THE IMPORTANCE OF NON-FRAGMENTATION SOURCES OF DEBRIS TO THE ENVIRONMENT[‡]

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ABSTRACT

Historically, satellite fragmentation has been assumed to be the major source of small orbital debris, based on U.S. Space Command observations. Although it was always known that only a few tens of kilograms of small debris could produce a significant debris hazard, there was no hard evidence that any space operations were releasing even these small quantities. Recent observations of small debris have lead to the discovery of numerous non-fragmentation sources; in some cases, these sources have produced a hazard that exceeds the hazard from satellite breakups. In the centimeter-size range, these findings include aluminum oxide slag from solid rocket motors, sodium potassium droplets from coolant systems, and copper needles from U.S. experiments. Smaller debris includes paint flecks from spacecraft surfaces and aluminum oxide dust from solid rocket motors. Since the number of known debris sources seems to be proportional to the amount of effort expended looking for new sources, and since observation programs to measure the small debris environment have just begun, many more sources are likely to be identified. These non-fragmentation sources could increase the need for mitigation efforts and complicate cost/benefit analyses of current efforts.

INTRODUCTION

Before 1980, all that was known about orbital debris was based on the tracking and cataloguing of relatively large objects by what is now known as the US Space Command. Beginning in the 1970's, researchers began to speculate about the existence of an uncatalogued population of smaller debris. By 1974, the most daring prediction placed the 1 mm orbital debris population at only 2.5 times the catalogued population /1/, well below today's measured population.

A lack of understanding of potential sources of orbital debris combined with a lack of experimental data prevented early investigators from quantifying the population of smaller orbital debris. Even worse, the potential for a significant uncatalogued population was overlooked until the late 1970's. This was true even though less than 200 kg of debris was required to produce an orbital debris environment below 2000 km altitude that was many orders of magnitude larger than the catalogued population, and represented a hazard that was comparable to the hazard from the natural meteoroid environment /2/. The foundation for any real understanding of orbital debris was so weak that, when aluminum was found to be the most

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common element in the hypervelocity impact pits on a 1973 Skylab experiment, the principle investigators interpreted these results as reflecting the chemistry of micrometeoroids /3/. When these investigators later found titanium, they developed a theory that the sun was ejecting pure titanium particles. Today, we would attribute the aluminum impacts to orbital debris fragments, possibly resulting from explosions, and the titanium impact to a paint fleck from another spacecraft.

The first identified source of small orbital debris which seemed capable of producing large quantities of smaller debris was satellite breakups. This potential source became a credible source because sufficient data existed. The US Space Command data could be combined with ground breakup data to conclude that a significant uncatalogued population might exist from past explosions in space; however, if such a population did not already exist, future collisions would cause the population to develop /4,5/. Beginning in the early 1980's, experiments were planned and later conducted to test these conclusions. While these experiments have proven that satellite breakups are an important source, they have also lead to the discovery of other, and sometimes more important, sources. Some of these sources have produced an orbital debris hazard exceeding the hazard produced from explosions, and have the potential to complicate our understanding of the benefits of future efforts to control the environment. In addition, since we have just developed capabilities to discover new sources of debris, there is no assurance that we have discovered the most important sources of orbital debris.

This paper will review the calculations that determine the amount of mass required to produce a significant orbital debris population, a summary of the existing data which identifies non-fragmentation sources of debris, and a discussion of how these sources may hide the need for certain mitigation efforts.

MASS REQUIRED TO PRODUCE A "SIGNIFICANT" DEBRIS POPULATION

What constitutes a significant orbital debris population depends on the spacecraft that must survive in the environment. However, at a minimum, whenever the hazard from the orbital debris environment is found to exceed the hazard from the natural meteoroid environment, any spacecraft designer must re-consider his design and operational procedures to ensure that they still meet their original goals. Therefore, for the purposes of this discussion, "significant" is defined as an orbital debris environment that exceeds the natural meteoroid environment, as described by Grun, et.al. /6/ and shown in Figure 1.

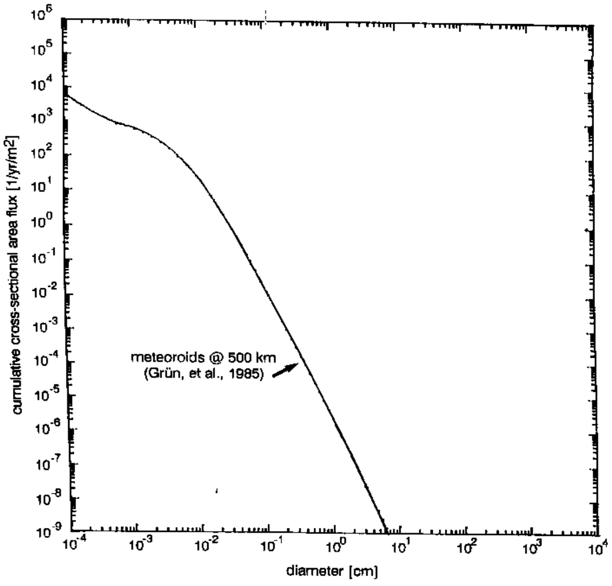


Figure 1. Meteoroid Flux in low Earth Orbit.

A non-fragmentation source will not scatter debris over as large an altitude band as will an explosion or collision breakup. If it is assumed that debris from a non-fragmentation source is limited to a small altitude band, ΔR, of 100 km, then the number of debris objects required to equal the meteoroid flux, F, can be calculated from

$$N = 4\pi R^2 \Delta R F/v \qquad (1)$$

where N is the number of orbital debris particles required to produce a flux F at a distance R from the center of the Earth. Velocity v is the average relative velocity that transforms spatial density into flux and is about 7 km/sec. The total debris mass required to equal the meteoroid flux is then the product of the number and the mass of each particle. The results of such a calculation are shown in Table 1.

Table 1. The number of orbital debris objects confined to a 100 km altitude band in LEO and the total mass of these orbital debris objects (assuming spheres with a mass density of 1 gm/cc) that will produce a flux that is equal to the meteoroid flux (impacts per cross-sectional sq. meter per year):

Diameter:	1 cm	1mm	100µ	10µ	1µ
Meteoroid flux:	$2x10^{-6}$	$8x10^{-3}$	8	500	5900
Number:	700	$2x10^{6}$	$2x10^{9}$	$2x10^{11}$	$2x10^{12}$
Total debris mass:	0.4 kg	1.2 kg	1.3 kg	0.08 kg	0.001 kg

Notice in Table 1 that only 700 objects 1 cm in diameter are required to produce a flux equal to the flux of 1 cm and larger meteoroids. If the mass density of the debris objects is 1 gm/cc, then the total mass of these 700 objects is only about 0.4 kg. If the mass density were larger, the total mass would be proportionally larger. The total debris mass peaks between 1 mm and 0.1 mm because the meteoroid mass distribution peaks between these two sizes. However, for any size, or any assumed mass density, one must conclude that very little debris mass is required by any source to produce an instantaneous significant orbital debris environment, especially if the debris from that source is confined to a small altitude band.

If the source is at a lower altitude, or the debris particles are very small, they will be removed by atmospheric drag within a short period of time. In this case, it is beneficial to look at the production rate required to maintain a given flux. If the source of the orbital debris is assumed to be in a circular orbit at some altitude above R, then the production rate required to maintain a flux F at R is given by /7/

$$dM/dt = 4\pi R^2 F m v_d/v \qquad (2)$$

where dM/dt is the rate that mass must be released by the source to maintain a flux F of orbital debris particles, each of mass m, at a distance R from the center of the Earth. Velocity v_d is the rate of change of the orbital semi-major axis due to atmospheric drag at R. To obtain values for v_d, an average solar activity of 130-F10.7 units was used in the NASA-JSC decay program. For any given diameter, the mass production rates are independent of the assumed mass density. The results of these calculations are shown in Table 2.

Table 2. Production rate of orbital debris required to maintain a flux at each altitude that is equal to the meteoroid flux:

Diameter:	1 cm	1mm	100μ	10μ	1μ
300 km altitude:	37 kg/yr	1200 kg/yr	13000 kg/yr	8300 kg/yr	940 kg/yr
400 km altitude:	5.5 kg/yr	180 kg/yr	1900 kg/yr	1200 kg/yr	140 kg/yr
600 km altitude:	0.22 kg/yr	7.3 kg/yr	77 kg/yr	50 kg/yr	5.7 kg/yr
800 km altitude:	0.020 kg/yr	0.66 kg/yr	7.0 kg/yr	4.6 kg/yr	0.52 kg/yr
1000 km altitude:	0.006 kg/yr	0.20 kg/yr	2.2 kg/yr	1.4 kg/yr	0.16 kg/yr

From Table 2, the largest production rates are for lower altitudes and orbital debris sizes near 100μ. For example, 13000 kg/year of 100μ particles must be produced from a circular orbit above 300 km in order to maintain a flux at 300 km equal to the flux of 100μ meteoroids. These production rates would be reduced by as much as a factor of 30 if the orbits of the released debris were elliptical, and their perigees were equal to the altitude of interest. For example, if the perigee of the debris were at 300 km and the apogee near 5000 km, then only 433 kg/year of 100μ particles would maintain a flux equal to the meteoroid flux. If the perigee were about 100 km below the altitude of interest, then the production rate for an elliptical orbit would be about the same as for the circular orbit \7\. For debris smaller than about 100μ, the source need not be in an elliptical orbit for the debris to be in an elliptical orbit. Solar radiation pressure can increase the orbital eccentricity of smaller debris causing their perigee to drop to lower altitudes even thought the sources of the debris may be at higher altitudes in a circular orbit.

EXISTING DATA INDICATING NON-FRAGMENTATION SOURCES

Most of the data which points to non-fragmentation sources resulted from either tests associated with or the operation of the Goldstone and Haystack radars, each operated in a special mode to sample the small orbital debris environment. Additional data resulted from hypervelocity impacts on spacecraft surfaces, such as the Space Shuttle and Long Duration Exposure Facility (LDEF) satellite. Data from these sources has been used to conclude that Radar Ocean Reconnaissance Satellites (RORSATs) have leaked a sodium-potassium coolant, that solid rocket motors eject not only aluminum oxide dust, but centimeter-size slag, that copper needles launched over 30 years ago are still in orbit, and that paint flakes off spacecraft surfaces. Each of these sources will be discussed.

Sodium-Potassium (NaK) from Russian RORSATs

One of the strongest characteristics of the altitude distribution of approximately 1 cm orbital debris as measured by the Haystack radar was the sharp peak between 850 km and 1000 km, as shown in Figure 2. This concentration of debris could not be explained by an explosion, since an explosion would spread the debris over a much larger altitude band.

Other measurements have found the debris to be in about a 65 degree inclination and have polarization characteristics of metal spheres. In addition, swarms of debris measured by the Goldstone radar could be associated with COSMOS 1900, a lower altitude RORSAT. The only theory consistent with these observations was that some or all of the 31 orbiting RORSATs were leaking a portion of the estimated 9 kg of the liquid metal NaK that each contained for use as a coolant for their nuclear reactors.

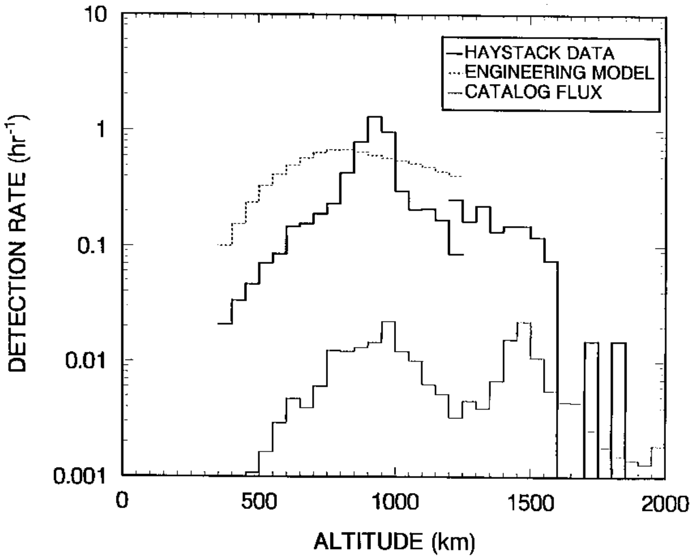


Figure 2. Haystack Radar Vertical Staring Count Rate. The count rates are as of 1994, after 548 hours of data below 1250 km and 67 hours of data between 1200 km and 2000 km /8/, and are compared with a 1990 model prediction /9/ and the expected count rate of cataloged objects.

The theory was tested by looking for a predicted number of NaK hypervelocity impacts on LDEF surfaces; approximately as predicted, two craters were found to contain only NaK. In addition, NASA funded MIT Lincoln Laboratory to detect, track and characterize the observed objects. MIT concluded that the objects were metal spheres with a mass density of approximately the same as NaK (about 0.9 g/cc) and were exactly in RORSAT orbits \10\.

The Goldstone radar has also looked at the altitude distribution for debris sizes near 0.25 cm and finds a similar peak between 850 km and 1000 km \11\. This data, plus the LDEF data, indicates the following: (1) The number of NaK droplets increases rapidly with decreasing sizes, perhaps to as small as 0.1 mm. (2) The measured flux of 1 cm particles is about 50 times the meteoroid flux. (3) The extrapolated flux of 1 mm particles is about 12 times the meteoroid flux. Independent calculations have also concluded that the orbital life-time for 1 cm NaK is close to 100 years.

Given the measured size and altitude distribution, about 60 kg of the 270 kg total RORSAT NaK has been released into the 850 km to 1000 km altitude band. As shown in Table 2, only about 0.01 kg/year of NaK has to be released to match the 1 cm meteoroid flux at 900 km, or 0.5 kg/year to maintain a flux that is 50 times the meteoroid flux. The original NaK was probably released when the core of the nuclear reactor was ejected. With over 200 kg of NaK still available in the RORSATs, any future releases of the remaining NaK could produce an even higher environment, or maintain the current environment for many hundreds of years. Future releases could come from orbital debris penetrations of the coolant loop, or corrosion of the coolant loop.

Aluminum oxide (Al_2O_3) from Solid Rocket Motors

Solid rocket motors use aluminum as part of their fuel. The aluminum burns to form aluminum oxide particles. For the rocket to maintain a high specific impulse, these particles must be ejected at high velocities that can be achieved only if the particles are very small, typically between 0.1μ and 100μ in diameter. About 30% \12\ of the exhaust products of a solid rocket motor are aluminum oxide particles. When the largest solid rocket upper stage, the IUS 1st stage, is used in LEO, it ejects about 3000 kg of aluminum oxide dust. Nominally, most of the dust from solid rocket motors fired in LEO is ejected into a trajectory that causes it to immediately reenter. However, solid rockets are also used in GEO. A 2nd stage IUS ejects about 900 kg of aluminum oxide. When one of these stages is fired in GEO it results in a flux of 1μ aluminum oxide particles, extending from LEO to GEO, that exceeds the meteoroid flux \13\. Solid rocket motors are used on a number of upper stages, and are also integrated into some payloads for final orbit adjustments. Since 1965, the annual number of solid rocket firings in space has varied from 11 to 47, averaging about 28. In 1997, there were 24 firings, ejecting about 16,000 kg of aluminum oxide. The rate of firings appears to be decreasing; however, the annual amount of mass ejected may be increasing as a result of using larger motors. Therefore, it is not surprising that very small hypervelocity impact pits containing aluminum oxide are commonly found on recovered spacecraft surfaces.

For at least 20 years there has been increasing concern that some small fraction of the aluminum oxide could be ejected as much larger particles /12/. Since a small fraction of larger particles would likely not affect engine performance, there was not much motivation for rocket designers to be concerned. As can be seen from Table 2, if even a fraction of a percent of the ejected aluminum oxide were a few millimeters or larger, they would eventually produce a significant flux in that size range.

Two data sets increased the need to search for evidence that larger aluminum oxide particles were produced by solid rocket motors: (1) The Haystack radar measured a higher count rate at lower altitudes when pointed south over 25 to 30 degrees latitude than when pointed vertically /8/. This can be seen when Figure 3 is compared to Figure 2. Model predictions were that the count rate of the south-pointing data should be lower than the vertical staring data. This could be explained only by a larger-than-modeled population with inclinations near 28 degrees /14/. (2) Close examination of high-speed video taken during a STAR-63 test firing identified what appeared to be the ejection of more than a hundred particles with diameters larger than 1 cm.

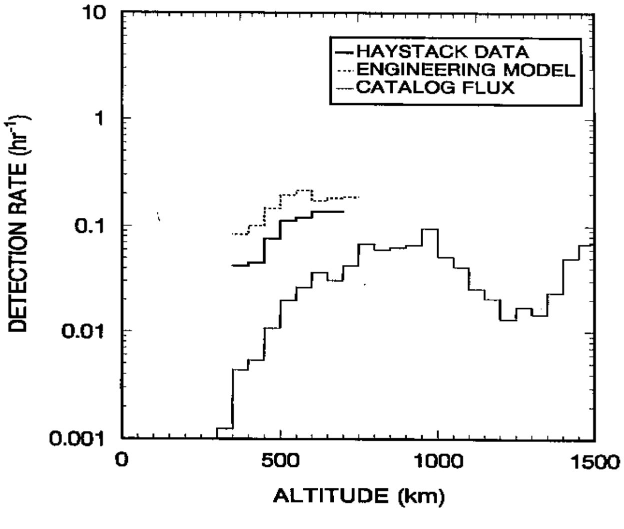


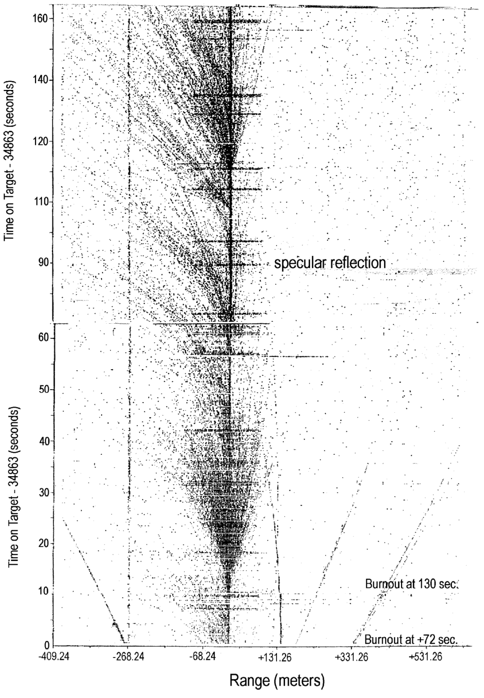
Figure 3. Haystack Radar 10° Staring Count Rate. The count rate is as of 1994, after 764 hours of data obtained by pointing the radar due south, 10 degrees above the horizon.

An inclination near 28 degrees is common for most of the US solid rocket firings. Under the assumption that each solid rocket motor firing during the 1980's produced 400 objects larger than 1 cm, it was shown that the flux of these particles at Space Station altitude was about 10% of the flux of debris from other sources, and could easily be much higher \15\.

After seeing unexplained variations in Shuttle solid rocket motor performance, and detecting on film large particles being ejected at the end of their burn, a 1994 JANNAF workshop /16/ concluded that all solid rocket motors generate "slag", a hot liquid mixture of aluminum oxide and unburned aluminum. How much of this slag comes out of the rocket depends on the rocket design and operation. Pools of slag form near the rocket nozzle, the amount depending on the motor design. Eventually, the pool spills over, releasing larger drops of slag that then solidify into large particles. Other slag may boil off after engine shut-down. If the stage is spinning, slag may be more difficult to eject. A STAR 48 motor, which releases about 680 kg of aluminum oxide dust, is believed to produce about 4 kg of slag, or about 0.6% of its aluminum oxide, in the form of slag, that could come out as large particles \17,18\.

Data has existed for some time which illustrates that solid rocket motors generate large particles; however, either the data was not analyzed, or was not known to be of interest to the orbital debris community. Film records of past Shuttle solid rocket motor boosters showing ejection of large particles were not fully analyzed until recently. Likewise, it was only after reading the National Research Council Report on Orbital Debris /19/ and realizing that their data would be of interest to the orbital debris community, that MIT presented data to NASA from their earlier Haystack radar observations of various solid rocket launches from Wallops Island. These observations detected a relatively large number of large particles being ejected after burnout /18/, as shown in Figure 4.

Figure 4. Portion of Radar Track of Ascending SRM Vehicle (MIT Lincoln Laboratory, NASA JSC. The data in the plot start at 72 seconds after burnout, and the radar reflections off the particles are displayed in time versus range from the vehicle.



Particles from Ascending Rocket Burn (Haystack Radar)

MIT Lincoln Laboratory
Support by NASA Johnson Space Center

All existing data points to solid rocket motors as a significant source of orbital debris. However, an accurate model describing the number, size, and velocity of large particles is still lacking, and there is a need for ground tests and on-orbit measurements to improve these models.

Copper Needles from USAF Communication Tests

Between October 1961 and May 1963, the US Air Force attempted to place a total of 750 million copper needles into Earth orbit at an altitude between 3500 km and 3800 km. Each needle was about 1.8 cm long. As part of a communications experiment, the length of the needles was chosen to resonate at the same wavelength as the Goldstone radar. The thickness of the needles and the inclination of the orbit were chosen so that solar radiation pressure would cause the eccentricity of the orbit to systematically increase, leading to the reentry of the needles within 5 years. However, the needles stuck together, changing their response to solar radiation pressure. Despite these problems, the Air Force declared the communications experiment a success and that all of the needles reentered by 1966 /20/.

The Goldstone radar is currently being used to sample the small orbital debris population in LEO. Beginning in October 1994 the radar expanded its search volume to an altitude of 3200 km. The measured flux from 38.4 hours of observation is shown in Figure 5. The increasing flux above 2800 km altitude was not expected. This flux was observed as swarms of objects with an effective diameter larger than one millimeter. These swarms were observed only in October and November of 1994 and in November and December of 1995. To account for the detection rate, about 40,000 objects had to be in this altitude band during these periods of time. From the precession rate of the swarms, their inclination was found to be near 96 degrees. Only one spacecraft was found to have been launched to the altitude and inclination indicated by the measurements: Midas 4, the first West Ford needle launch /11/.

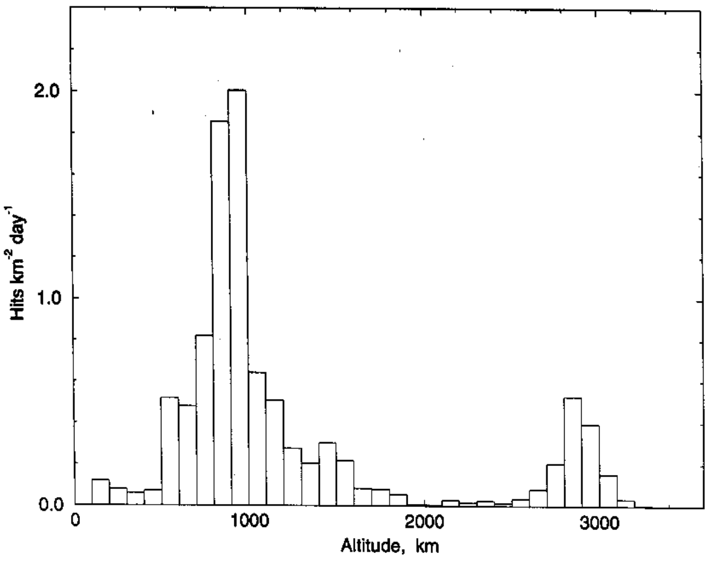


Figure 5. Average Flux Measured by the Goldstone Radar between October 1994 and March 1996. Below 280 km and above 3000 km, the collections area of the radar becomes uncertain.

The only consistent explanation of these Goldstone measurements is that large clusters of needles are still releasing individual needles or smaller clusters of needles. Solar radiation pressure increases the eccentricity of the individual needles or small clusters so that they can be detected near their perigee by the Goldstone radar. A few months later, solar radiation pressure circularizes the orbits, so they can no longer be detected below 3200 km. The number of needles or smaller clusters that spend most of their time above 3200 km is not known.

Paint Flecks from Painted Spacecraft Surfaces

The first hint that paint may be a major source of orbital debris came from an STS-7 window pit analysis /21/. This mission experienced the largest hypervelocity window pit of any mission up until that time, so an analysis was performed to determine the source of the impact. It was concluded that the window was hit by a 0.2 mm white paint fleck at a velocity between 3 and 6 km/sec. Since then, paint has been a common source of impact craters on returned spacecraft surfaces. For example, paint dominated the confirmed orbital debris impacts on the forward facing surfaces of the Chemistry of Meteoroids Experiment on LDEF /22/, as shown in Figure 6.

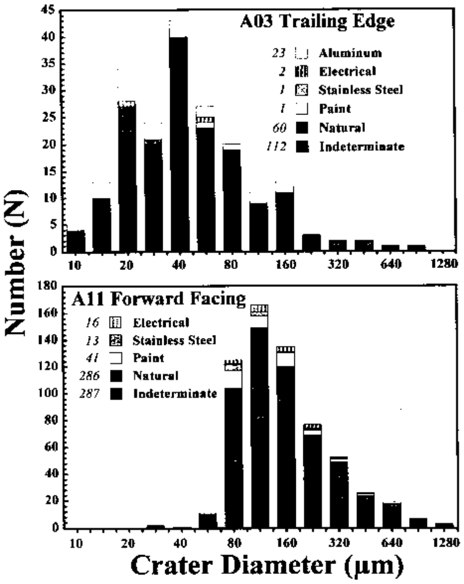


Figure 6. Results of LDEF's Chemistry of Meteoroids Experiment. The forward facing surfaces was aluminum; therefore, aluminum impacts could not be detected and would be found within the indeterminate group. The trailing surface was gold.

The fact the paint would be a major debris source might have been predictable. In orbit, atomic oxygen attacks the binder in paints, causing the paint to flake off from painted surfaces. Space Shuttle missions see this effect when freshly painted hand rails return from orbit less shiny and pitted. Painted surfaces on the LDEF spacecraft, 38 degrees off the RAM direction, lost between 10 and 70 g/m^2 of paint per year, depending on the type of paint. LDEF orbited for six years between 500 km and 330 km altitude. Atomic oxygen decreases with increasing altitude, so the rate of paint release will decrease with increasing altitude. In addition, the loss rate is not linear with time; based on shorter duration Shuttle missions, corrected to the same altitude as LDEF, loss rates were about a factor of 10 higher for the first 2 weeks /23/.

Paint could come off spacecraft for other reasons, e.g., small meteoroid and orbital debris impacts, thermal cycling or UV radiation. There are about 3000 payloads and rocket bodies in

Earth orbit, many of them with painted surfaces. A detailed study to determine the amount of paint expected at various altitudes has not been conducted, nor has any spacecraft exposed to altitudes higher than the Space Shuttle orbits (i.e., approximately 600 km) been examined. As a result, the distribution of orbital paint flecks remains unknown.

DISCUSSION

An important consideration in controlling long-term debris growth is an understanding of the non-linear growth in debris caused by collisions. The rate of growth in the debris population due to collisions varies as the square of the number of objects in orbit and is currently small. However this growth rate is uncertain due to uncertainties in breakup models. Therefore, there may be a temptation to estimate the future growth of all debris by measuring the growth of the smaller debris population. If the sources of smaller debris are from unknown sources that are either linear or show no growth, then we may not detect a lesser population that is growing non-linearly until the growth rate is too high to be reversed.

Although a number of non-fragmentation sources have been identified, they were identified only because they stood out as a result of new measurements and, in some cases, only after much analysis to understand and test theories about the measurements. Even so, we do not completely understand the non-fragmentation sources that have been identified. For example, will RORSATs continue to release NaK? Are there other spacecraft using cooling systems that may leak? Measurements have not been made of smaller than centimeter debris in low inclinations orbits and high altitude orbits, such as semi-synchronous and geosynchronous orbit, regions where solid rocket motors are most popular. What have solid rocket motors done to these regions? Could there be other sources in these regions?

Because of the intense analysis required to identify debris sources, it is likely that there are undiscovered sources of debris in existing data. For example, LDEF's IDE experiment detected a large number of debris swarms, indicating a large number of continuous sources of small debris; however only a few of theses swarms have been analyzed to determine a source /24, 25/. Within the Haystack data, only the most obvious differences with model predictions have been looked at in detail. Because the number of debris sources that have been identified seems to be proportional to the amount of time and effort expended looking for new sources, it is likely that new sources will be identified as new analyses and measurements are made. With this much uncertainty in the sources of debris, it might be impossible to identify a lesser population that is non-linear and growing faster than the current, more numerous populations.

CONCLUSIONS

All sources of orbital debris were first identified as a result of direct measurements of the environment. Early measurements of larger objects identified explosions and the possibility of collisions as a source of small debris. Later measurements of small debris identified non-fragmentation sources of debris that have, in some cases, produced a more hazardous environment than satellite breakups. In the short-term, non-fragmentation sources of debris may be more important than satellite breakups. The non-fragmentation sources identified so far are still not fully understood, and have the potential to be more important than our current interpretation predicts. In addition, it is likely that other non-fragmentation sources exist. Until the short-term sources of debris are understood, they may hide longer-term sources of debris that may be irreversible.

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