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Sources of Orbital Debris and the Projected Environment for Future Spacecraft

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The major source of the nearly 5000 objects currently observed orbiting the Earth is from rocket explosions. These explosions have almost certainly produced an even larger unobserved population. If the current trend continues, collisions between orbiting fragments and other space objects could be frequent. By the year 2000, satellite fragmentation by hypervelocity collisions could become the major source of Earth-orbiting objects, resulting in a self-propagating debris belt. The flux within this belt could exceed the meteoroid flux, affecting future spacecraft design.

Background

THE hazards from orbital debris were first examined in 1966 for the Apollo program, and in 1970 for Skylab and possible future programs.[1] The probabilities at that time were sufficiently low that no action was taken, although the larger collision probabilities for structures 100 m in diameter did produce some concern. Later, Brooks et al.[2] demonstrated that the observed population was increasing in number, and that an even larger number of untracked objects should be expected from the explosions that have occurred in space. In 1978, Kessler and Cour-Palais[3] predicted that within the next 10 to 20 years, the space object population could become "self-regenerative" through fragments generated by collisions between satellite fragments and old payloads and rocket motors. At that time, the orbiting debris population would constitute a larger hazard than the natural meteoroid hazard for certain types of missions.

In order to minimize this hazard, it is important to understand orbital debris and its self-regenerative quality, with the goal of either protecting against or controlling the future environment. This paper will update the environment as it is known today, identify its sources, and present data predicting a current untracked population. A future environment will be predicted. The damage to future spacecraft from the environment and the sensitivity of the environment to controls are identified as areas of future work.

Observed Population

As of December 31, 1979, 11,665 objects had been officially "launched" into space.[4] Of these, 4549 were still in orbit. Another 170 objects had been detected by NORAD but were still awaiting official status.[5] The probability of a particular spacecraft colliding with any of these 4719 orbiting objects is a function of that spacecraft's orbital position and velocity. However, for most types of orbits, the probability is mainly (within a factor of 2) a function of spacecraft altitude—the major exception being for spacecraft in orbits of inclinations between 100 and 130 deg where the probability can be several times the average for that altitude.[2] Averge probabilities were calculated from a 4% random sample of satellites in the October 78 catalogue.[6] A 4% sample was chosen because it was small enough to both allow for the necessary computer requirements and the identification of sources of each object, yet large enough, at most altitudes, to be statistically significant. However, the number of objects at altitudes less than 450 km was sufficiently low that the sample was gradually increased with decreasing altitudes. All objects below 200 km were used. The resulting flux on 1-m^2 cross-sectional area is shown in Fig. 1. The average collision velocity was found to be 10 km/s. Note that a hypothetical space station having a 100-m diameter and 500-km altitude would experience a collision rate of about 0.005/yr. Allowing for population growth and an orbital lifetime of 10 years, the probability of collision would approach 0.1. Thus, for structures of this size and larger and altitudes between 400 km and 2000 km, collision probabilities with the observed population are high. Smaller structures at lower altitudes have significantly less of a collision probability with the observed population.

Sources of the Observed Population

The source of each satellite used in the 4% random sample was researched using the TRW Space Log[7] and the Satellite Situation Report.[8] The result of this research is shown in Table 1. Note that 95% of the tracked population is nonfunctioning and hence orbital debris. The largest single source of this debris is from explosions, with most coming from 11 accidental U.S. explosions. Some of these rockets were presumably dead in space for as long as 3 years before exploding. An engineering problem obviously existed within some of these rockets which allows the proper functioning of the rocket, but causes the spent stage to become a "time bomb" in space. Once such problems are identified,

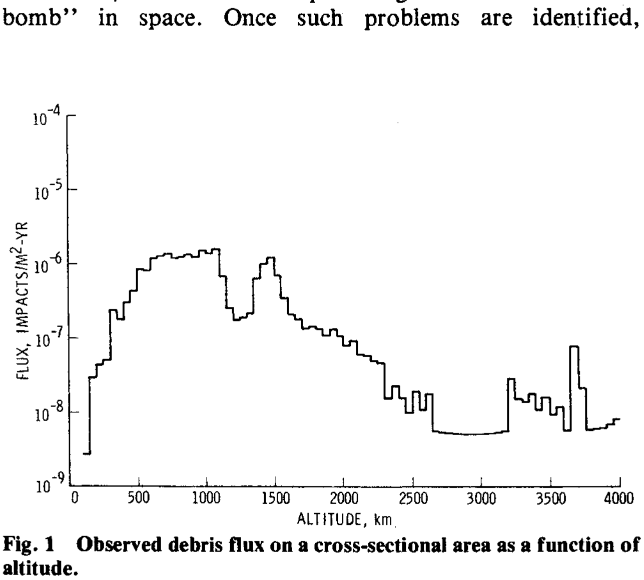

Fig. 1 Observed debris flux on a cross-sectional area as a function of altitude.

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Table 1 Source of in-orbit population tracked by NORAD

Space object	Percentage of tracked population in orbit %	Notes		
Operational payloads	5	Distributions are roughly equally divided between USSR and U.S.		
Nonoperational payloads	12			
Mission related (rocket bodies, shrouds, etc.)	18			
Explosion fragments	54	6 Delta stages	20%	U.S. 42%
		3 Agenas	12%	
		2 other	10%	
		8 USSR satellite tests	12%	
To be determined origin	11	While a certain fraction of these may prove to be nonexistent, most are probably explosion fragments. Many will reenter before they become part of the official catalogue. Some are in geosynchronous orbit, possibly refound objects whose orbits are no longer maintained.		

engineering fixes would do more than any other single action toward limiting the observed population. Since 1972, the only U.S. explosions have come from the Delta rockets. Steps have recently been taken to stop these explosions.

The relatively small number of observed fragments generated by the eight USSR antisatellite tests may be misleading. High-intensity explosions produce a very large number of small, unobservable fragments.[9] Thus, their contribution to the total debris picture could be much larger.

Since all explosions produce a certain number of small fragments, one would expect an orbiting population too small to be detected by ground radar. Recent test results and analysis indicate that this population may be larger than the observed population.

Unobserved Population

In genral, NORAD's operational system does not track objects smaller than about 10 cm at 1000 km, or 4 cm at 400 km. During a special test conducted by NORAD in 1978, this sensitivity was increased slightly. The results of the test revealed an unobserved population that was between 7% and 14% of the observed population. However, a much larger percentage of previously unobserved objects was found below 400 km. Most of these objects had sizes smaller than 4 cm. Due to atmospheric drag, orbital lifetimes for objects this low and small are very short—some as short as a few hours. The obvious source of these objects is from higher altitudes where they were too small to be observed either by this test or the operational system. A similar test in 1976 produced similar results.[10] Thus, a sufficient reservoir of small, untrackable objects at a higher altitude must exist to produce a continuous flow of objects "raining down" through lower altitudes because of atmospheric drag. The size of this reservoir could be determined from the turnover rate at lower altitudes, if the altitude of the reservoir were known. For example, the time an object in circular orbit spends at various altitudes as it reenters is inversely proportional to the atmospheric density at that altitude. Thus, a reservoir about 450 km would require the population at 450 km to be a factor of 2 larger than the population at 400 km. A reservoir above 600 km requires a population at 600 km that is 40 times the population at 400 km. Of course, the reservoir is actually distributed in altitude and a more complex approach is required to obtain the unobserved population number. Such an approach requires developing a time-dependent model that describes the explosion fragments. The model is then refined by testing it against the NORAD test and other observations. Such a model is currently being developed.

A quicker, though less accurate, technique to determine part of the unobserved population is to examine the size distribution as a function of altitude. If the source size distribution is independent of altitude, then the normalized distributions observed at each altitude should be identical, except for the effects of atmospheric drag at lower altitudes. Drag changes the shape of the size distribution, with smaller objects removed more rapidly.

As noted in Table 1, the primary source of fragments is the low-intensity explosions of U.S. rockets, primarily the 2nd stage of the Delta. If these explosions were simulated on the ground, they would provide significant insight into the actual distribution of orbiting debris. However, the only similar data available are from the low-intensity ground explosion of an Atlas missile, which produced 1337 fragments.[9] These data were tested for consistency to represent the source size distribution.

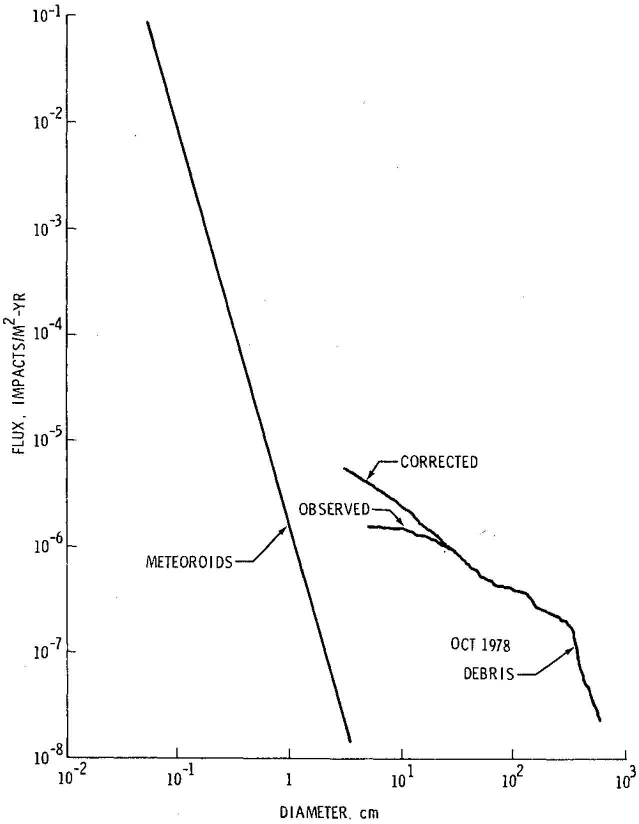

Fig. 2 Cumulative flux in 1978 on cross-sectional area between 600- and 1100-km altitude.

The size distribution of fragments from the Atlas missile test was compared with the orbiting size distribution of fragments. Between 600 and 700 km, the two distributions (normalized to the number of larger objects in each sample) were very much alike for sizes larger than 20 cm. Below this size, the number of objects produced from the Atlas explosion begins to exceed the number of objects observed. Between 1000 and 1100 km, the two normalized distributions were alike for sizes larger than 40 cm, again with the Atlas data exceeding the number of smaller objects observed. If atmospheric drag were responsible for removing a significant number of observed objects at these altitudes, then the minimum size in which the Atlas data fit the observed fragment population should *decrease* with altitude. The observed *increase* in the minimum size is consistent with the loss in ability of the NORAD radars to detect objects at higher altitudes.

In the altitude range between 300 and 450 km, objects as small as 4 cm are detected; however, the size distribution is controlled by atmospheric drag. The rate in which objects drag through this region is inversely proportional to the particle diameter, assuming a constant mass density. Thus, the Atlas size distribution was weighted by the fragment diameter, normalized, and compared to the normalized size distribution of fragments in this altitude range. The two distributions were very much alike, implying that most of the 4-cm fragments may be detected at this altitude.

Thus, to assume that the Atlas missile data represent the source size distribution of fragments in space to 4 cm is consistent with the observations. Figure 2 compares the observed debris flux in the 600-1100 km region with the corrected debris flux using the Atlas missile data. Note that the orbital debris flux is already much greater than the flux of comparable size meteoroids. Note also that the corrected flux to 4 cm is about a factor of 3 larger than the observed flux. Since the NORAD radars apparently cannot consistently detect objects smaller than 4 cm at any altitude, any attempt to estimate their number becomes highly uncertain. The Atlas data above indicates that a significant number of these particles exist; however, other sources, such as high-intensity explosions or collisional fragmentation could produce a much larger number.

From this analysis, it is obvious that the flux shown in Fig. 1 results from smaller objects at lower altitudes, while these same size fragments go undetected at higher altitudes. The number of these fragments was estimated by assuming that the Atlas missile data represent the true size distribution of fragments to 4 cm. The ratio of the 4-cm flux to the observed flux was then determined for various altitude bands by using the techniques previously discussed and illustrated in Fig. 2. This ratio was then plotted as a function of altitude, curve-fitted to remove statistical fluctuations, then multiplied by the fluxes given in Fig. 1. The results are shown in Fig. 3. Note that the unobserved population increases over the observed population with increasing altitudes, becoming a factor of 10 above the observed population at 3000 km.

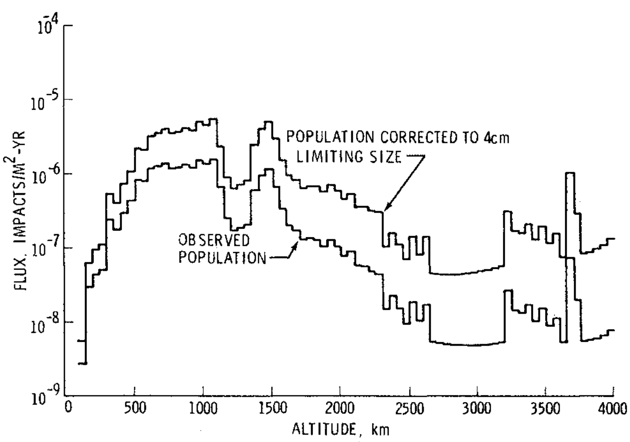

Fig. 3 Observed flux corrected to 4-cm limiting size.

Projected Environment

Whereas the current major source of orbital debris is from explosion fragments, the future major source will probably be fragmentation through collisions. Using the corrected distribution shown in Fig. 3 and the associated distributions of size, velocity, and latitude dependence, the probability that any two objects will collide was calculated in an identical manner as the 1976 observed population.[3] The probability obtained was 0.06/yr, or 1 collision every 17 years. This compares to 0.013/yr obtained in 1976, with the increases resulting from adding the unobserved population (factor of 3) and the 1978 increases in number and area (factor of 1.5). Within the next 20 years, if current trends continue, the number of objects in space will easily double, possibly quadruple. Since the probability that any two objects will collide is proportional to the square of the number of objects, the collision frequency by 1998 would be between 0.24/yr and 1/yr.

This new potential source of fragments is important because of the large number of fragments that are generated in typical hypervelocity collisions. Based on the current "corrected to 4 cm" population, a typical collision would involve a fragment between 4 and 40 cm in diameter colliding at 10 km/s with a payload or rocket body of approximately 3-4 m in diameter, producing an average of 300 kg of ejected mass. Such a collision would produce 1.4×10^4 particles larger than 1 cm and 3.5×10^6 particles larger than 1 mm[3]. Figure 4 predicts a future debris flux where the current population is increased by a factor of 2.5, and 3 collisions have occurred. If the past trend of the satellite population increasing at the rate of between 300 and 500 objects per year[3] continues, this could be representative of approximately the year 1995. Note that collision products would dominate the projected environment for sizes smaller than 4 cm, causing the

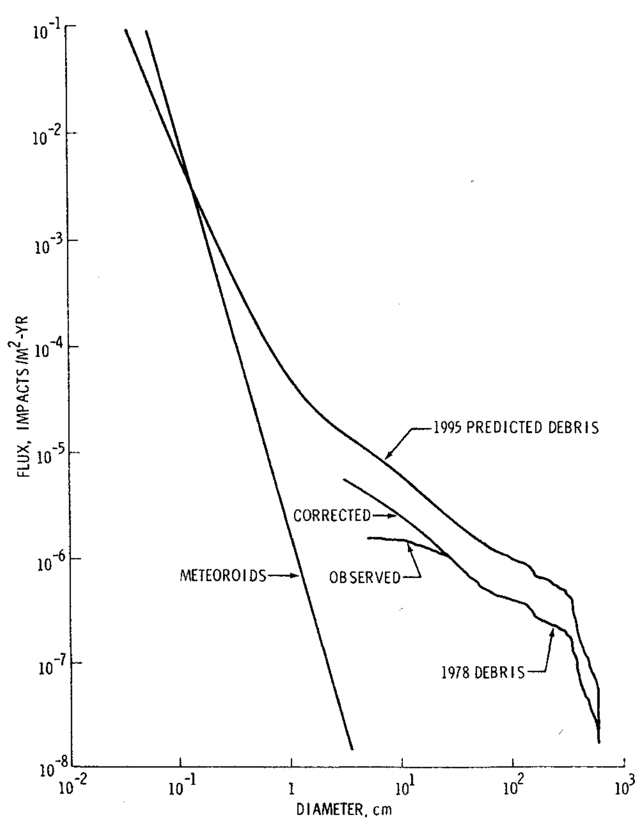

Fig. 4 Cumulative flux in 1995 between 600- and 1100-km altitude.

flux from orbital debris to exceed the meteoroid flux over most sizes of interest for both manned and unmanned activities in the 600 to 1100-km region of space.

Environmental Controls

Three fundamental options exist for dealing with the debris environment: 1) accept the risk, 2) add shielding to reduce the risk, and 3) alter the environment. For certain types of missions, the risk is at an acceptable level. For example, the Space Shuttle has an average cross section of 250 m^2 and an operational altitude of about 300 km. At this altitude, the current collision probability for the Space Shuttle is about 1×10^{-4}/yr. This is less than the probability of an accidental death on Earth (5×10^{-4}/yr, of which half is from traffic accidents).[11] However, this acceptability will decrease with time, with larger structures, and with higher altitudes. The inherent structure will protect most spacecraft from impacts of 1 mm and smaller. The addition of shielding may be a practical alternative to protecting against impacts between 1 mm and 1 cm. However, the amount of shielding required to protect against impacts larger than 1 cm becomes very large and may be totally impractical in terms of additional weight requirements. Thus, the alternative of controlling the environment may be essential to certain types of missions.

The most effective control technique consists of eliminating objects from space before they become a source of fragments. Emphasis should be placed on designing rockets to eliminate explosions in space. The combination of explosion fragments (acting as projectiles) and nonfunctioning rocket bodies and payloads (acting as targets) produces an effective mix of objects that will eventually produce a self-regenerative fragmentation process through collisions. This process may also be minimized by minimizing the number of targets. The eventual disposition of a rocket body or payload could be planned before it is placed into space. Techniques have been developed to cause geosynchronous transfer orbits to reenter simply by controlling the time of their launch.[12] With the Space Shuttle, it may prove beneficial to retrieve old payloads and rocket bodies. The designation of an area of space to become a "garbage dump" may be useful. However, these options should not be implemented without careful consideration of their effectiveness, alternatives, and other possible consequences. A program is being developed to understand the current and projected environment, and the most effective methods of control. This program will enventually lead to a space object management philosophy where remedial actions will be recommended. However, since the problems are international in scope, coordination with the international community will be required to implement any controls.

Conclusions

If current trends continue, the orbital debris population will become self-regenerative through collisions. The resulting environmental hazard of other spacecraft may exceed the hazard from the natural meteoroid environment, depending on the type of spacecraft and its position in space. Although the hazard may be reduced by the addition of shielding to some spacecraft, control of the environment may be necessary for others. Control techniques are known, although their necessity and relative effectiveness are not well understood.

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