 by Jonathan McDowell

LITTER IN ORBIT:

How to Clean Up Space Junk

LITTERBUGS This artist's representation of space debris in low-Earth orbit is based off of actual data but exaggerates the size of individual objects so that they will be visible at this scale.

GEO 35,800

Thousands of pieces of debris orbit Earth, and it's going to take a coordinated effort to solve the problem.

Sixty years ago, Sputnik became Earth's first artificial satellite. But it wasn't the only thing launched that day — the main rocket stage of the launch vehicle also ended up in orbit, to become the first piece of space debris. There are now more than 9,000 metric tons in orbit around Earth, and 80% of that is orbital debris — "space junk."

Space is famously big, so you might think that even tens of thousands of orbiting objects would have plenty of room to themselves. Indeed, the average distance between debris at any moment is hundreds of miles. But each of those objects is flying around Earth at swift speeds: 28,000 km/hr (17,400 mph) in the lowest, fastest orbits. They sweep through so much space in the course of a short time that the occasional cosmic collision is not only likely but inevitable.

In the Kessler syndrome collisions become so frequent that a chain reaction gradually reduces the near-Earth satellite population to aluminum confetti and makes space travel impractical.

On February 10, 2009, a half-ton communications satellite, Iridium 33, smashed into a dead Russian satellite at a relative speed of 41,940 km/hr and an energy of 54,000 megajoules. (A single megajoule is the energy of a one-ton truck hitting you at 100 mph.) In a fraction of a second, both satellites were reduced to thousands of pieces of shrapnel, many of which remain in orbit today and pose a threat to other space traffic.

As the amount of space junk increases, we risk what's called the *Kessler syndrome*, in which collisions become so frequent that a chain reaction gradually reduces the near-Earth satellite population to aluminum confetti and makes space travel impractical.

Debris Demographics

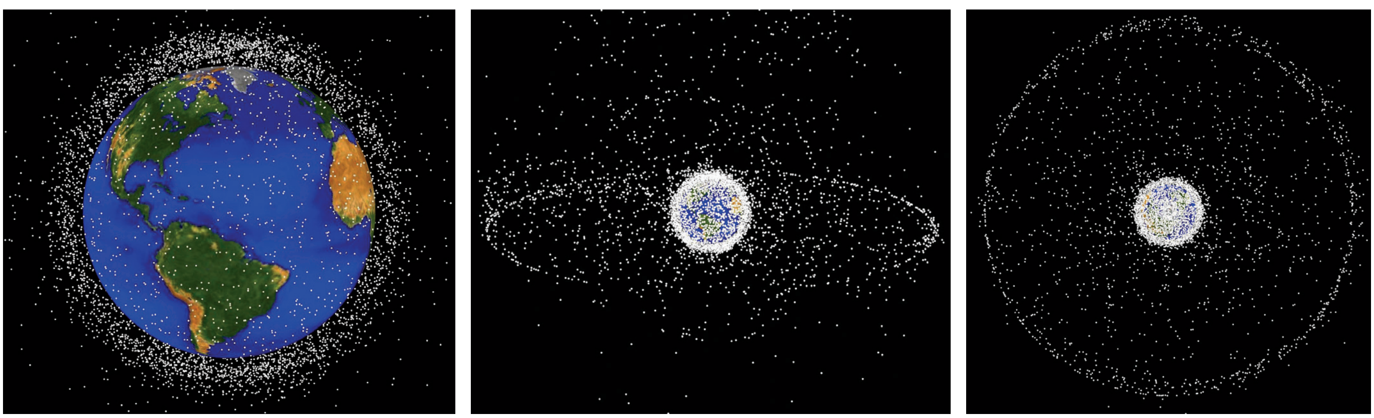
We can distinguish two main kinds of junk: Deliberate littering includes dead satellites, expended rocket stages, and discarded parts such as covers and lens caps. Debris can also result from destructive events, such as rocket explosions, satellite collisions, and antisatellite tests. As the number of satellites has gone up, the number of different types of space junk has also increased over time. In the classic Space Race years of the 1960s, only a few dozen satellites were operating at any one time, but today there are almost 2,000 — and the amount of orbital garbage has ballooned accordingly. The junk increased dramatically in 2007, when China tested an antisatellite missile and destroyed one of its weather satellites, and again in 2009, thanks to the Iridium collision. A handful of incidents have undone decades of efforts to reduce the amount of space junk.

Any piece of debris orbits Earth in a path similar to that of the satellite that made it. Most satellites are either in *low-Earth orbit* (LEO), between 200 and 1,700 km above the surface, or in the 35,800-km-high *geostationary orbit* (GEO), where satellites take 24 hours to circle the planet in order to stay in the same location on the sky as seen from Earth. GEO is mostly used for communications and television-broadcasting satellites, although low-power communications payloads used for cellphone and email traffic can be found in LEO, too.

A special set of near-polar orbits within LEO are known as *Sun-synchronous orbits* (SSO), where satellites pass over the same part of Earth at roughly the same local time every day. Here you can find the satellites that image Earth, both for civilian mapping and government surveillance purposes.

At intermediate heights (*medium Earth orbit*; MEO) between LEO and GEO, the intense Van Allen radiation belts make it harder for satellites to operate. Nevertheless, GPS navigation satellites are among those that operate here in 12-hour orbits.

▼**JUNK NEAR EARTH** The vast majority of debris exists in low-Earth orbit (*left*), but a significant number of objects are in or near geostationary orbit (*center*), which, aligned with Earth's equator, allows satellites to match our planet's spin. A polar perspective (*right*) provides a different view of the density of objects in LEO and GEO orbits. View the debris in motion at **https://is.gd/spacedebrismovie**.



LITTERBUGS: ESA; JUNK NEAR EARTH: NASA (3)

MEO

1,700

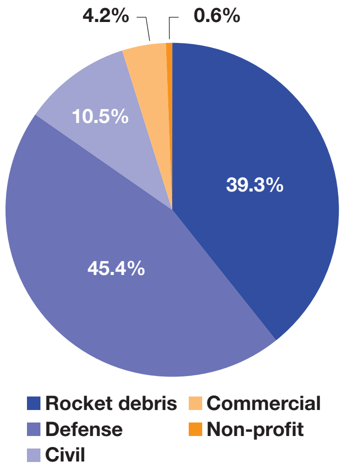
LEO

200 km

All of these orbits are roughly circular — relatively few satellites operate in *highly elliptical orbits* (HEO), where the low and high points (perigee and apogee) are very different from each other. But a lot of junk lies in HEO, mostly from rocket stages, which were left there while delivering a satellite to GEO.

Still, most of the known junk is in LEO, and thanks to the 2007 Chinese military weapons test, the majority of that is in SSO.

That distribution may be an illusion, though, as it's much harder to detect small debris in the higher orbits farther from Earth. The same object in a 10 times higher orbit is 1/100 as bright to optical telescopes and appears 1/10,000 as bright to radar reflection. We'll know better what the high-orbit debris situation is in a few years, when new satellites dedicated to mapping high-altitude space debris give us the true picture. It's likely to be depressing news.



◀ **WHO'S LITTERING?** The littering by civilian and commercial satellites is relatively minor compared to the debris generated by military satellites (medium purple) and exploded rocket stages (dark purple).

Litter Prevention

The major spacefaring nations are now taking steps to lower the risk of a Kessler cascade. Although no international law controls space littering, informal agreements exist between the world's major space agencies. The Inter-Agency Space Debris Coordination Committee provides a forum for these agencies to set recommendations — for example, how high above GEO you should boost your dying satellite so it won't bump into operational ones. The leading centers for research on debris are the Orbital Debris Program Office at NASA's Johnson Space Center in Houston, Texas, and the European Space Agency's Space Debris Office in Darmstadt, Germany, which also hosts regular international conferences on the problem.

These groups have found that there's no one-size-fits-all solution when it comes to space junk. Different kinds of junk need different approaches.

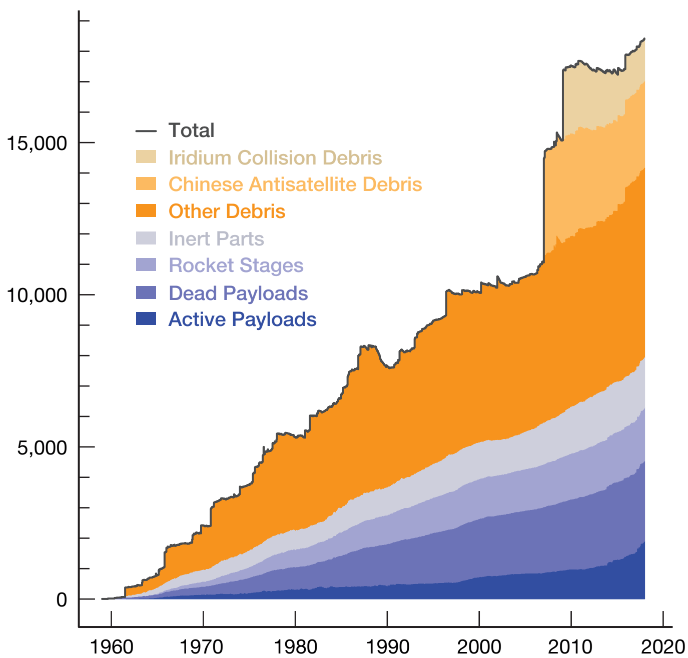
Active satellites are "passivated" at the end of their missions. This neologism indicates that the owners try to get rid of all energy sources that might cause the satellite to blow up at a later date — usually, by venting all rocket propellant and all the fluid from any batteries. In the past, battery explosions had been another significant contributor to space junk.

If the satellite is in a low orbit, it will be lowered toward Earth as much as possible before getting rid of its rocket fuel. The idea is to make it vulnerable to atmospheric burn-up. Getting the satellite to reenter immediately is best, since you can then control where it burns up, but there may not be enough fuel to do this. Even reducing the perigee a bit will help, since the atmosphere gets much denser the lower you go, and atmospheric drag will become more effective in bringing the satellite down, perhaps in months instead of decades.

For satellites in GEO, it wouldn't be practical to bring the satellite down from that high. Instead, they go into a so-called "graveyard orbit," a few hundred kilometers above the geostationary belt. Satellites placed here will stay out of the belt for hundreds of years, even with the perturbing gravity of the Moon and Sun.

Such actions mark a drastic change from 30 years ago, when most low-orbit satellites didn't have the ability to change their orbits at all. A rocket put them in space, and they orbited solely under the influence of gravity and air drag. Nowadays, most satellites with a mass of more than a few hundred kilograms have their own rocket-propulsion systems to alter the orbit at mission's end.

But recent years have brought us a new problem: Since 2003 nanosatellites (less than 10 kg) have become common, most using a standard design known as a CubeSat (*S&T:* Nov. 2013, p. 64). More than 500 CubeSats are now in orbit, and almost none of them have their own rocket engines, posing a challenge for other satellites. Even if a CubeSat is still operating, if it can't get out of the way it might as well be space debris as far as an approaching satellite is concerned. Until recently many CubeSats were launched to low orbits with



▲ **A GROWING PROBLEM** The amount of space junk has increased dramatically over a few decades. Most debris comes from accidental rocket explosions or deliberate military tests. Single collision events, such as the deliberate Chinese test or the accidental Iridium/Cosmos crash, can worsen the situation significantly. Littering of inert parts, rocket stages, and dead satellites makes up most of the rest. Active satellites (dark purple) are only a small fraction of the orbital traffic.

GREGG DINDERMAN / S&T; SOURCE: J. MCDOWELL (2) short lifetimes to perform technology demonstrations. But as CubeSat systems mature, operational constellations are being designed to stay up longer.

In the past couple of years, a wave of new experimental CubeSats have been built to test various ways to get out of LEO cheaply once they're done working. One company is advocating tiny solid rocket motors, but an early test fired in the wrong direction. Most of the current experiments use some variation of *drag brakes*: Either a balloon or parachute pops out of the tiny satellite at the end of its mission and inflates to a much larger size. Friction with the upper atmosphere then decelerates the satellite, ensuring reentry within a few weeks or months.

A bunch of older rocket stages are still in orbit as ticking time bombs.

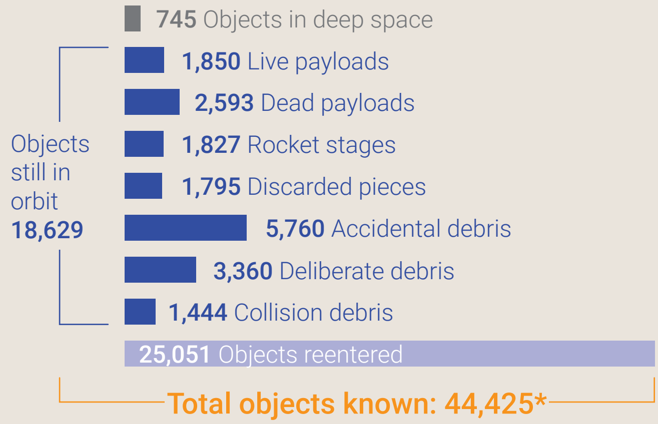
To address the longevity of both CubeSats and larger items, Japan has shown an interest in electrodynamic space tethers, launched coiled up and then unreeled. Earlier U.S. experiments demonstrated tethers many kilometers long. As the tether passes through Earth's magnetic field, currents run along the wire, converting the satellite's orbital motion into heat. As a result, the satellite slowly drops out of orbit. Unfortunately, space tethers have seen a variety of problems in deployment and implementation, which makes it unlikely that they will ever see wide use.

Rocket stages present a slightly different challenge, since they usually run on batteries that last only a few hours. But disposing of them uses the same general idea as for large satellites. When the rocket completes its mission of delivering a satellite, its tanks won't be entirely empty — technicians always leave a little extra in reserve. And since there's no air in space, the rocket also carries an extra tank of oxidizer to help it burn the fuel. As long as the leftover fuel and oxidizer are kept separate, there's no problem. But if the gaskets in the plumbing erode, perhaps months or years after the mission, the two can mix and you can get a large bang. (Of course, in space, no one hears it explode.)

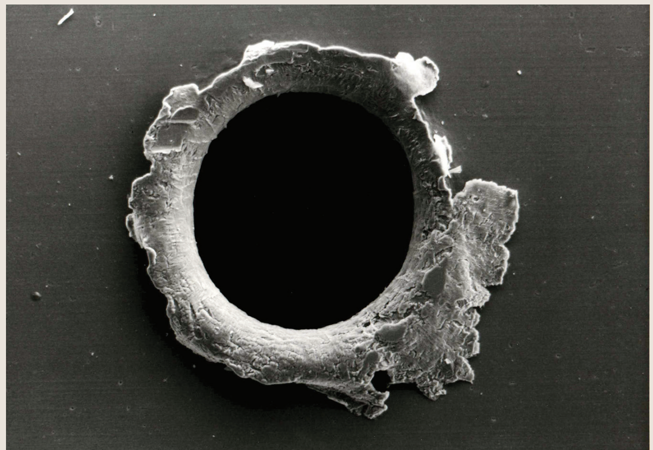
Most modern rockets are designed so that the engine can restart at the end of the mission and use up all the leftovers, preferably making the rocket stage reenter, too, so that it spends only hours instead of years in space. But a bunch of older rocket stages are still in orbit as ticking time bombs: One type of Russian rocket motor, called SOZ, was responsible for four explosions over the past two years. In each case, the motor had been orbiting for about a decade.

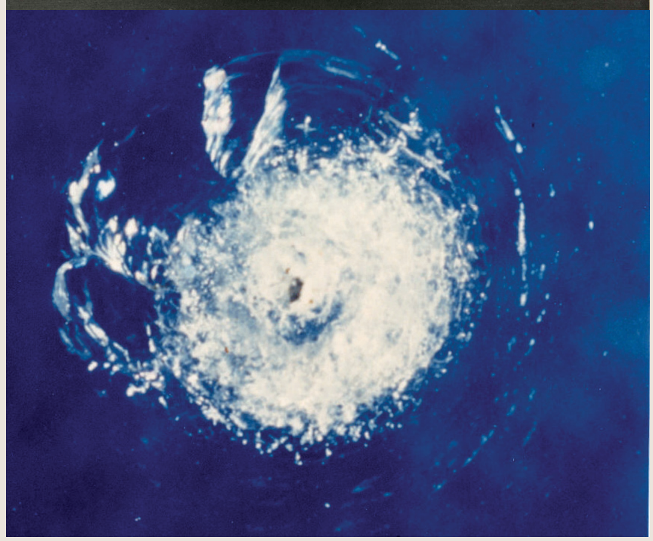
Satellite operators have also learned to do less littering. In the early days of the space age, satellites would often jettison instrument covers that were no longer needed using springs or explosive bolts. Now such covers are often mounted on hinges so that they remain attached. It's more expensive and potentially less reliable, but avoids extra debris.

DEBRIS STATISTICS
(through December 25, 2017)



* Includes 43,086 cataloged objects and 1,339 objects that are known but not tracked.





▲▲ **"SHOTGUN" BLAST** This view shows a small hole that orbital debris created in a panel of the Solar Maximum Mission.

▲ **WINDOW CRACK** Orbital debris the size of a paint chip made this small pit in the window of the *Challenger* during NASA's 7th Space Shuttle mission.

NASA (2)

▶ **SPECTACULAR BREAKUP** A European Space Agency's unmanned cargo re-supply spacecraft, dubbed Jules Verne, burned up over the Pacific Ocean in 2008 after delivering supplies to the International Space Station. An observing campaign monitored the reentry to compare against computer modeling. Watch the breakup at **https://is.gd/julesvernebreakup.**

BIGGEST UNCONTROLLED REENTRIES (reentry mass in metric tons)

12.2	Zenit-2 rocket 11S772/ EPN 03.694	June 21, 1985	*Pacific Ocean*
13.2	UR-500 No. 207 (Proton-1 rocket)	September 18, 1965	*Unknown*
13.2	UR-500 No. 212 (Proton-3 rocket)	January 4, 1966	*Unknown*
13.2	UR-500 No. 209 (Proton-2 rocket)	August 21, 1966	*Unknown*
13.6	Saturn S-IVB-205 (Apollo 7 rocket)	October 18, 1968	*Indian Ocean*
14.5	Saturn S-IVB-204 (Apollo 5 rocket)	January 23, 1968	*Off Australian Coast*
14.6	Tselina-2 No. 3L/Zenit-2 11S772 rocket (Kosmos-1714)	February 27, 1986	*Pacific Ocean*
16.2	Apollo BP-13/ Saturn SA-6	June 1, 1964	*Pacific Ocean*
16.3	Almaz-1 space station (Salyut-2)	May 28, 1973	*Pacific Ocean (near Fiji)*
16.4	Apollo BP-15/ Saturn SA-7	September 22, 1964	*Indian Ocean*
17.0	N-6 No. 1 satellite (Proton-4)	July 24, 1969	*Unknown*
17.2	Saturn SA-5 rocket/ Jupiter nosecone	April 30, 1966	*Brazil*
18.5	DOS 3 space station (Kosmos-557)	May 22, 1973	*Indian Ocean*
39.0	DOS 6 space station/TKS-M module (Salyut-7/Kosmos-1686)	Feb 7, 1991	*Argentina*
45.1	Saturn S-II-13 (Skylab rocket)	January 11, 1975	*Atlantic Ocean (west of Madeira)*
75.7	Skylab space station	July 11, 1979	*Australia*

REENTRIES

One aspect of the space junk problem that tends to get media attention is what happens when larger chunks reenter Earth's atmosphere.

While a lot of the debris pieces are made of aluminum, which melts during reentry, some denser and hardier parts survive the fiery descent and reach Earth's surface. In the 60 years since Sputnik, though, no one has been hurt, and there has been no serious damage from things falling from the sky. In 1962 the service module of Sputnik 4, the prototype Vostok spaceship, reentered over the U.S. — a piece of it was found in the middle of a street in Manitowoc, Wisconsin, but there wasn't even a crater.

The most notorious reentry was also the biggest ever: the 77-ton Skylab space station, which broke up harmlessly over Australia in 1979. Since then, most large spacecraft have been brought down under control using rocket engines, usually in the so-called "spacecraft cemetery" in the central southern Pacific Ocean.

Nowadays, when even a moderate-size spacecraft does make an uncontrolled reentry, like the 7.5-ton Chinese Tiangong 1 space lab on April 2nd, it makes headlines.

▲ **LONE STAR** The main propellant tank of the second stage of a Delta 2 launch vehicle landed near Georgetown, Texas, on January 22, 1997. The approximately 250-kg tank is primarily made of stainless steel and survived reentry relatively intact.

Bad Behavior in Orbit

All of these techniques are working to keep space junk at a lower level, but they can't prevent deliberate explosions and collisions. These have been another big source of debris historically, one that is completely avoidable. Soviet satellites often carried self-destruct packages to prevent them falling into American hands if they reentered. Unfortunately, sometimes these packages would go off by accident. The Soviet missile early warning system used one-ton infrared observatories called Oko (old Russian for "eye") to watch for American missile launches from orbit. These satellites only lasted a few years at best, remaining in highly elliptical orbits as space junk, and their self-destruct systems had a regrettable habit of activating months or years after the satellite's demise, strewing debris on a path ranging all the way from LEO to GEO altitudes.

The U.S., USSR, and China have also all played with weapons designed to destroy an enemy's space systems. Fortunately, none of these weapons have been used against an opponent, but they've been tested against the country's own satellites. The weapons have usually been aimed at a dedicated target. But a U.S. Air Force test in September 1985 did use an F-15 to take out a still-operational U.S. Navy solar physics observatory, causing some bitterness from the Navy scientists whose data suddenly stopped coming in. (Wags at the time suggested the traditional Air Force/Navy rivalry had escalated to confusion about who their real enemy was.)

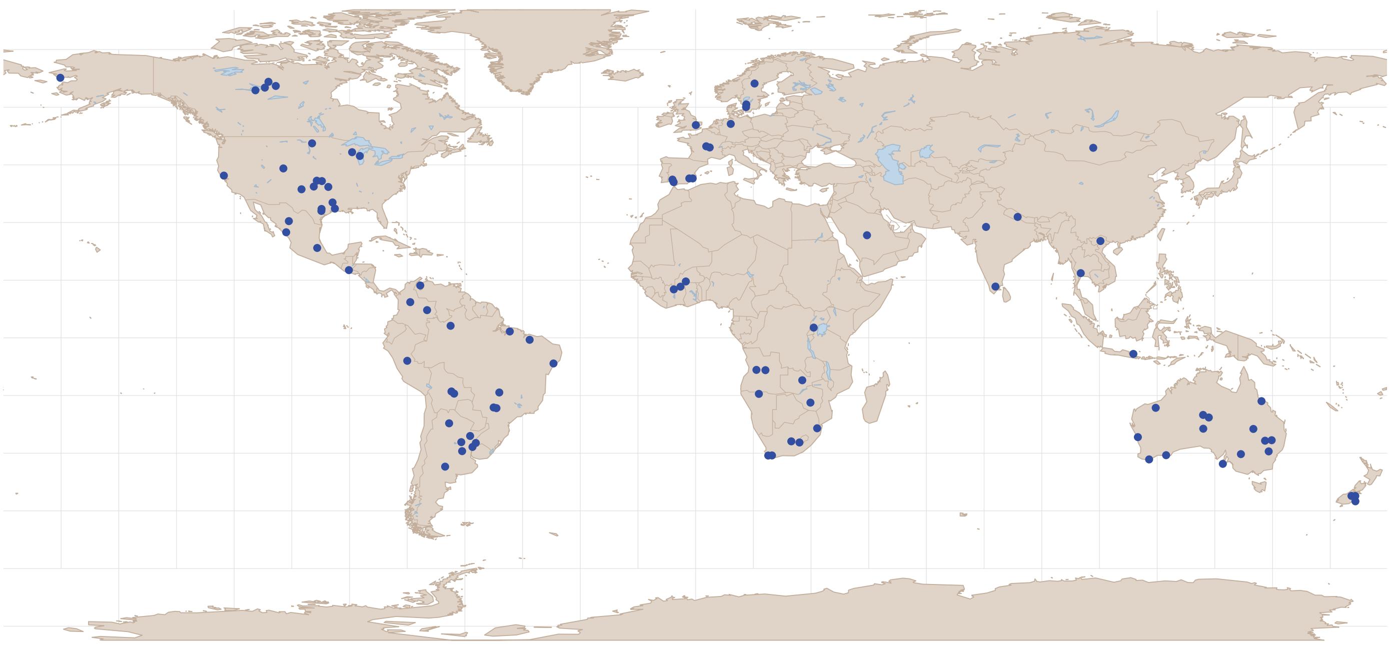
Deliberate collisions are simple to avoid: Let's just not do that sort of thing. But that still leaves the accidental ones. At the moment, the debris from accidental collisions is still a small fraction of all the space junk (only about 3%), so do we really need to worry about it? The problem is that if you have ten times the number of satellites, you typically make ten times the amount of all the other kinds of debris. But you get a hundred times as many collisions; the probability of an orbital crash goes as the square of how much traffic there is. So if we keep increasing our use of space, in a few decades the collisions are likely to surpass everything else and become the main space debris problem. Then we'll be in trouble — Kessler's prediction may come true.

So far, our efforts to reduce how much debris we generate have met with mixed success. Attention is now shifting to more active measures.

Space Garbage Trucks

With tens of thousands of small debris objects floating in near space, some fairly imaginative, and indeed desperate, ideas have been suggested. Powerful Earth-based lasers could melt small debris pieces. Or, a satellite could deploy a huge sticky net, perhaps covered in the aerogel used to collect solar wind samples, and act as a sort of space vacuum cleaner. (Of course, an actual vacuum cleaner wouldn't work in the vacuum of space!) Such devices go under the heading of *active debris removal*, the term of art for space garbage collection.

Perhaps these removal mechanisms aren't really needed, though, because it turns out the smallest objects aren't the worst problem. Most of them have a fairly large area-to-mass ratio: They're more like feathers than cannonballs, so they're strongly affected by atmospheric drag. In orbits below 500 kilometers, objects will usually reenter over the course of the solar cycle. Every 11 years, as our star reaches solar



▲ **REENTRIES AROUND THE WORLD** Debris fragments have been recovered on the ground worldwide. Even so, the hazards posed by reentering spacecraft and debris are extremely small. Space agencies and nation states typically aim for a casualty risk of less than 1 in 10,000 probability for a single uncontrolled reentry.

JULES VERNE: ESA / NASA; LONE STAR: NASA; MAP: GREGG DINDERMAN / S&T; SOURCE: ESA maximum, its wind stretches out Earth's atmosphere. As high-density air reaches higher altitudes, it clears out much of the LEO debris.

Further, simulations show that the biggest contributors to a Kessler cascade would be the largest satellites. The Iridium-Cosmos collision is a case in point — it's this sort of crash that makes the most debris. So maybe we should focus on getting rid of the monster space junk first; there's less of it, so that's an easier problem.

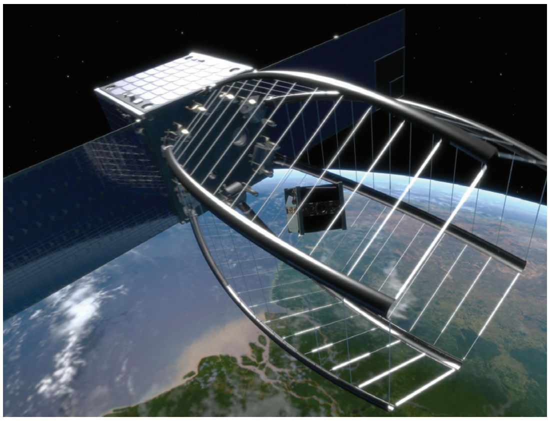
We will soon have the technology to do just that. Building on the collective experience in sending robotic cargo ships to the International Space Station (ISS), companies may soon build satellites to grab onto and repair or refuel communications payloads, even those that — unlike the ISS — weren't designed for visitors. Such space tugs could also move their prey to a different orbit, perhaps sending them down to controlled reentry over the ocean.

But whose stuff can you deorbit? NASA, for example, would be allowed to deorbit its own space junk, but the legality of grabbing onto someone else's dead satellite is questionable, even if it belongs to a country that no longer has a space program. Space lawyers are already talking about this issue!

Space tugs wouldn't come cheap, either. Different satellites fly at various orbital inclinations to the equator. Changing from one orbit to another would require too much fuel to be practical, so tugs would have to stay at a narrow range of inclinations.

Nevertheless, in the long run I expect we'll see a fleet of space garbage trucks sidling up to long-dead spacecraft and nudging them to their doom. Or, perhaps, sending them to very high orbits, where the low orbital velocities make it cheaper to change inclination. You could potentially collect billions of dollars of defunct high-tech material in an orbital scrapyard, where materials could be recycled.

At this point, the challenge has become more political and economical than technical. I believe that some kind of international tax on satellite operators will be needed to fund the orbital cleanup system. As usual with environmental problems, it's one thing to realize we have a disaster on our hands — it's quite another to agree to do something about it. Let's hope we still have space exploration a century from now!



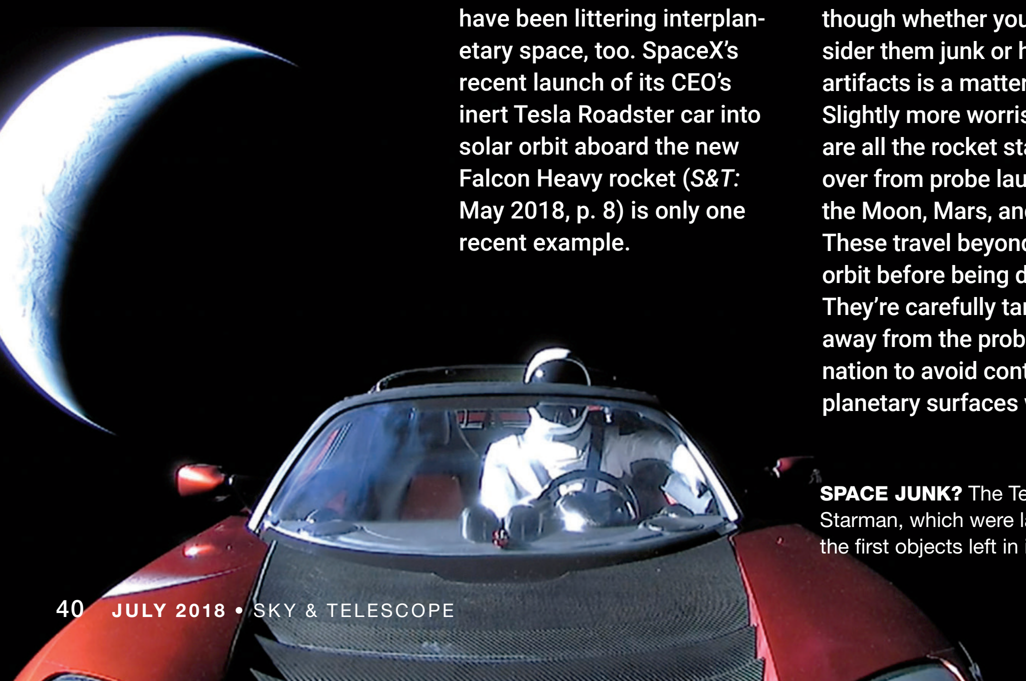
▲ **INVENTION OF NECESSITY** The Cleanspace One concept, which features a Pac-Man-like mechanism for capturing space junk, is one of many inventive ideas on the drawing board for dealing with orbital debris.

■ In addition to studying black holes and devising data-analysis software, astrophysicist **JONATHAN MCDOWELL** (Harvard-Smithsonian Center for Astrophysics) is an avid investigator of space history. His free online newsletter, *Jonathan's Space Report*, has provided technical details of satellite launches since 1989. Find out more at **planet4589.org**.

INTERPLANETARY SPACE JUNK

In this article I have concentrated primarily on the junk that orbits Earth. But humans have been littering interplanetary space, too. SpaceX's recent launch of its CEO's inert Tesla Roadster car into solar orbit aboard the new Falcon Heavy rocket (*S&T:* May 2018, p. 8) is only one recent example.

The surface of the Moon is scattered with the relics of the Apollo lunar missions – though whether you consider them junk or historical artifacts is a matter of taste. Slightly more worrisome are all the rocket stages left over from probe launches to the Moon, Mars, and Venus. These travel beyond Earth orbit before being discarded. They're carefully targeted away from the probe's destination to avoid contaminating planetary surfaces with any terrestrial microbes that might have hitched a ride on the vehicles. But that avoidance is only for the stages' first orbit around the Sun. Over the decades, centuries, and millennia to come, there's about a 10% chance that these abandoned rockets will end up smashing into one world or another. Although it's unlikely there will be any biological material left onboard to violate the planetary protection criteria by that point, they'd still make a big mess.



SPACE JUNK? The Tesla Roadster and its dummy occupant, dubbed Starman, which were launched into a solar orbit earlier this year, weren't the first objects left in interplanetary space.