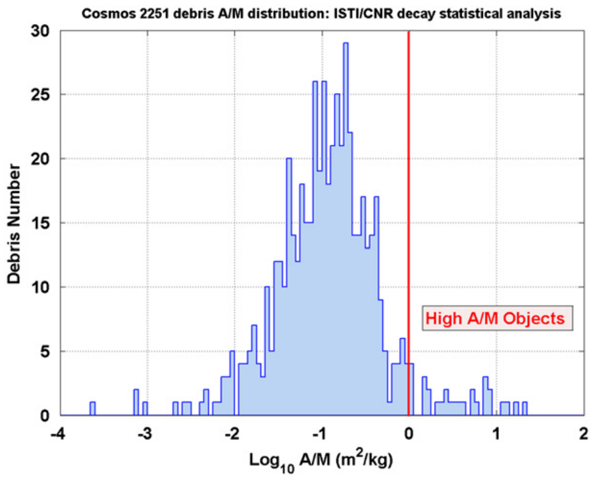

Fig. 2. A/M distribution of the Cosmos 2251 fragments inferred from a statistical orbital decay analysis.

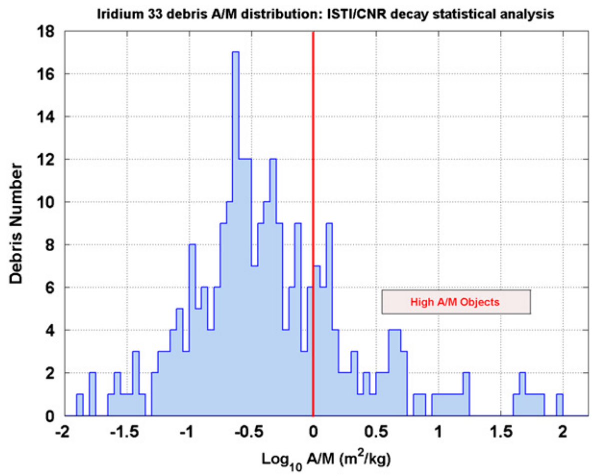

Fig. 3. A/M distribution of the Iridium 33 fragments inferred from a statistical orbital decay analysis.

than the average, but in this case the driving perturbations would be direct solar radiation pressure and luni-solar third body attraction. However, depending on the initial conditions, quite long lifetimes become possible in high Earth orbits also for very high A/M objects, affecting the orbital debris environment for several decades or even more.

In order to grasp the long-term dynamical behavior in some high Earth orbits of interest and trace the possible origins of this unexpected (and still not fully uncovered) class of high A/M objects, a special perturbations propagator, using a high accuracy numerical integrator, was used to perform realistic simulations with a force model including the zonal and tesseral harmonics of the Earth's gravity potential, the luni-solar third body perturbation, the direct solar radiation pressure, with the Earth's shadow, and the thermospheric density for air drag computations, when appropriate. The results obtained for the synchronous and semi-synchronous orbital regimes are detailed in the following sections.

2. The geosynchronous orbital regime

The computations were carried out by simulating the release in geostationary orbit, with a negligible relative velocity, of test objects with average $C_R \times$ A/M up to 60 m^2/kg (were C_R is a dimensionless radiation pressure coefficient, which typically assumes values between 1 and 2) [6,7]. The tumbling period of the objects was assumed to be short compared to the orbital period, a more than reasonable assumption in this case, justifying the use of average values of $C_R \times$ A/M. Eight release longitudes were chosen, four corresponding to the geopotential equilibrium points (two stable and two unstable) and the other four between them. The test objects were propagated for 54 years, a time span approximating the well-known