Debris and Future Space Activities[1]

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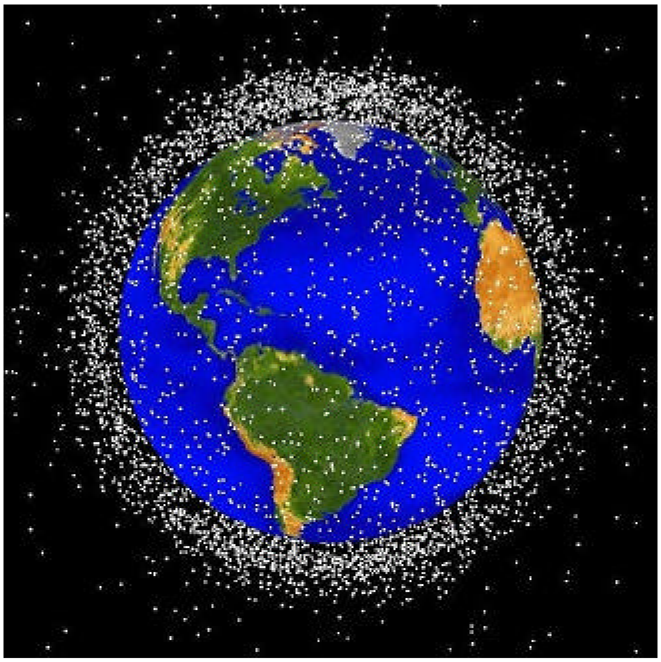
Abstract: There is already so much space debris in low orbits that it poses a significant threat to satellites. Weaponization of near-earth space could seriously exacerbate this problem. Even one war in space could encase the entire planet in a shell of whizzing debris that will thereafter make space near the earth highly hazardous for peaceful as well as military purposes. With enough orbiting debris, pieces will begin to hit other pieces, setting off a chain reaction of destruction that will leave a lethal halo around the Earth. No actual space war even has to be fought to create this catastrophe; a country that felt threatened by America's starting to place lasers or other weapons into space would only have to launch the equivalent of gravel to destroy the sophisticated weaponry. Space debris is thus both an environmental and a strategic issue that is likely to constrain future space activities.

Space is the most fragile environment that exists because it has the least ability to repair itself. Only the Earth's atmosphere can remove satellites from orbit. When the sun flares up in its eleven year cycle, it heats the upper atmosphere and makes it expand so that debris and spacecraft in low orbits are subjected to increased drag. But the higher the original orbit, the less air there is to collide with.

Near-Earth space is already at risk from human activities, and it is in great need of protection by scientists and humanity at large.[2] Scientists like me should be especially concerned, both because we are increasingly dependent on scientific instruments in near-Earth space, and also because we are in a position to foresee the problems human activities are causing and to propose measures to mitigate or avoid them. In particular, we need to emphasize that a war in space could create a battlefield that will last forever, encasing our entire planet in a shell of whizzing debris that will thereafter make space near the Earth highly hazardous for peaceful as well as military purposes. Debris in orbit higher than about 800 km above the Earth's surface will be up there for decades, above 1000 km for centuries, and above 1500 km effectively forever. Over 9000 objects larger than 10 cm in diameter are currently tracked, and there are probably more than 100,000 pieces of orbiting debris larger than a marble.[3] But crowded near-Earth orbits are where the Bush administration wants to put parts of its proposed missile defense system such as Space-Based Lasers and thousands of "Brilliant Pebbles" space-based interceptor missiles. Such weapons were forbidden by the 1972 Anti-Ballistic Missile (ABM) Treaty, but the United States withdrew from this treaty in June 2002.

Maybe the reason missile defense has gotten as far as it has is that so few people understand the laws of physics. The nickname "Star Wars" for missile defense all too accurately reflects the popular fantasy impression of how things work in space. In the Star Wars movies and in hundreds of other popular science fiction films, we see things blow up in space and the fragments quickly dissipate, leaving space clear again. But in reality, space never clears after an explosion near our planet. The fragments continue circling the Earth, their orbits crossing those of other objects. Paint chips, lost bolts, pieces of exploded rockets—all have already become tiny satellites, traveling about 27,000 km per hour, ten times faster than a high-powered rifle bullet. There is no bucket we could ever put up there to catch them. Anything they hit will be destroyed and only increase the debris. A marble traveling at that speed would hit with the energy of a one-ton safe dropped from a three-story building. With enough orbiting debris, pieces will begin to hit other pieces, fragmenting them into pieces, which will in turn hit more pieces, setting off a chain reaction of destruction that will leave a lethal halo around the Earth. To operate a satellite within this cloud of millions of tiny missiles would become impossible: no more Hubble Space Telescopes or International Space Stations. Even the higher communications and GPS satellites would be endangered. Every person who cares about the human future in space should also realize that weaponizing space jeopardizes the possibility of space exploration.



Catalogued objects near earth.[4]

As a scientist whose research has benefited enormously from space observations, these prospects horrify me. Most of the important astronomical satellites have been placed in the Low-Earth Orbit (LEO) region (from the lowest practical orbits, about 300 km altitude, up to about 2000 km). The Cosmic Background Explorer (COBE) satellite, in a polar orbit at 900 km altitude, allowed the discovery in 1992 of the fluctuations in the first light of the universe—the heat radiation that was emitted as the hot primordial plasma first cooled and became transparent about 300,000 years after the origin, long before the first stars formed. The temperature fluctuations COBE detected are relics of ancient differences in the density of the primordial universe from place to place. These initial conditions are what led over billions of years to the formation of galaxies and larger-scale structures in the universe, according to popular but—before COBE—unconfirmed theories such as Cold Dark Matter.[5]

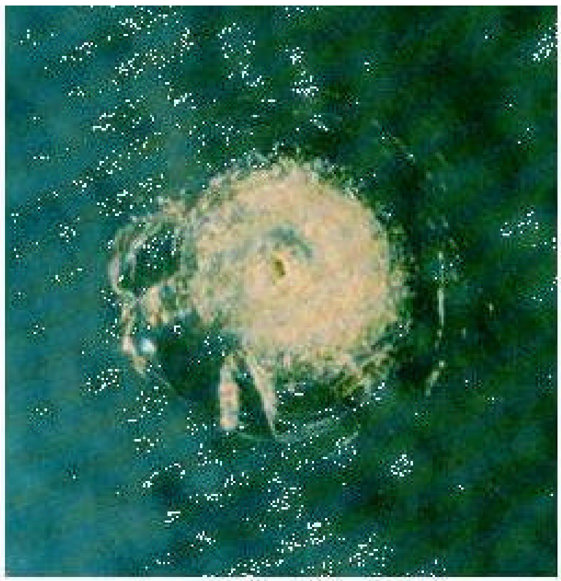
The Hubble Space Telescope (HST), in a 600 km orbit, has observed many Cepheid variable stars in about 20 nearby galaxies, which has finally allowed accurate measurement of the expansion rate of the universe and thus, indirectly, the time since the Big Bang.[6] The Hubble Deep Fields—the longest time exposures with HST—have given us unprecedented images of the first galaxies, which are helping us to understand the history of our own cosmic home, the Milky Way galaxy.[7]

In the seventeenth century, Newton's separation of physics into universal laws and special initial conditions provided a paradigm that still guides the field, even though the universal laws themselves have been revised several times. Darwinian evolution plays a similar central role in biology, connecting the structures of organisms and of ecological communities with the underlying molecular genetics. Geology just advanced tremendously a few decades ago with the confirmation of the plate tectonics paradigm. Now it is cosmology's turn, with the crucial help of observations from astronomical satellites. The data from COBE, HST, and other new observatories should at last give astrophysicists a solid foundation on which to construct an overarching theory of the origin and evolution of the universe, an achievement that is also bound to have deep implications for the development of human culture.[8]

In addition, most Earth-observing satellites are in Low Earth Orbit, both those that study changes in climate and vegetation and also military surveillance satellites. These low orbits permit the highest resolution imaging, and are also easiest to reach with existing launch vehicles.
For example, NASA's LANDSAT-7 is in a 705 km orbit and the European Space Agency's ERS-2 is in a 780 km orbit. NASA's new international Aqua satellite was launched in May 2002 into a 705 km orbit. These satellites are all in sun-synchronous (near-polar) orbits.

But such satellites are already at increasing risk from space debris. At any moment, only about 200 kg of meteoroid mass is within 2000 km of the Earth's surface. Within this same altitude range there is roughly 3,000,000 kg of orbiting debris introduced by human activities. Most of this mass is about 3000 spent rocket stages and inactive payloads. Approximately 40,000 kg of debris is in some 4000 additional objects several cm in size or larger, most of which resulted from more than 120 satellite fragmentations. The main threat to satellites near Earth is from the 1000 kg of 1 cm or smaller debris particles, especially the approximately 300 kg of debris smaller than 1 mm. Such BB-size fragments of debris have the same destructive energy as a bowling ball moving at 100 km/hr. An average small satellite in an 800 km orbit now has about a one percent chance per year of failure due to collision with a BB-size piece of debris.[9] The danger to a large satellite such as Hubble Space Telescope or the International Space Station is even greater.[10] And the amount of small debris is increasing. Random collisions between man-made objects in LEO are still relatively rare, but the density of such objects may already be sufficiently great at 900-1000 km and 1500-1700 km that a chain reaction or cascade of collisions can be sustained.[11] Further growth of the debris population will increase the threat at even lower orbital altitudes. The resulting debris environment will obviously be very hostile to satellites in LEO.

Sally Ride recalled a run-in with space debris on her first shuttle flight. "About halfway through the flight there was a small pit in the window of the space shuttle and we didn`t know what it was. An awful lot of analysis was done while we were in orbit to make sure that the strength of the window would sustain reentry. It did. We were all fine. But the analysis afterward showed that our window had been hit by an orbiting fleck of paint, and the relative velocities were enough that the paint actually made a small but visible gouge in the window. Well, a fleck of paint is not the same as a small piece of metal traveling at that same speed. So, as soon as you start increasing the amount of junk in a low-Earth orbit, you have an unintended byproduct that starts putting some of your own quite valuable satellites at possible risk." Ride asked: "What if anti-satellite testing proceeds and we start testing rockets that clobber satellites and explode them in space? What if enough of that goes on that there`s the equivalent to a test range up in low-Earth orbit?" [12]



Windshield of the space shuttle damaged by a paint chip hurtling through space.

Offensive weapons in space pose the worst threat to satellites in LEO. Fortunately, offensive weapons have not yet been introduced into space—except for a few tests such as a Soviet space mine explosion, or the intentional destruction in 1985 of the still-operating Solwind satellite in a demonstration by the U.S. military. Each of these tests generated hundreds of pieces of trackable debris. But kinetic kill vehicles such as the proposed thousands of "Brilliant Pebbles" are sure to generate great quantities of space debris just during their initial deployment, and far more if they are ever used. Since each of these attack satellites will circle the earth every 90 minutes, basing weapons in space requires hundreds of individual satellites in order that at least one be near its time-urgent target, such as a missile in boost phase.[13]

Any kind of space warfare will put all satellites at risk. The explosion of nuclear weapons in space (prohibited by the Outer Space Treaty, but routinely considered by military planners) would indiscriminately destroy unprotected satellites by electromagnetic pulse (EMP) or nuclear radiation.[14] Perhaps worst of all would be the deliberate injection into LEO of large numbers of particles as a cheap but effective anti-satellite measure. Any country that felt threatened by America's starting to place lasers or other weapons into space would only have to launch the equivalent of gravel to destroy the sophisticated weaponry. Many of these pieces of metallic gravel and fragments of broken weaponry would join all the other debris in orbit. It would hasten the fragmentation of the 3,000,000 kg of dead satellites and rocket bodies now in LEO, and thus produce an enormous cloud of debris that would threaten all satellites in LEO.

Policies that can help avert a space “tragedy of the commons”[15] include the following:

• Do not introduce attack weapons into space.

• Avoid fragmentation of satellites from explosions due to accidents and anti-satellite weapons tests, the main cause of space debris. Prohibit explosions of any kind in space.

• Design boost and deployment systems for satellites that minimize the production of space debris. Require all satellites in LEO to carry a mechanism, such as rockets or inflatable devices to increase drag, which will cause them to reenter within a period of (say) 25 years after their useful life is over.

• Ban nuclear reactors in orbit, since they are an environmental threat and they are useful only for military purposes.[16]

• Minimize light pollution from orbit.

The space age is only 45 years old, yet we humans may already have placed so many artificial objects in the near-Earth environment that random collisions between them can produce a cascading number of debris fragments that will threaten and eventually prevent scientific and other uses of low Earth orbit. Such a debris belt would have other unfortunate consequences: for example, fragmentation of this debris by further collisions can eventually produce enough dust to cause a lingering twilight as it is illuminated by sunlight, a new and particularly unpleasant sort of light pollution.[17] It will without doubt be necessary for all space agencies to take active steps to prevent the buildup of debris, and it is an encouraging first step that NASA and ESA have succeeded in eliminating the Delta and Ariane upper stage explosions that were a major source of orbital debris. But much more effort will be needed, and it may even be necessary to deploy special spacecraft to remove some of the larger pieces of space debris at the altitudes where the critical density for a cascade have already been reached. Designing such devices will be a useful exercise,[18] not least because it will help to impress on public officials the cost of space debris.

National political leaders usually take a short-range view, hardly ever stretching past the next change of government. Astronomers measure time in millions and billions of years. We must help to educate the general public to think with at least an intermediate perspective of centuries and millennia about the environmental degradation that our increasingly powerful technology is causing on and near our beautiful but fragile planet—the only one like it that we know in the entire universe.

1. The Powerpoint presentation of this talk—as presented at the Conference on Future Security in Space, at New Place (near Southampton, England) on May 28-29, organized by the Monterey Institute of International Studies Center for Nonproliferation Studies and by the University of Southampton's Mountbatten Centre—is available as a pdf file on the web at physics.ucsc.edu/cosmo/mountbatten.pdf .

2. G. B. Field, M. J. Rees, and D. N. Spergel, “Is the Space Environment at Risk?” Nature **336**, 725 (1988). J. R. Primack, “Protecting the Space Environment for Astronomy,” in *Preservation of Near-Earth Space for Future Generations*, John A. Simpson, ed. (Cambridge Univ. Press, 1994), pp. 71-76.

3. A good introduction is N. L. Johnson, “Controlling Debris in Space,” Scientific American **279** (2) 62 (August 1998). Standard references on space debris include N. L. Johnson and D. S. McKnight, *Artificial Space Debris* (Orbit Books, Malabar, Florida, 1991); *Space Debris* (European Space Agency, Paris, 1988); *Orbital Debris: A Technical Assessment* (National Academy Press, Washington, D.C., 1995); *Interagency Report on Orbital Debris* (Office of Science and Technology Policy, 1995) available online at www.sn.jsc.nasa.gov/debris/report95.html); *Technical Report on Space Debris* (United Nations, New York, 1999); P. D. Anz-Meador, *History of On-Orbit Satellite Fragmentations*, 12th Edition (Johnson Space Center 29517, July 2001, available online as orbitaldebris.jsc.nasa.gov/measure/SatelliteFragHistory/; and NASA's Orbital Debris Quarterly, available online as orbitaldebris.jsc.nasa.gov/newsletter/news_index.html .

4. Source: NASA Johnson Space Center (JSC) Office for Human Exploration Science website sn-callisto.jsc.nasa.gov/graphics/LEO640.jpg .

5. G. R. Blumenthal, S. M. Faber, J. R. Primack, and M. J. Rees, “Formation of Galaxies and Large-Scale Structure with Cold Dark Matter,” Nature **311**, 517-525 (1984).

6. Freedman, W. L., et al., “Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant,” Astrophys. J. **553**, 47 (2001).

7. R. S. Somerville, J. R. Primack, and S. M. Faber, “The Nature of High-Redshift Galaxies,” Monthly Notices of the Royal Astron. Soc. **320**, 504 (2001).

8. N. E. Abrams and J. R. Primack, “Cosmology and 21st Century Culture,” Science **293**, 1769 (September 7, 2001).

9. D. J. Kessler, R. C. Reynolds, and P. D. Anz-Meador, “Orbital Debris Environment for Spacecraft in Low Earth Orbit,” NASA Technical Memorandum 100-471 (April 1988); J. M. Ryan, “Tossed in Space: Orbital Debris Endangers Instruments and Astronauts,” The Sciences, **30** (4), 14 (July/August 1990).

10. NASA has designed portions of the space station with shielding to provide protection against objects smaller than 1 centimeter. It has concluded that shielding against larger objects would be too costly. Debris from about 0.5 to 20 cm in diameter is of most concern because the debris may be too large to shield against and too small to track and avoid. NASA will require DOD to detect,

track, and catalog objects as small as 1 cm. However, DOD stated that achieving this capability would be technically challenging, according to *Space Surveillance*, General Accounting Office Report GAO/NSAID-98-42, pp. 16-17.

11. D. J. Kessler and B. G. Cour-Palais, "Collision Frequency of Artificial Satellites: The Creation of a Debris Belt," J. Geophys. Res. **83** (A6) 2637 (June 1, 1978); D. J. Kessler, "Collision Probability at Low Altitudes Resulting from Elliptical Orbits," Adv. Space Res. **10** (3)393 (1990); D. J. Kessler, "Collisional Cascading: The Limits of Population Growth in Low Earth Orbit," in *Space Dust and Debris*, Adv. Space Res. **11** (12) 63 (1991). Complete breakup is likely to occur in a collision when (impactor kinetic energy)/(colliding object mass) > 40J/g, so a 0.1 kg piece of debris can fragment a 100 kg satellite if it hits at 10 km/s velocity; see *Orbital Debris* (ref. 3) p.91.

12. Sally Ride, Drell Lecture, Stanford Center for International Security and Cooperation, April 10, 2002, as quoted in Stanford University press release.

13. Suppose, for example, that Space Based Lasers are placed in orbit at about 500 km altitude. Lower orbits are impractical since the satellites would re-enter in only a few years, while higher orbits may be impractical since power falls off as the square of the distance. The number of such satellites necessary in order that one be over (within a 45 degree angle of) any given point on the Earth's surface is then just $4\ r^2$, where r is the ratio of the satellite's altitude to the Earth's radius, 6400 km. For this example, the number of satellites required is 650. If polar latitudes are not covered this number would shrink slightly, but if two satellites are to be over a given target at any time the number of satellites required would be about 1000.

14. See, e.g., J. R. Wertz and W. J. Larson, eds., *Space Mission Analysis and Design* (Kluwer Academic Publishers, Dordrecht, Holland, 1991), esp. sec. 8.2.

15. G. Hardin, "Tragedy of the Commons," Science **162**, 1243 (1968). See also G. Hardin and J. Baden, eds., *Managing the Commons* (Freeman, 1979).

16. See, e.g., J. R. Primack, "Gamma-Ray Observations of Orbiting Nuclear Reactors," Science **244**, 407, E1244 (1989); J. R. Primack, N. E. Abrams, et al., "Space Reactor Arms Control: Overview," Science and Global Security **1**, 59 (1989); S. Aftergood, D. W. Hafemeister, J. R. Primack, O. F. Prilutsky, and S. N. Rodionov, "Nuclear Power in Space," Scientific American **264** (6) 42 (June 1991).

17. S. van den Bergh, "Summary Paper," in *Light Pollution, Radio Interference, and Space Debris*, D. L. Crawford, ed. (Astronomical Society of the Pacific, San Francisco, 1991), p. 329; D. McNally and R. H. Rast, "The Effect of Spacecraft and Space Debris on Astronomical Observations," Advances in Space Research **23,** 255 (1999); J.-C. Mandeville, J.-M. Perrin, and A. Vuillemin, "Space Borne Photometry Perturbations from Solar Light Scattered by Debris: a First Estimate," Acta Astronautica **48**, 229 (2001).

18. See, for example, D. Rex, "Space Debris Mitigation and Space Systems Design," Acta Astronautica **41**, 311 (1997). Cf. R. Crowther, "Space Junk—Protecting Space for Future Generations," Science **296**, 1241 (17 May 2002).