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THE KESSLER SYNDROME: IMPLICATIONS TO FUTURE SPACE OPERATIONS

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The term “Kessler Syndrome” is an orbital debris term that has become popular outside the professional orbital debris community without ever having a strict definition. The intended definition grew out of a 1978 JGR paper predicting that fragments from random collisions between catalogued objects in low Earth orbit would become an important source of small debris beginning in about the year 2000, and that afterwards, “…the debris flux will increase exponentially with time, even though a zero net input may be maintained”. The purpose of this paper is to clarify the intended definition of the term, to put the implications into perspective after 30 years of research by the international scientific community, and to discuss what this research may mean to future space operations. The conclusion is reached that while popular use of the term may have exaggerated and distorted the conclusions of the 1978 paper, the result of all research to date confirms that we are now entering a time when the orbital debris environment will increasingly be controlled by random collisions. Without adequate collision avoidance capabilities, control of the future environment requires that we fully implement current mitigation guidelines by not leaving future payloads and rocket bodies in orbit after their useful life. In addition, we will likely be required to return some objects already in orbit.

INTRODUCTION

Since the beginning of the space program through the 1970’s, it was generally believed that NORAD was tracking all man-made objects in Earth orbit and that the catalogued objects represented the major collision threat to other operational spacecraft. In 1978, Kessler and Cour-Palais published the paper *Collision Frequency of Artificial Satellites: The Creation of a Debris Belt*.[1] The paper concluded that if the past growth rate in the catalogued population continued, around the year 2000 a more hazardous population of small debris would be generated as a result of fragments from random collisions between cataloged objects. This new source of debris would quickly produce a hazard that exceeds the hazard from natural meteoroids, and over a longer period of time the growth in small debris would become exponential, even if a zero net input rate in the catalogue is maintained. Shortly after the publication, John Gabbard from NORAD (known

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for his “Gabbard Plot”), introduced the term “Kessler Syndrome” to describe the future collisional cascading described in the paper. Over the years, the term has developed definitions from the press that are not necessarily consistent with the paper or Mr. Gabbard’s intent.

A segment of the Japanese animated TV series *Planetes*,[2] set in the year 2075, is an example of a popular definition of the Kessler Syndrome that includes both factual and exaggerated components. While an episode appropriately defines the Kessler Syndrome as the cascading of fragments from collisions breaking up other intact objects at an increasing rate, it goes on to say that, once initiated, “…. billions of other pieces [would be generated] in a very short time [and] the Earth would be surrounded by debris …. completely cut off from space.” In general, collisional cascading is a slow process, but very much depends on the population density and size of the objects in orbit. Current population densities would require decades to produce a significant change in the small debris environment, and much longer to approach a condition where the Earth might be “completely cut off from space”. However, it is conceivable that some ill-planned rapid expansion in the use of low Earth orbit could produce a much more rapid increase in small debris as a result of collisional cascading.

This paper will examine the predictions made in 1978, test them against current data and more refined models, and examine alternatives for controlling the future orbital debris environment.

COLLISIONAL CASCADING CONCEPT

The concept of collisional cascading of objects in orbit did not originate with the study of orbital debris. The concept can be traced to studies of the origin of the solar system, ring formation around planets, and the origin of meteoroids and meteorites from asteroids. Fundamental orbital mechanics predict (with rare exceptions) that any two orbiting objects that pass through the same distance from the objects that they are orbiting about represent an unstable condition. The condition is unstable because the two objects will eventually collide[3] and break up into a number of smaller fragments, creating an even larger number of objects sharing the same distance, and therefore increase the collision rate. The number and size of the smaller fragments depend on the collision velocity, which mostly depends on the orbital inclinations of the objects…a higher inclination will result in a higher collision velocity and consequently the more numerous smaller objects would more frequently break up larger objects.

Early in this collision process, most of the total area of the population is in the larger objects, so that collisions between larger objects dominate the process of turning large objects into a distribution of smaller objects. Both the current population of man-made objects in Earth orbit and objects in the asteroid belt at 2.8 AU from the sun are in this early collision process and represent an increasing hazard to spacecraft operating in these regions. Over a much longer period of time, the resulting very large number of smaller objects shifts the total area to be dominated by smaller objects so that collisions between much smaller particles begin to dominate the process. In addition, each collision reduces both the inclination and eccentricity of the population, until eventually only a disk of orbiting dust remains, leaving a ring around the equator of the central body….much like the ring around Saturn. If the ring is sufficiently far from the central body (i.e. outside the Roche limit), then gravitational forces within the ring begin to dominate, allowing the dust to coalesce into a planet around the sun, or into a moon around a planet. This final process is similar to that described by Alfvén with his “apples in a spacecraft” analogy, where all the loose apples in a spacecraft will eventually end up in the center of the spacecraft.[4]

However, a ring is not likely to ever form in low Earth orbit because atmospheric drag will remove dust particles long before their inclinations approach zero. Unfortunately, as has been concluded by a number of investigations, atmospheric drag will not remove larger collision fragments at a rate faster than they can be generated by the current population of intact objects. Consequently, certain regions of low Earth orbit will likely see a slow, but continuous growth in collision fragments that will not stop until the intact population is reduced in number. The question becomes how much confidence should we have in these conclusions and what are our options for dealing with the issue. There are three independent components of the predictions that can be examined: (1) The frequency of collisions between catalogued objects. (2) The consequences of collisions. (3) The rate of atmospheric decay of collision fragments.

The Frequency of Collisions between Catalogued Objects

The frequency of collisions between catalogued objects varies as the square of the number of objects in orbit, while other sources of debris are proportional to the number of objects in orbit. Consequently, as the population increases, it is inevitable that fragments from collisions will become more important than any other source of small debris. The model used in the 1978 publication to predict the frequency of collision was very simple compared to models used today. A random sample of only 125 objects was used to represent a catalogued population of 3866 objects, with the assumption that this orbit distribution was independent of time. Yet, only two parameters represented the major uncertainty in predicting the collision rates: The future growth rate in the catalogued population and the physical cross-sectional size of the objects in orbit. The paper assumed three different growth rates in the catalogue, the smallest being 320 objects per year. An average collision cross-section of 4 m^2 was used, assuming a particular distribution of radar cross-sections (RCS) represented the physical cross-section.

A reconstructed growth rate for catalogued objects in Earth orbit is given in the Orbital Debris Quarterly News[5] and shown in Figure 1. This plot is slightly different than a plot of objects that are catalogued as of a certain date. For example, the 1976 catalogued contained 3866 objects, whereas Figure 1 shows about 5000 objects in Earth orbit. This is because in 1976 there were about 5000 objects in Earth orbit that could have been catalogued, but a large number of them had not yet been tracked and entered into the catalogue. Similarly, the 15,000 objects shown in Figure 1 to currently be in orbit is incomplete and can be expected to grow in number with time. The difference between a catalogue that includes all catalogued objects (including interplanetary objects) and only those in Earth orbit is minor, representing a difference of less than 2%.

Consequently Figure 1 should represent a fairly accurate measure of the actual growth rate in the catalogue….except for the most recent times. The actual growth rate in the catalogue is shown to be about 300 objects per year, except for a period between 1989 and 2007. As pointed out by Johnson[6], the period between 1989 and 2007 illustrates two significant reasons that the population did not continue to grow at its past linear rate….one real, the other not. High solar activity beginning in 1989 caused a large number of fragments to reenter, producing a temporary real reduction in the growth rate. But also during this period the cataloguing of new fragments was abnormally slow, with as many as 2000 objects being tracked but not catalogued…creating the illusion of a reduced growth rate in the catalogue.

The success of the orbital debris program was also a factor where, beginning in 1979, upper stage rockets were identified that had a tendency to explode in orbit after completing their mission. Beginning in the early 1980's, changes made in either their design or operational procedures eliminated this tendency. This reduced explosion frequency combined with the slow rate in cataloging may have prevented the growth rate from exceeding 300 objects per year after 1989. Other factors contributed a minor amount to a reduced debris growth rate, such as the economic collapse of the USSR, a series of higher than average solar cycles beginning in 1979, and other design and operational guidelines established by the orbital debris community. However, in

2007 and 2009, two collisions in orbit (one intentional and the other accidental) created sufficient debris for the number of objects in Earth orbit to again fall alone the 300 object/year growth rate line.

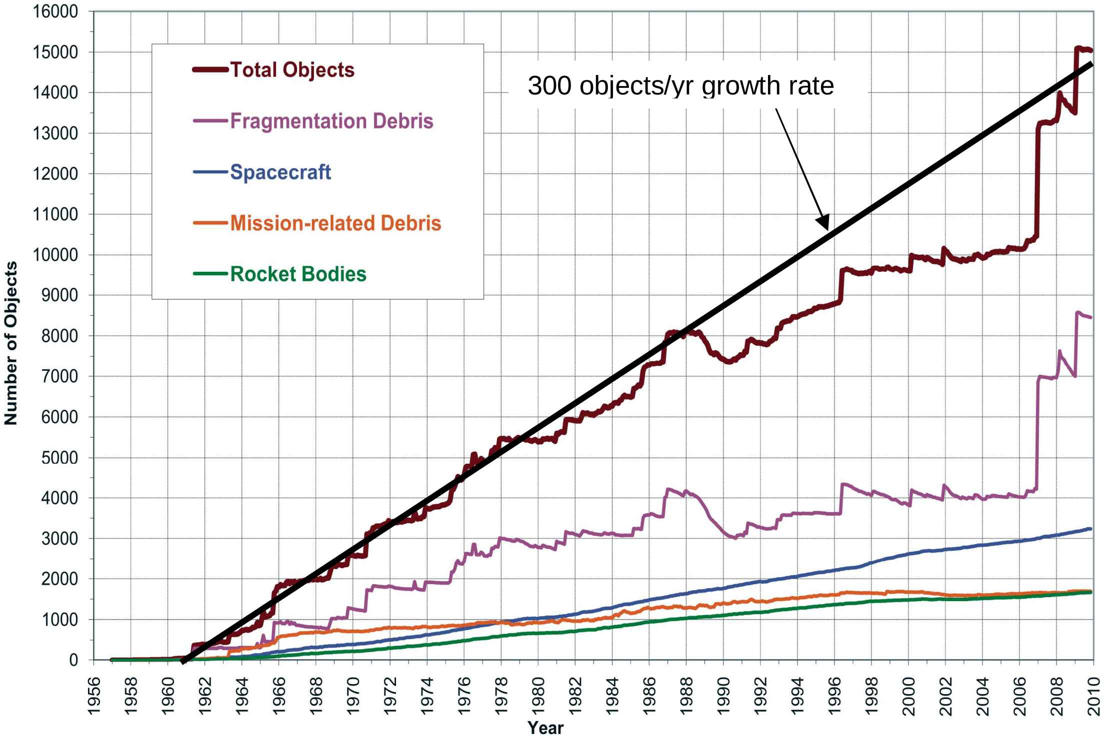

Figure 1. Reconstructed Number of Catalogued Objects in Earth Orbit.

Since the actual growth rate has been only slightly lower than the lowest assumed rate in 1978, it is instructive to compare the 1978 prediction with the actual collision rate. To-date, there have been four known accidental hypervelocity collisions between catalogued objects, as shown in Table 1.

Table 1. Random Collisions between Catalogued Objects.

Date	Objects involved	Altitude	Number of fragments
23 Dec 1991	Cosmos 1934 Debris from Cosmos 926	980 km	2
24 July 1996	Cerise spacecraft 1986 Ariane explosion fragment	685 km	1
17 Jan 2005	Thor-Burner 2A rocket 2000 Chinese explosion fragment	885 km	4
10 Feb 2009	Iridium 33 Cosmos 2251	790 km	>1500

Figure 2 compares the rate of these collisions with the 1978 predictions. All except the 1996 (Cerise) collision likely contributed to the current hazard to spacecraft from the small debris; only the 2009 (Iridium) collision was catastrophic and contributes to future collision cascading. The observed collision rate would be in close agreement with the 320 object/year growth rate if the adopted collision cross-section were increased by about 50%. Such an increase would have been included in the prediction if the NORAD catalogue RCS distribution had been adopted rather than the Perimeter Acquisition Radar (PAR) RCS distribution. The NORAD RCS distribution was about 50% larger than the PAR RCS distribution. At the time, there was a bias toward a smaller RCS distribution to avoid including collisions that only involved little mass, such as an extended solar panels or a boom. In retrospect, the smaller PAR RCS distribution was likely the result of including smaller objects that were not catalogued rather than omitting solar panels and booms.

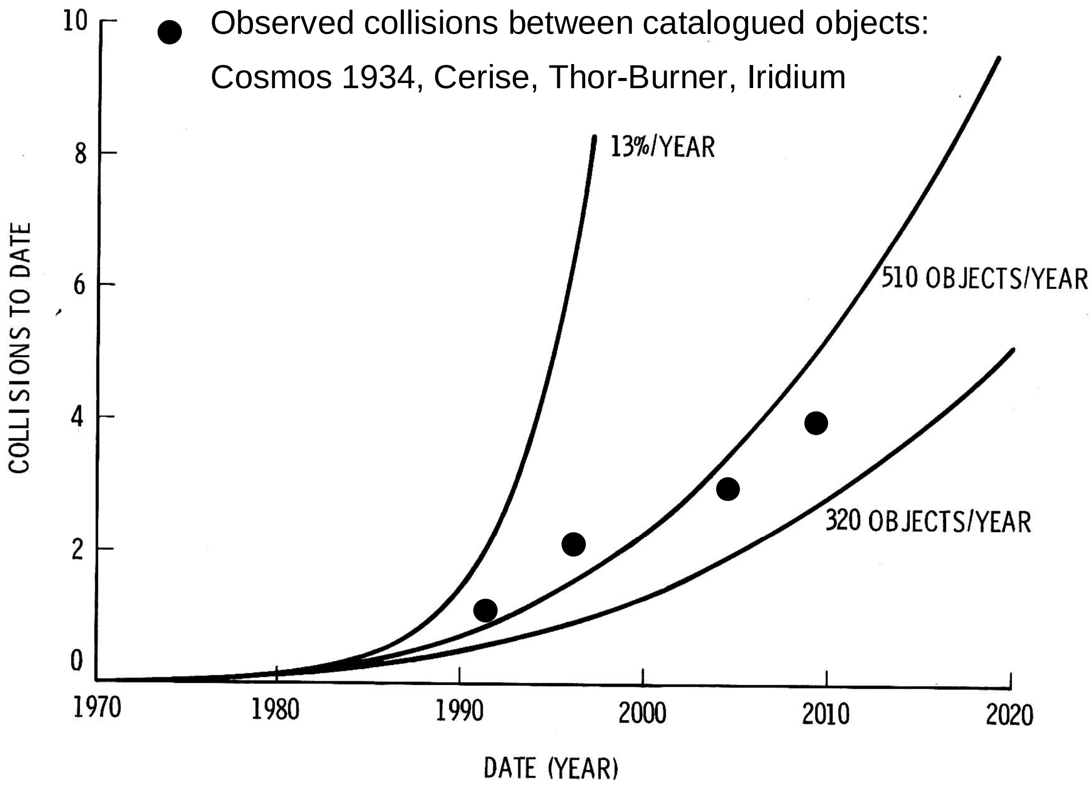

Figure 2. Number of Collisions Predicted in 1978 between Catalogued Objects Compared to the Observed Collision Rate. Various catalogued growth rates were assumed in 1978; the actual growth rate was about 300 objects/year.

Over the past 30 years, NASA has compiled an extensive database giving the actual physical dimensions and masses of payloads and rocket bodies. In addition, NASA has used spacecraft fragments from hypervelocity breakups in the laboratory to calibrate RCS with the physical dimension of fragments. Consequently, current models are based on a much better understanding of the actual collision cross-section of objects in orbit. The latest NASA model, LEGEND (LEO-to-GEO Environment Debris model),[7] uses this database to predict future collision rates. Figure 3 compares LEGEND's prediction with the observed collisions, assuming three options of future growth: Business As Usual (BAU); Post Mission Disposal (PMD) at 90% compliance; No Future Launches (NFL). Because LEGEND is a Monte Carlo model, the average of many runs must be used to obtain the average number of collisions. The Cerise collision, in which a fragment collided with a boom, was omitted from this plot because the spacecraft size database does not include protrusions such as solar panels or booms. Without this event, the agreement between LEGEND and observed collisions is nearly perfect, with a possible under-prediction of the collision rate. Note that the BAU curve in Figure 3 is almost identical to the 320 objects/year curve in Figure 2, illustrating that given a growth rate in the population, models need not be very complex to predict average collision rates.

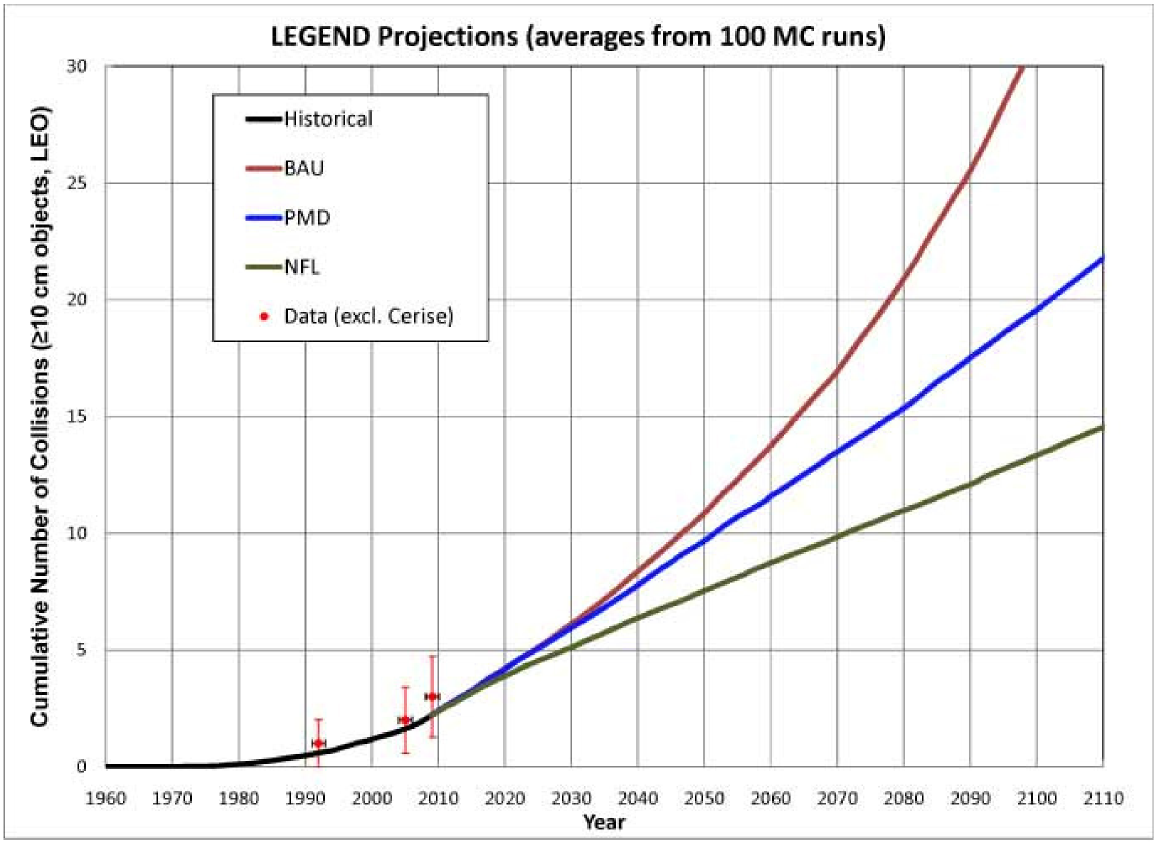

Figure 3. LEGEND Predicted Collision Rate between Catalogued Objects compared to 1991, 2005, and 2009 Observed Collisions. The slope of the curve in 2009 predicts a rate of approximately 0.14 debris-producing collisions per year between catalogued objects.

If one assumes that an average linear increase in the population with time, an average size, and an average collision velocity adequately represents the population over a time interval, then the cumulative number of collisions is given by Equation (1), where t is time and K is a constant that includes those averages. The value of K can be evaluated from the observed collision rate by forcing the curve through the observed collision data, as is done in Figure 4. The resulting curve represents the expected cumulative number of collisions if the catalogue continued to increase at the past linear rate.

$$C = K\,t^{3} \tag{1}$$

Figure 4 also includes a linear fit to the four data points, which represents the average collision rate between 1981 and 2009. This line could also be interpreted as representing the expected cumulative number of collisions if the population had remained constant for a time interval beginning shortly after 1991. Any projection of the future number of collisions almost certainly lies between these two curves. Consequently, we can expect the next collisions to occur around 3 to 6 years after the 2009 collision…more likely closer to 3 years. Or to be more exact using Poisson statistics, if the past linear growth continues, then there is a 63% probability that by the year 2012, one or more additional collisions will have occurred between catalogued objects.

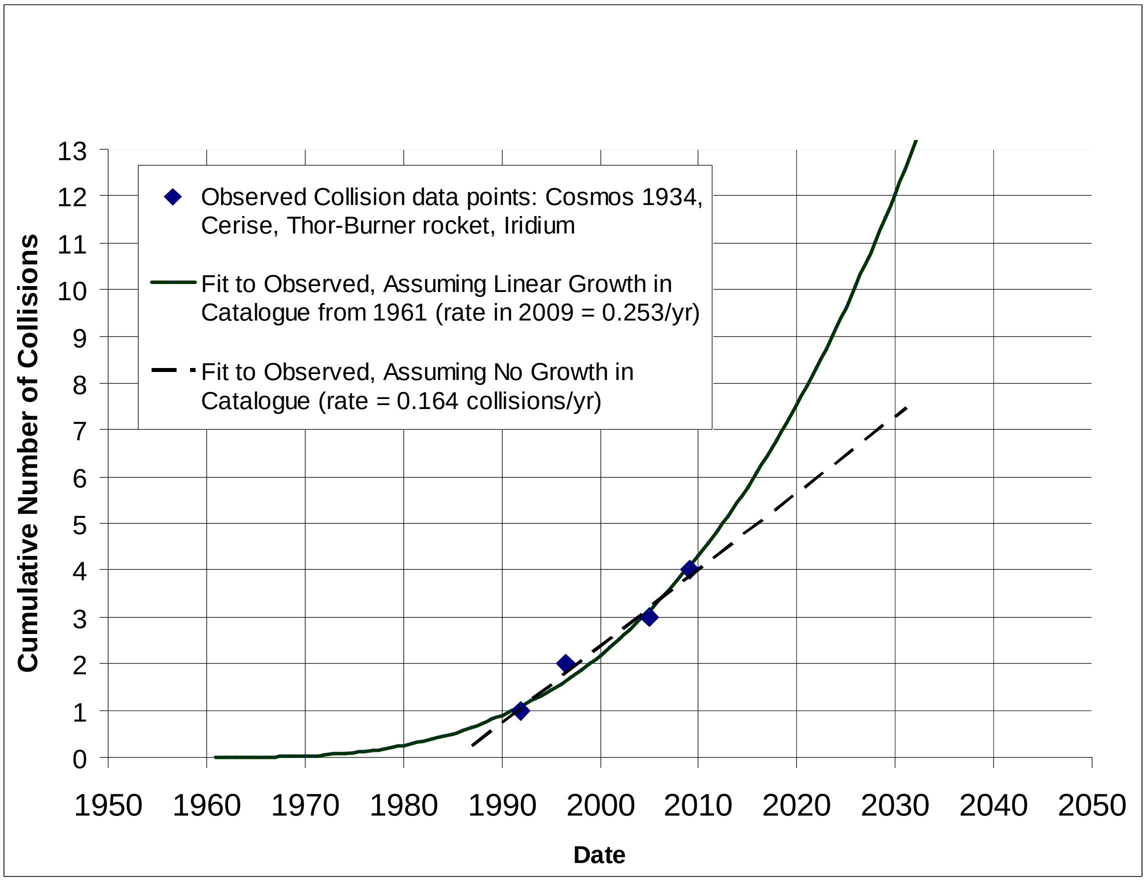

Figure 4. Curve Fits to Observed Collisions Between Catalogued Objects.

The Consequences of Collisions

Thirty years ago, there was little data on the consequences of collisions between large man-made orbiting objects. The existing hypervelocity data were mainly the results of tests conducted to improve spacecraft protection from meteoroids, or to understand the fragmentation of rocks on the lunar surface or in the asteroid belt. Early models drew from that data. However, in the past 30 years, ground tests have been conducted to understand both the resulting size distribution from collisions in orbit, as well as to determine the threshold for catastrophic breakup. In addition, military tests involving an intentional collision in orbit have provided additional data. The results of these tests generally confirmed the early models, but also improved them and offered new insight on both the mass of the fragments and the orbits into which these fragments are ejected.

All the tests so far have been with payloads and none have been conducted on rocket bodies. The difference could be important since a large empty tank on a rocket body may not capture all the energy of a collision; or, if the tank is large enough, may dissipate that energy over the opposite tank wall, acting like a Whipple shield. Currently it is assumed that payloads and rocket bodies fragment under identical conditions and produce identical fragment distributions.

For the purpose of classifying collisions by the amount of debris generated, the consequences of collisions between catalogued objects can be divided into three types:

1. Negligible non-catastrophic. These collisions do not significantly affect either the long-term or short-term environment. This type of collision produces a negligible amount of debris, and therefore has been ignored in past modeling. However, now that we can identify collisions between catalogued objects, we don't want to confuse these collisions with more important ones. When a fragment collides with a thin surface and nothing else, then the total mass of debris generated is limited by the mass of the fragment, which is usually small. The Cerise collision is an example. Had Cerise not been an operational spacecraft, where the operators were able to determine that only the gravity-gradient stabling boom had been severed, this event would likely have been assumed to be a more important non-catastrophic collision, producing much more small debris.

2. Non-catastrophic. These collisions contribute only to the short-term environment. In general, a non-catastrophic collision is one between a fragment and an intact object, and will generate an amount of debris that is about 100 times the mass of the impacting fragment. A significant fraction of the mass goes into sizes that are too small to catalogue, yet pose a hazard to operational spacecraft. Only a few of the fragments may be large enough to catalogue, and therefore do not represent a significant contribution to long-term collisional cascading, but can represent a significant short-term contribution to the hazard of operational spacecraft.

3. Catastrophic. This type of collision contributes both to the short-term and long-term environment. A catastrophic collision produces a small fragment population similar to the non-catastrophic collision, plus a population of larger fragments that do significantly contribute to collisional cascading. From the combination of ground tests and on-orbit tests, it has been concluded that the energy threshold for catastrophic breakup is 40 joules per gram of target mass.[8] This corresponds to a target mass to projectile mass ratio of 1250 at 10 km/sec. In addition, the same tests concluded that 90 to 100 of the generated fragments are large enough to catastrophically break up another target mass of the same size. Therefore, catastrophic collisions are important to both the short-term and long-term orbital environment.

If two intact objects collide at anywhere near orbital velocities, the collision will be catastrophic. However, if a fragment collides with an intact object, whether the collision is catastrophic or not depends on the mass of the fragment, which represents a significant uncertainty. Early models used the RCS and the relationship between area and mass given in Reference 1 to estimate the collision mass. This relationship predicts that all fragments larger than 20 cm would have a mass of over 1 kg, and, therefore, would almost always cause a catastrophic collision when colliding with an intact spacecraft. A distribution of masses for a given RCS was always preferred, but only recently has that capability been developed. The breakup model[9] used by LEGEND for example, now uses a distribution of area to mass ratio based on both drag history of fragments and distributions of fragment obtained from ground tests. As a result of these distributions, LEGEND predicts that only 45% of the collisions between catalogued objects will be catastrophic, and 55% will be non-catastrophic. After ignoring the "negligible non-catastrophic" Cerise collision, these percentages are well within the statistical uncertainty of the three remaining observed collisions. However, we cannot yet be sure that the other two non-catastrophic collisions were not also negligible…this is an area of future research.

Rate of Atmospheric Decay of Catalogued Collision Fragments.

The stability of the orbital debris environment depends not only on the rate fragments are generated, but also on the rate fragments decay from orbit. Without atmospheric decay, it would require only two objects maintained in orbits that cross each other to represent an unstable environment. The rate of orbital decay can be predicted within 10% to 20% accuracy, if the area-to-mass ratio is known and if the initial orbit is known. Older models had to make assumptions in order to obtain these parameters. Now, however, with four catastrophic collisions in orbit (one accidental and three intentional tests), fewer assumptions are necessary to obtain the rate of orbital decay.

The 1985 USAF P-78 anti-satellite test is a good example of what information can be obtained from this type of data[10]. Unlike the 1986 Delta-180 test, this test was at a high enough altitude that there was sufficient time to catalogue all the fragments that could be catalogued, and low enough to observe the entire history of the fragments as they decayed. Consequently, the decay and potential contribution to collisional cascading of these collision fragments can be used in models with very few assumptions. The only necessary assumption is that the measured RCS, which has been calibrated from ground fragments, is a measure of the physical cross-section of the fragments. This assumption then allows for the determination of fragment mass from the area-to-mass ratio derived from the observed decay rate. It was concluded that between 80 and 95 of the P-78 fragments had a mass of 0.68 kg or greater, large enough to catastrophically break up another satellite of the same 850 kg mass as P-78 at an impact velocity of 10 km/sec. While a larger number of fragments were catalogued, those with mass less than 0.68 kg were the first to decay from orbit, leaving the more massive fragments in orbit for the longest time.

There is no comparable collision breakup data for upper stage rockets. However, there is data from upper stage explosions in orbit, and that data was also examined in Reference 10. Since collisions involve much more energy than explosions, there are reasons to question directly applying this explosion data to upper stage collision fragments. But the finding that the explosion fragments have larger area to mass ratios and therefore decay from orbit much faster than the P-78 fragments does point to a need for comparable collision data for upper stages. In the absence of such data, the P-78 data was assumed to apply to both payloads and upper stages (with cautions) to define which regions of low Earth orbit were unstable, or above a "critical density".

MODEL PREDICTIONS

Given that there is the potential for an exponential grown in the debris population due to collisions, the question becomes what are the conditions that will lead to this growth. Two modeling techniques have been used to answer this question: (1) Balancing the source and sink terms in equations describing the source as a rate of fragment production and the sink as a rate of removal by atmospheric drag. (2) Running models that predict the environment many years into the future. Reference 10 is an example of the first technique, and the LEGEND model described in Reference 7 is used in the second technique.[11]

Critical Density Model

In Reference 10, the P-78 anti-satellite test was assumed to represent a typical collision in terms of the number of fragments produced and the rate of decay of those fragments. Fragments from collisions at other altitudes were assumed to decay at a rate that is proportional to atmospheric density at the collision altitude. It was also assumed that the intact population was maintained at its 1999 level. Using these assumptions, equations were derived to determine the conditions for fragments to be generated faster than they are removed by atmospheric drag. The results identified two types of instabilities: (1) An unstable environment, characterized by an insufficient number of fragments for the number of intact objects present. The number of fragments in such an environment will increase with time, but eventually reach equilibrium. Afterwards, the environment would be stable with this higher number of fragments for as long as the number of intact objects remained constant. (2) A “runaway” environment, characterized by the number of fragments increasing to infinity for as long as the intact population remained constant.

These results have some important implications: The final fragment population depends only on the intact population at a particular altitude. A reduction of the number, sizes, or orbital inclinations of the intact population will result in a reduction in the number of fragments that would eventually be in the environment. In addition, fragments generated by explosions or anti-satellite tests will not “trigger” instability…such events only speed up the time until the unstable environment reaches an equilibrium.

Of course the runaway equilibrium fragment population of infinity would never be reached because it would require replacing an infinite number of intact objects after every collision in order to maintain a constant intact population. Nevertheless, this instability must be taken seriously since it means that there is a practical limit to the number of objects that can be maintained in orbit without increasing the small debris population.

Figure 5 shows the predicted areas of instability from the results in Reference 10 for regions below 2000 km altitude, compared to the 1999 spatial density of intact objects. The figure shows that all regions between 600 km and 1700 km are unstable. The results in Reference 10 also conclude that the number of satellites in most of this unstable region is well above the unstable threshold, leaving little uncertainty that the instability exists. This instability is likely to be characteristic of many altitudes above 600 km since the sink for fragments becomes weaker with altitude. Heavily populated regions around 900 km and 1400 km are predicted to be above the runaway threshold. This runaway instability is the result of the peak spatial densities at nearby altitudes, where collision fragments are both scattered as a result of the collision forces and decayed to lower altitudes, contributing to the instability in nearby altitudes. For example, the peak spatial density between 900 km and 1000 km contributes to a runaway instability between 800 km and 900 km. Other heavily populated regions at higher altitudes, such as semi-sync or geosynchronous orbits, are almost certainly also above the runaway threshold since a sink for fragments is virtually non-existent.

However, being unstable or above the runaway threshold does not necessarily mean that immediate action is required, although it does raise some long-term policy considerations. Another important consideration is the rate that the environment increases. Reference 10 illustrates that the 1400 km growth rate is much slower than the regions below 1000 km with a simple "two particle types in a box" model for the two altitudes. However, a much better tool for examining these rates is a model such as LEGEND.

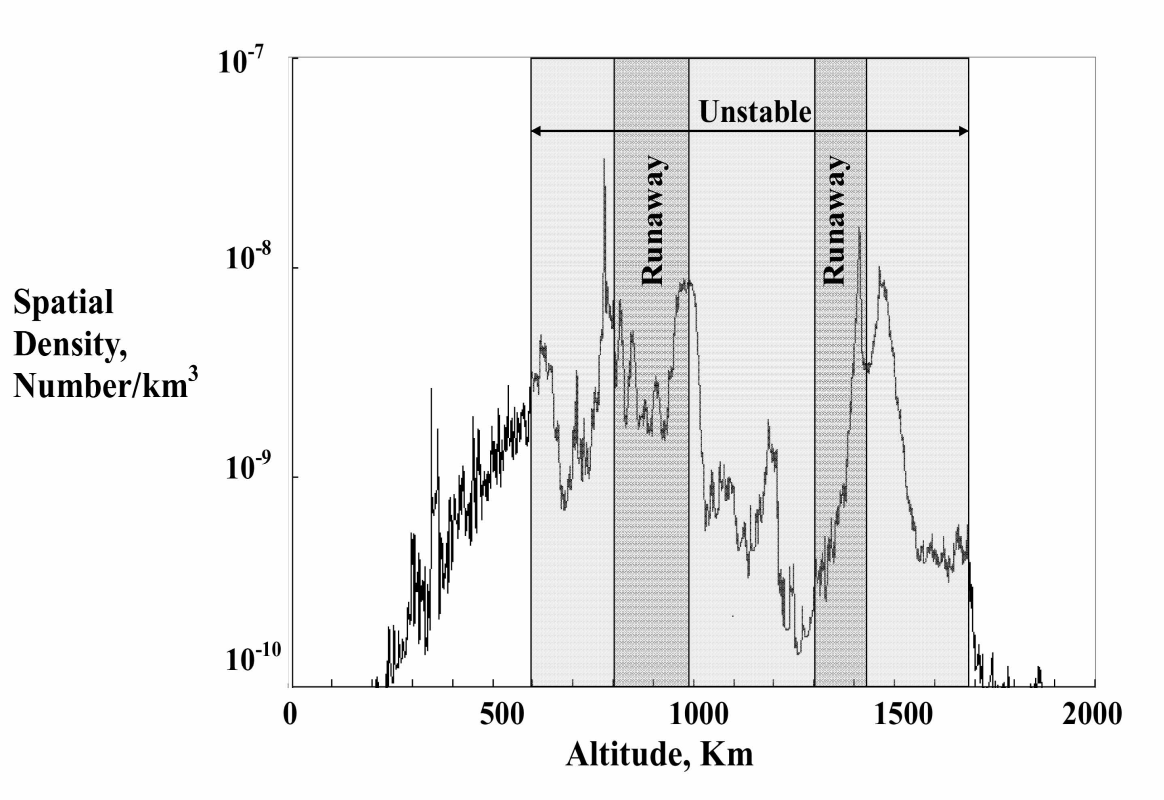

Figure 5. Instability Regions Below 2000 km Compared to 1999 Catalogue of Intact Objects.

LEGEND Model Instability Predictions

The NASA LEGEND model includes an accurate atmospheric decay model, experiment-based breakup models, and both historical and future traffic models to predict the future orbital debris environment. The model uses a Monte Carlo approach and is three-dimensional in order to simulate possible future environments as accurately as possible. Consequently, each run of the model will predict a different future environment, but many runs can be averaged to determine the average, or most probable, future environment. Also, because it is three-dimensional, the potential contribution of different objects toward the future environment can also be evaluated.

In Reference 11, the LEGEND model was used to test the critical density conclusions of previous authors and publications. Figure 6 shows LEGEND's predicted debris fragments under the assumption of no future launches. The results are consistent with the earlier predictions that the current environment is above a critical threshold. During the 200 years shown in Figure 6 the results appear to be a runaway environment. However, the assumption of "no future launches" allows the 500 intact objects currently in this band to slowly be removed by atmospheric drag and collisions, so eventually the number of intact objects would drop below the runaway threshold of about 400 concluded in Reference 1. The LEGEND model also confirmed that the altitude band found to contribute the most collision fragments was between 900 km and 1000 km, also consistent with the runaway conditions predicted in Figure 5. An examination of the contribution to collisions by inclination concludes that two clusters of inclinations within this altitude band contribute more heavily to the number of collision fragments…those around 83 degrees and 99 degrees.[12] Collision probabilities are the greatest between any two objects when the sum of their inclinations is near 180 degrees.[13]

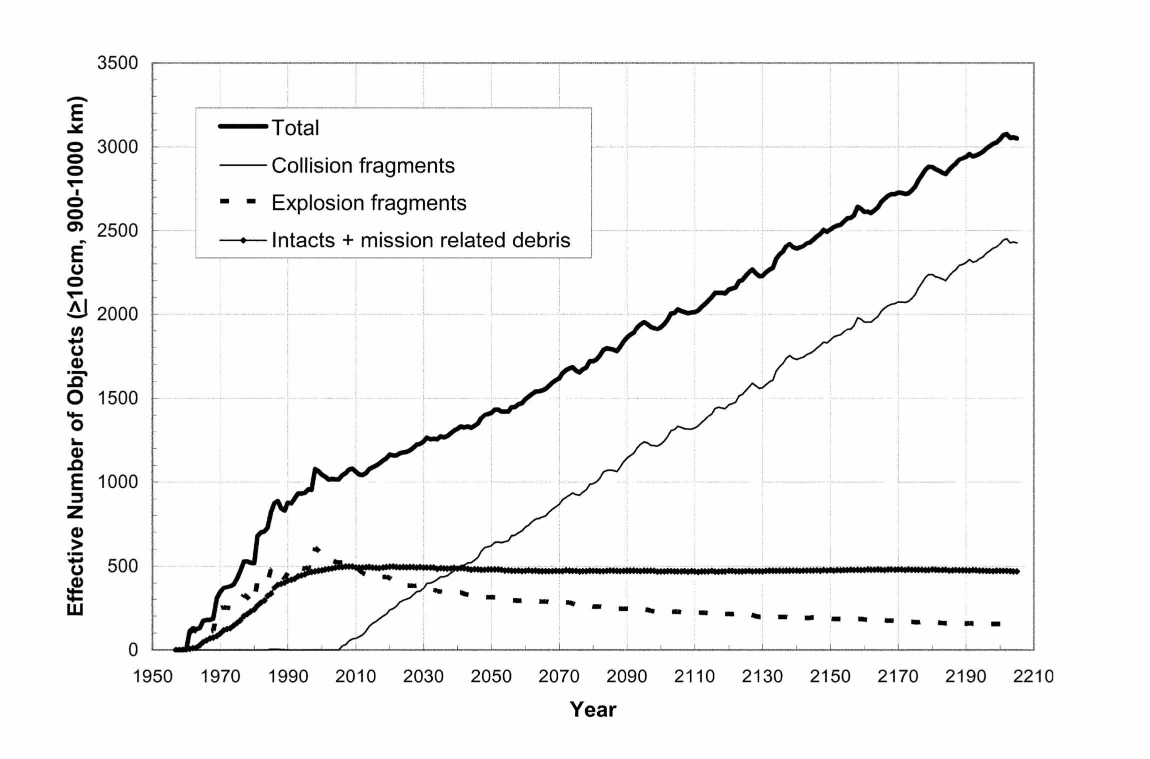

Figure 6. LEGEND Model Prediction of the Number of Catalogued Objects between 900 km and 1000 km. Assumes no launches after 2004.

CONTROLLING THE DEBRIS GROWTH IN LEO

There are only two ways for an intact object in Earth orbit to avoid an eventual catastrophic collision: Either be removed from orbit or get out of the way of an approaching object while in orbit. Both techniques may be necessary to control the growth in LEO debris.

Post Mission Disposal and Active Debris Removal

Over the last decade, the international community has slowly adopted the voluntary policy of Post Mission Disposal (PMD). The PMD guidelines require a payload or upper stage to be removed from orbit within 25 years after its operational life. This can be fairly easily accomplished on a new payload or upper stage by utilizing existing propulsion systems or by installing a device to lower its orbit sufficiently so that it reenters within 25 years. However, few objects already in orbit have that capability. Consequently, since the current environment is already above a critical density, even 100% compliance with these guidelines would not prevent the debris environment from increasing. Therefore, some Active Debris Removal (ADR) of objects currently in orbit is required to control the growth in LEO debris. The issue now becomes one of minimizing the number of objects required to be removed in order to prevent the environment from exceeding an acceptable level.

Again the LEGEND model was used to determine the amount that individual intact objects are likely to contribute to the population of collision fragments.[14] After excluding obvious non-contributors to future collision fragments, LEGEND adopted the criterion, $R_i(t)$, to determine which intact objects were most likely to contribute to the future environment, as defined in equation 2, where $P_i(t)$is the probability of collision for object i at time t, and m_i is the mass of object i.

$$R_i(t) = P_i(t)\, m_i \qquad (2)$$

This criterion is applied to the intact objects in LEGEND, and those with the highest value of R are assumed to be removed at a given rate. Figure 7 shows these results, assuming 90% compliance with PMD, with ADR rates of 2 objects/year and 5 objects/year. Note that PMD plus a removal rate of 5/year will prevent the number of catalogued fragments from increasing beyond the current catalogue.

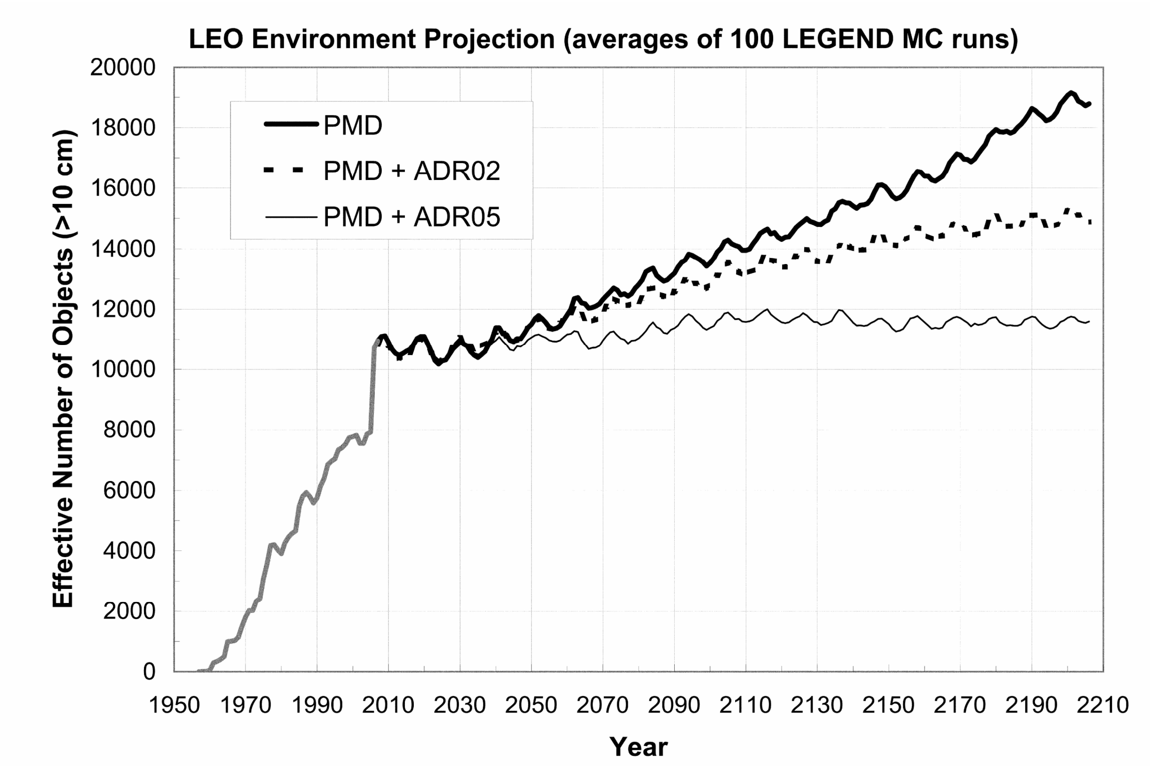

Figure 7. LEGEND Model Predictions of the Number of Catalogued Objects for 3 Scenarios: PMD only, PMD plus ADR of 2 objects per year, and PMD plus ADR of 5 objects per year.

If there is less than 90 % compliance with PMD, then the rate of ADR would have to be increased. However, unless an inexpensive technique can be developed to perform ADR, it would be much more cost-effective to require mandatory compliance with PMD.

Active Collision Avoidance

As with PMD, Active Collision Avoidance (ACA) is not a total solution to controlling the growth of future debris, since most of the current population does not have the capability to maneuver. In addition, tracking and position prediction has not been optimized for this purpose. However, if given sufficient resources, it could be a partial solution for future operational payloads. To become a realistic option, prediction accuracy must be improved in order to minimize the number of false maneuvers and gain the confidence of the payload operators. Just as debris removal concentrates on the more probable future debris sources, ACA could also concentrate on the more probable sources, reducing the burden of both PMD and ADR.

The largest uncertainty in predicted satellite position is the down-range position, which is critical to predicting a potential collision between two objects with velocity vectors perpendicular to one another. However, near "head-on" collisions between objects with inclinations of 83 and 99 degrees were found to be major contributors to future collision debris, and these types of encounters are less sensitive to the down-range uncertainty. In addition the objects of greatest concern are more massive objects above 900 km altitude, reducing down-range uncertainty compared to less massive objects at lower altitudes. Consequently, if collision avoidance is optimized for the purpose of preventing collisions of operational payloads that are in orbits most likely to contribute to future collision debris, then ACA could become a significant contributor toward controlling the growth of debris in LEO.

CONCLUSION

There is little doubt that the result of the so-called "Kessler Syndrome" is a significant source of future debris, as predicted over 30 years ago. Although new operational procedures have been developed over this period that have slowed the growth in orbital debris, these procedures have not been adequate to prevent growth in the debris population from random collisions. In order to prevent this growth, we are at a point where we must obtain near 100% compliance with guidelines established over 10 years ago and, in addition, we must retrieve a number of objects that are already in orbit. Fortunately, by selectively retrieving the most likely future debris sources, the rate of retrieval may be manageable, as long as at least 90% of future launches adhere to current debris mitigation guidelines….a percentage that has not been met in the past. A more focused collision avoidance capability may help, but without adherence to current guidelines and an active debris removal program, future spacecraft operators will face an increasing orbital debris population that will increasingly limit spacecraft lifetimes.

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