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EARLY DETECTION OF COLLISIONAL CASCADING

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ABSTRACT

Theoretical analyses of the orbital debris environment have shown that collisions could eventually become the dominant source of orbital debris. The models suggest that this process has already begun in some altitude regimes, specifically in the region from about 900 to 1000 km. It is important to verify these predictions by measurement in order to provide solid justification for early preventive measures. Collisions of two large objects are predicted to be very infrequent at the present time. However, the models predict that collisions of small debris with large objects will take place at an appreciable rates. These collisions will not destroy the large object, but will generate a shower of microdebris. The particles generated can enter exceptionally long-lived elliptical orbits. It is suggested that an orbital experiment be developed to measure the microdebris fluxes resulting from these collisions, although further modeling of the situation is needed to better understand the distribution of the microdebris.

1. BACKGROUND

Theoretical analyses of the orbital debris environment by Kessler and Cour-Palais (Ref. 1), Eichler and Rex (Ref. 2) and by Kessler (Ref. 3) have shown that collisions could eventually become the dominant source of orbital debris in low earth orbit. Debris will be added to the environment more rapidly by collisions than it can be removed by atmospheric drag. Their models suggest that this process has already begun in some altitude regimes, specifically in the region from about 900 to 1100 km.

As objects accumulate in low earth orbit, the altitude range where collisions generate debris spontaneously will grow larger and larger. If current accumulation rates are sustained, much of low earth orbit will pass into the critical range by the middle of the next century (Ref. 3). It is important then, to begin soon to stop the accumulation of objects in low earth orbit. However, this is not as simple as it seems, since it would require that spent upper stages and dead satellites be removed from orbit. Deorbiting requires the expenditure of resources-- either propellant or use of a drag device, or both. Theoretical predictions of events which may happen a half-century from now are not very powerful arguments for implementation of actions with significant economic impacts, such as would be sustained if removal of spent objects from orbit were to be required. Consequently, it is important to seek experimental evidence that the theoretical predictions are correct. This evidence would strengthen the case for removal of spent objects from low earth orbit.

Collisions between large objects in orbit are very infrequent at the present time. Only one event (breakup of Kosmos 1275) is suspected to be the result of an on-orbit collision. Statistical models predict that one such collision might occur every 10-30 years. Clearly, the rate of such collisions cannot be used to test the predictions of Eichler and Rex (Ref. 2) and of Kessler (Ref. 3). However, the collisions of small objects with large objects are predicted to be much more frequent. Detection of such collisions represent a possible test of the theoretical predictions. The purpose of this work was to explore the possibility for detection of collisions of small objects with large objects in order to make this test.

2. HOW FREQUENTLY ARE COLLISIONS EXPECTED TO OCCUR?

The total collision rate for any given size of small debris particle is defined as the particle flux for that particle size times the total area exposed to impact. The total area for large objects (diameter greater than 10 cm) in orbit was calculated by summing the cross-sectional areas of all the objects in the U.S. Space Command catalog, using the radar cross-sections of the objects to calculate their areas. The result of this calculation is shown in Figure 1, where the total area per 50 km altitude band is plotted against altitude. The area shows a sharp maximum in the range 900-1100 km, where the models predict that spontaneous growth of the debris environment has already begun.

The population of small debris at various sizes is not available from direct measurement at all altitudes. Models of the debris environment use the available data to predict the debris population for various sizes and altitudes. The NASA model of the debris environment is called EVOLVE (Ref. 4). It was used to calculate the fluxes of small debris in the 900-1100 altitude range for two epochs, namely 1990 and 2020. These fluxes for 1990 are plotted in Figure 2.

Collision rates in the 900-1100 altitude range were calculated for each particle size by multiplying the particle flux by the total exposed area of large objects. The result is shown in Figure 3. For a 10 mm diameter particle, 3 collisions per decade (10 years) are predicted at the present time, growing to 5 collisions per decade by 2020. For smaller particles, the collision rate is much larger. For a 1 mm diameter particle, there are predicted to be 75 collisions per year at the present time, growing to 130 each year by 2020.

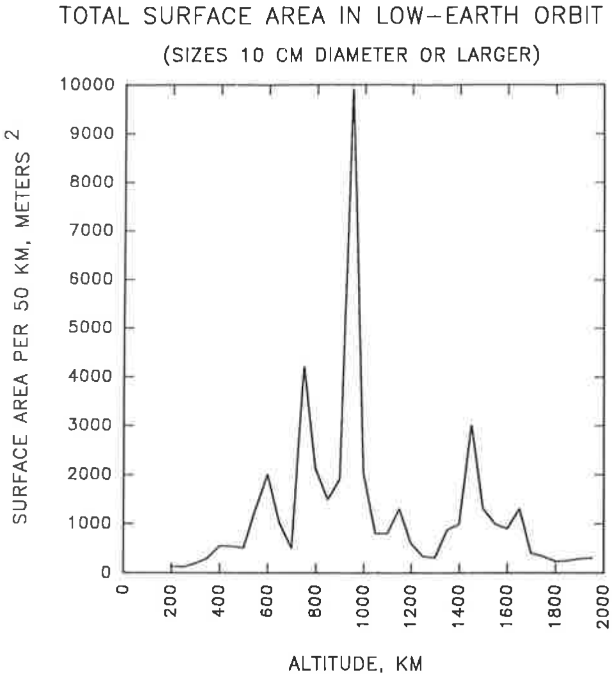

Figure 1. Total area of cataloged objects in orbit

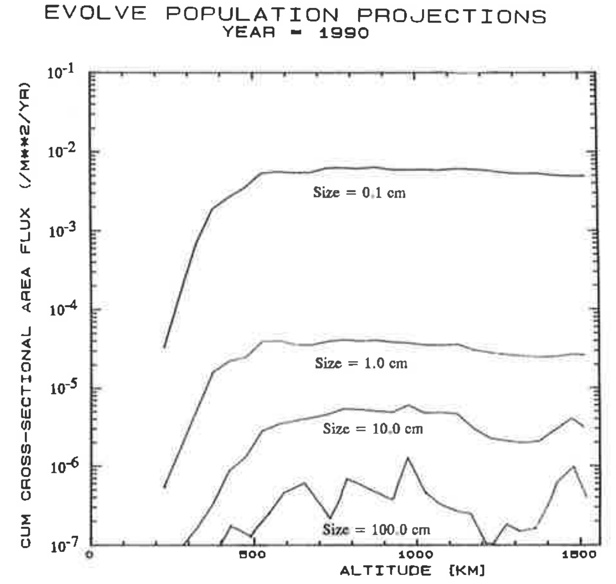

Figure 2. EVOLVE model prediction of small debris population

3. DETECTION OF COLLISIONS

The mean collision velocity is expected to be of the order of 10 km/sec. Collisions at this velocity fall into the hypervelocity regime, where the impact velocity is larger than velocity of sound in the colliding objects. Hypervelocity collisions generate unique phenomena. A brilliant light flash accompanies the collision as a result of the high temperatures generated. A pulse of gas is generated by the same means. A large number of very small particles is generated. This is illustrated in Figure 4, where the yield of small particles from a hypervelocity collision is compared with the yield of particles from an explosion. The hypervelocity collision is unique in the number of very small particles produced.

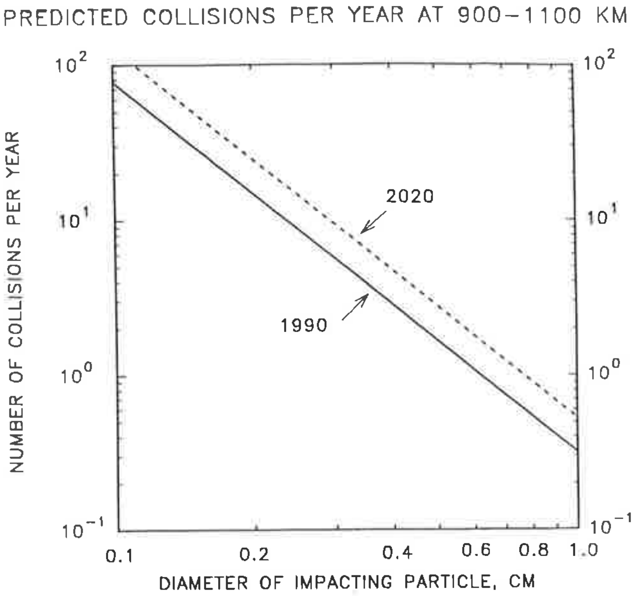

Figure 3. Collision rates at 900-1100 kilometers altitude

Light flashes and gas pulses are transient events, with short durations. However, each collision will generate many very small particles, that will be thrown into long-lived elliptical orbits. These objects may remain in orbit long enough to be detected.

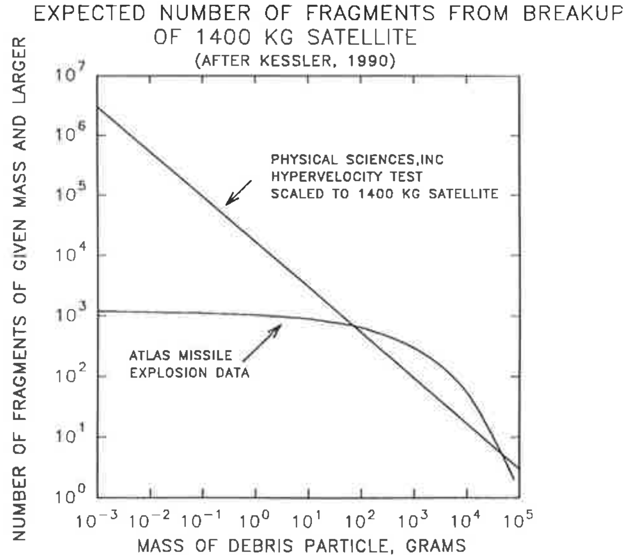

Figure 4. Comparison of the yield of fragments from hypervelocity impact with fragment yield from explosion.

The best approach for detection of the expected collisions might be to measure the small debris population, and look for population increases associated with collisions, and a growth rate of microdebris in excess of that expected from normal breakups. A number of different on-orbit sensors for small particles have been developed and flown in orbit, primarily to detect the natural micrometeoroid population. These sensors would also serve for detecting the microdebris from collisions.

4. YIELD OF SMALL DEBRIS PARTICLES FROM COLLISIONS

Kessler and Cour-Palais (Ref. 1) used data from Bess (Ref. 5) to develop general expressions for the mass and particle size distribution of ejecta resulting from a hypervelocity impact between a spacecraft structure and a smaller object. The ejecta mass is about 115 times the impacting mass, and the number N of fragments of mass M and larger resulting from the collision is given by

$$N=0.8(M/M_e)^{-0.8} \qquad (1)$$

where M_e is the total mass of ejecta.

These expressions were used to calculate the yield and size distribution of ejecta particles from the collisions, with results shown in Figure 5 (assuming the ejecta particles to be composed of aluminum with a density of 2.4 gm/cm^3). Of the order of 1000 one-hundred micron particles are generated by each impact. Two orders of magnitude more ten-micron particles are generated. The cumulative annual yield of ejecta particles from these collisions is shown in Figure 6. Millions of the smallest particles are produced each year.

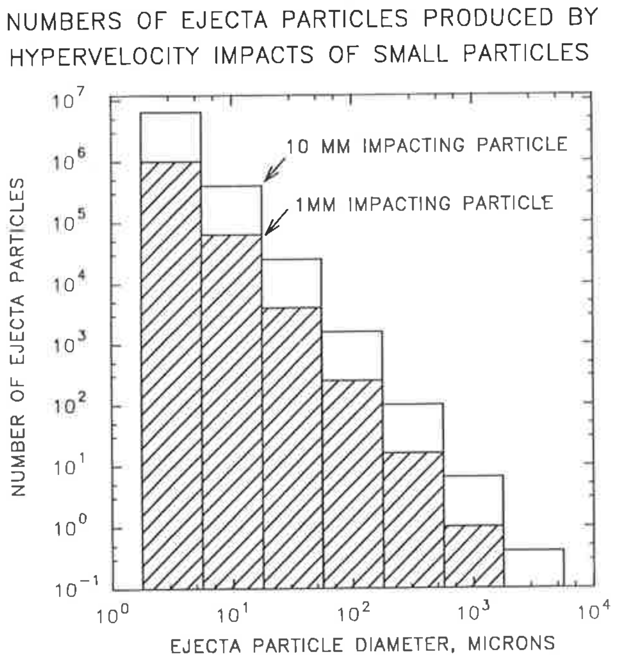

Figure 5. Yield of ejecta fragments from collisions

5. ORBITAL CHARACTERISTICS OF EJECTA FROM COLLISIONS

The ejecta from collision of a small object with a large one follows a characteristic pattern illustrated in the sketch of Figure 7. The ejecta will fly out from the impact point along the surface of a well-defined cone, about 70 degrees wide (for 7 km/sec impacts). The axis of the cone will be approximately normal to the surface of the large object, regardless of the direction of impact. The ejecta have high velocities. The smallest particles have the highest velocities, and can approach the velocity of the impacting particle. Measurements of the ejecta velocities from Christiansen (Refs. 6,7) are summarized in Figure 8, which shows that the smallest ejecta particles can have velocities half or more than half of the velocity of the impacting particle. These facts have important effects on the orbital characteristics of the ejecta from the collision. A test case will illustrate this point:

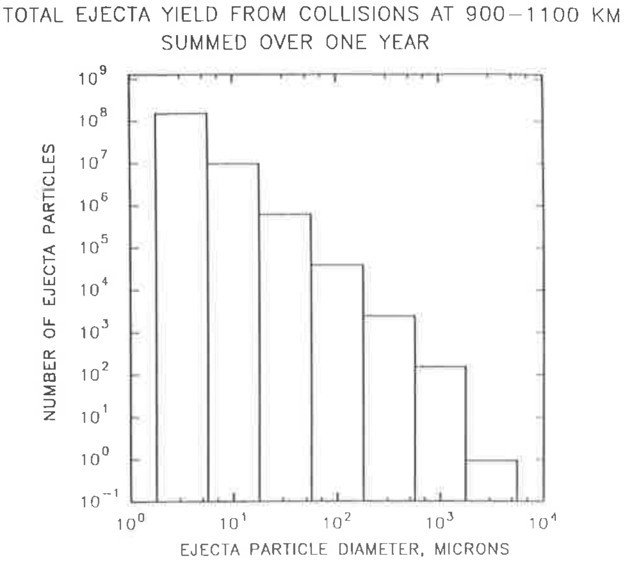

Figure 6. Cumulative annual yield of ejecta fragments

Assume that a large object in a 65 degree inclination circular orbit at 1000 km is impacted by a small object with a relative velocity of 10 km/sec at a position 35 degrees from the direction of flight. Ejecta with velocities greater than 3 km/sec will escape Earth, if lunar-solar perturbations are neglected. Particles smaller than 100-300 microns will exceed this velocity, and will thus escape, unless lunar-solar perturbations alter their orbits. Ejecta with less than 3 km/sec velocity will enter elliptic orbits, with perigees ranging from 600 km to 1000 km, and inclinations ranging from 46 degrees to 65 degrees. The orbital lifetimes of objects in these highly elliptic orbits is very long-- greater than 500 years if lunar-solar perturbations are not taken into account. It is expected that these perturbations will shorten the lifetime, and will also reduce the tendency of the smallest particles to escape, but quantitative calculations have not been done.

It appears from this example, that the collisions will tend to fill a large volume of space with long-lived microdebris. At locations near the impact point, the microdebris density would become quite large for a time after the collision, as the microdebris orbits converge towards a pinch point. The probability of encountering such a region of high microdebris population has not been calculated.

5.CONCLUSIONS

The models predict that collisions of small orbital debris objects with large ones should occur frequently. These collisions will generate showers of small particles, many of which will escape the Earth, but others will remain in long-lived elliptical orbits. Particle detectors in orbit should detect these particles. They will be in highly elliptical orbits, spread throughout a large volume of space, except for temporary concentrations of particles which will occur around the pinch points of the orbits.

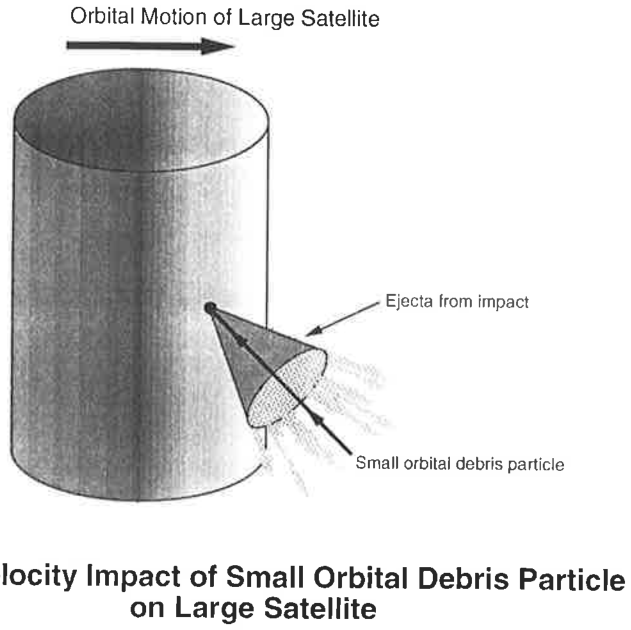

Figure 7. Ejecta pattern from typical hypervelocity impact

Some of the LDEF measurements point to the existence of explosion or collision fragments in elliptical orbits. For example, the rear surface of LDEF suffered impacts of microdebris, which can be explained as resulting from microdebris in highly elliptical orbits (Ref.8). Much of the microdebris is expected to be flakes of paint pigment and aluminum oxide particles from solid rocket exhausts. However, copper, silver, nickel, and stainless steel were identified in some of the impact pits on the trailing surface (Ref. 9). These particles must have been generated by fragmentation of structural or electrical components, either by explosion or by hypervelocity collision. The IDE experiment on LDEF detected persistent streams or peaks of microdebris, consistent with an origin of the debris from something like a point source, which could be an impact (Ref. 10).

Many types of microdebris sensors have been developed, primarily for the purpose of micrometeoroid measurement. One of these sensors could be deployed in earth orbit to monitor the microdebris environment. It probably should operate near 1000 km, should detect the direction and size of the impacting particles, and should remain operational as long as possible. With special attention to reliability and redundancy, it might be possible to operate for several decades.

However, the situation that would be seen by an orbiting microdebris sensor needs more complete modeling. The orbits of ejecta from collisions of small objects with large ones are complex. How many particles escape Earth gravity? How long do the "pinch" points persist? What is the microdebris background signal anticipated? And so on. Further analysis is needed to determine more completely the fate of ejecta particles from collisions described here.

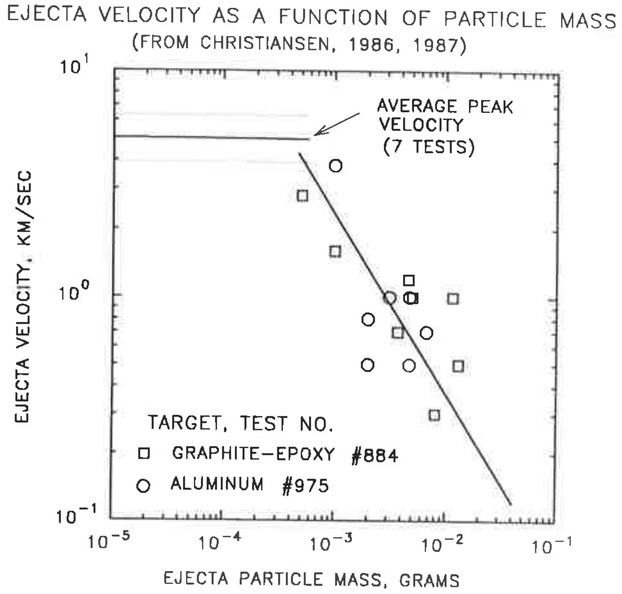

Figure 8. Velocities of ejecta particles from hypervelocity impact.

7. ACKNOWLEDGEMENTS

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