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News & Highlights

Climate Change and Pollution Threaten Exploding Space Economy

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On 28 April 2025, Amazon's Project Kuiper launched its first 27 satellites [1], joining a growing number of private companies and government-backed programs aiming to blanket the Earth with many thousands of satellites in low Earth orbit (LEO) (Fig. 1) [2]. Yet, even as Amazon (Seattle, WA, USA), SpaceX (Hawthorne, CA, USA) with its Starlink constellation, Shanghai Spacecom Technology (Shanghai, China) with its Qianfan constellation, and others push to saturate the globe with satellite-based internet coverage, recent research suggests that this new space race is associated with underappreciated and poorly understood, but likely negative, environmental impacts [2–6].

Additional research suggests that the orbital environment is being altered by the same human activity causing climate change on Earth, with potentially calamitous long-term consequences for the burgeoning space economy [7]. As reported in a June 2025 paper in *Nature Sustainability*, researchers have determined that the greenhouse gas (GHG) emissions increasing temperatures near the Earth's surface could effectively force satellites to operate in lower orbits to ensure the atmosphere can recycle them at a reasonable cadence. The paper's authors suggest that this shrinking of the orbital zone in which satellites can be relatively quickly dragged back to Earth may act to diminish the available orbital space by anywhere from one-third to 82% by the end of the century, depending on the extent of future carbon emissions [7].

For decades, the satellite industry has operated under the assumption that LEO below an altitude of 625 km would clean itself. Although thin, the atmosphere at altitudes between 160 and 2000 km creates atmospheric drag, a natural braking mechanism that causes satellites and space debris to lose altitude, and eventually burn up during reentry [8,9]. This process is key to preventing the long-term accumulation of space junk, and it forms the basis for many organizations' post-mission disposal guidelines. However, as human activity pumps more GHG emissions into the atmosphere, it may reduce the atmospheric drag expected to help clear out aging satellites and debris.

"We have been able to record measurements over the last several decades showing a long-term reduction in the density of the thermosphere, 550–600 km in altitude, the region of the atmosphere where a significant portion of satellites are operating," said William Parker, first author of the *Nature Sustainability* paper and a doctor of philosophy candidate at the Massachusetts Institute of Technology (Cambridge, MA, USA).

The effect is counterintuitive. While GHG emissions trap heat in the lower atmosphere, causing the planet to warm, it has the opposite effect in the middle and upper atmosphere. At altitudes above the tropopause (averaging around 11 km), the interface between the troposphere and the stratosphere, GHG emissions act as a coolant, causing the upper atmosphere to contract downward and leaving the air at the edge of space thinner than before [7,9].

This contraction might seem like good news—less drag means less fuel needed by active satellites to maintain their orbits. But it also means the natural mechanism for removing the thousands of defunct satellites and pieces of debris in orbit becomes less effective. "Debris and dead satellites will stay in orbit for longer, increasing the probability of collision," said Ingrid Cnossen, an independent research fellow with the Space Weather and Atmosphere team at the British Antarctic Survey in Cambridge, UK. "Satellite operators may not be aware of this issue."

To counteract the reduction in drag satellites may have to operate at lower altitudes, where they would need to regularly use thrusters to avoid getting dragged down to Earth [9]. In addition, more satellites would be squeezed into a more confined space. Debris already in orbit will not be removed as quickly. All this increases the risk of satellite-destroying collisions [10].

Another source of variability in thermospheric density that is more well known and attracts significant attention is the solar wind. Interactions between the solar wind and the Earth's magnetic field and the magnetosphere can heat up the thermosphere, causing the upper atmosphere to expand and ultimately create significant additional drag [11]. "Solar wind is something that operators are very concerned about—it throws active satellites off course if not compensated for," Cnossen said. Satellite operators put "a lot of effort" into trying to predict those short-term density fluctuations, Cnossen said. The long-term change is a more subtle effect, she added. "The satellite industry would be wise to also consider what lays ahead on longer timescales, looking several decades ahead."

Whether on short or long timescales, the number of satellite adjustments needed to counter variation in thermospheric density is compounded by the sheer scale of the massive satellite constellations making their way to orbit, each with the goal of offering faster, cheaper internet for underserved regions, remote military installations, and mobile phone users worldwide [12]. Starlink currently operates more than 7000 satellites, with plans to expand to 42 000 [13]. As of August 2025, Amazon had launched just over

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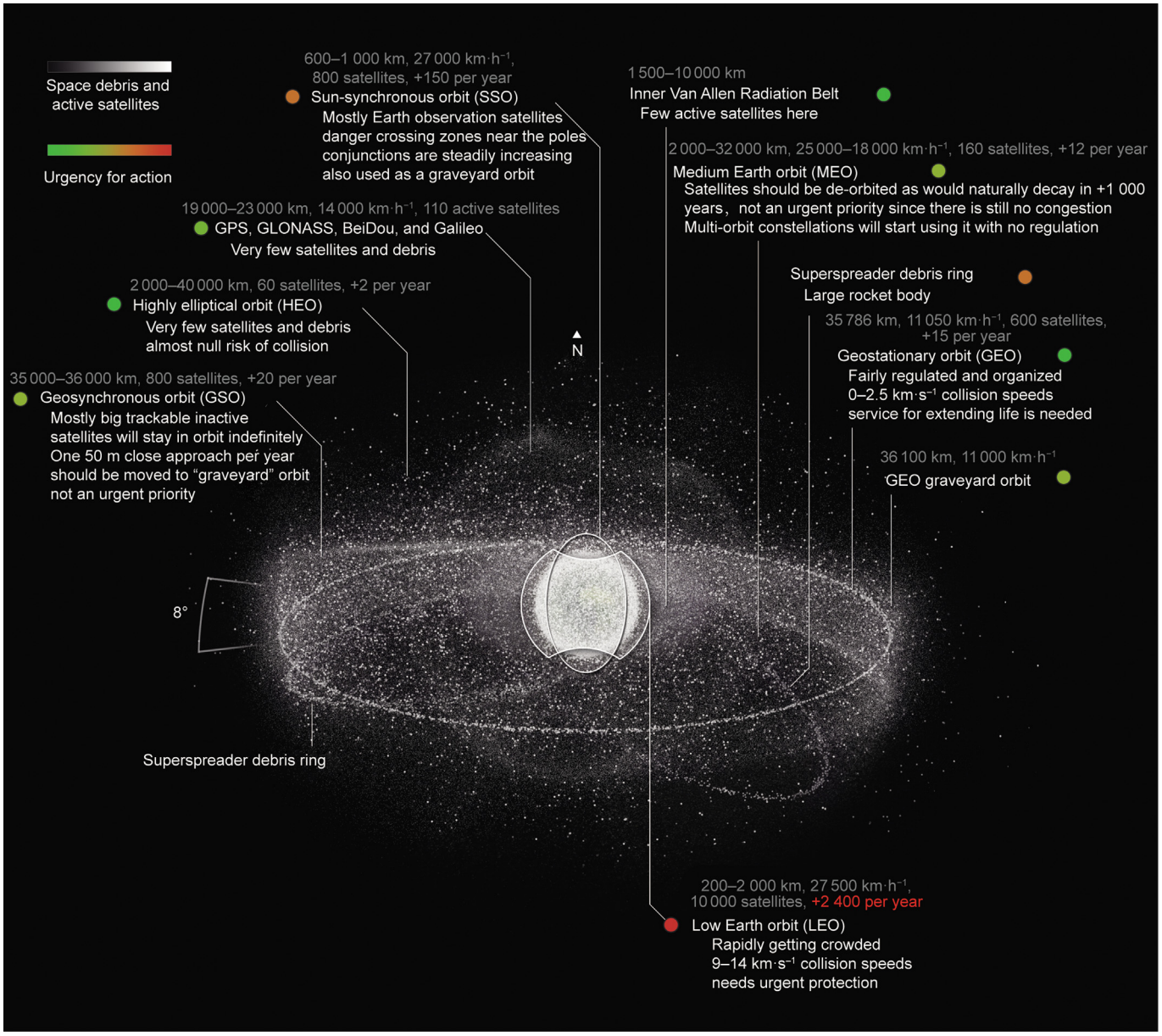

Fig. 1. This 2023 representation of the location and density of active satellites and large chunks of space debris indicates which orbits around Earth are in the most need of action to prevent catastrophic collisions. Among the most at-risk orbits are the LEO, which currently hosts around 10 000 satellites, and the superspreader debris rings, populated with large, discarded rocket bodies. GPS: Global Positioning System; GLONASS: Global Navigation Satellite System. Credit: Pablo Carlos Budassi/Wikimedia (CC BY 4.0).

100 Kuiper satellites (the latest via a SpaceX Falcon 9 rocket), with plans to deploy more than 3200 over the next several years [14]. Meanwhile, Shanghai Spacecom Technology envisions more than 14 000 Qianfan satellites orbiting in a synchronized formation [13]. "It is mind-boggling how quickly these constellations are growing," said Connor Barker, a research fellow in atmospheric chemistry at University College London (London, UK). Barker notes that more propellant is now being used to launch satellites that are part of massive constellations than for all other types of launches combined.

While the unprecedented increase in satellite activity demands an increased level of diligence and cooperation, existing frameworks may not be up to the task. The United Nations Office for Outer Space Affairs and its Committee on the Peaceful Uses of Outer Space has set up two different working groups—Working Group on the Long-Term Sustainability of Outer Space Activities [15] and the Expert Group on Space Situational Awareness [16]—to begin looking at this issue and bring expert viewpoints into global conversations around space traffic coordination. In addition, the International Astronautical Federation [17] and the International Association for the Advancement of Space Safety [18] have active space traffic management committees. "These conversations will be ongoing over a number of years," said Jonathan McDowell, an astronomer at the Harvard Smithsonian Center for Astrophysics in Cambridge, MA, USA. "They are not likely to result in a global space traffic management system, but rather ways to coordinate between different national initiatives."

Already, there have been collisions and many close calls [10]. SpaceX alone performed 50 000 collision avoidance maneuvers in just the first six months of 2024 [19], and coordination with international space agencies has been less than seamless. The US National Aeronautics and Space Administration, the European

Space Agency (ESA), and the China National Space Administration have all reported instances where commercial satellites have forced their spacecraft to take evasive maneuvers [20–22].

Global best practices and guidelines around post-mission disposal have historically been voluntary. While the US Federal Communications Commission in 2022 moved from recommending that operators remove defunct satellites within 25 years to within five years starting in 2024 for many of its licenses [23], compliance, lack of funding, and inability to de-orbit safely remain problems. "The bigger challenge than the length of the guideline is compliance itself," said McDowell. "The European Space Agency is moving toward a 'zero debris impact' standard, but it is enforced through contracts, not regulation." ESA's zero debris approach seeks to stop the generation of space debris by 2030 through improved satellite design and disposal methods and better space traffic surveillance and coordination [24]. McDowell added that enforcement mechanisms, such as fines or potential consequences for future licenses, may be necessary across space agencies.

Parker said that in the absence of broadly agreed-upon rules for LEO, whoever gets there first gets to set the standards and behavioral norms. However, essentially each operator can set their own tolerance for risk and decide for themselves when a collision avoidance maneuver is necessary. "That is not a good thing for the long-term health of the environment," he said. "You need to have predictable behavior from different operators."

Geopolitical tensions also present a challenge to reaching broad consensus on orbital traffic management protocols [2,10,25]. Meanwhile, recognizing space clutter as a potentially catastrophic problem, companies such as ClearSpace (Renens, Switzerland), Astroscale (Tokyo, Japan), and Northrop Grumman (Falls Church, VA, USA) are developing technologies designed to de-orbit dead satellites and other space debris [26]. Space agencies in Europe, Canada, Japan, the United States, and elsewhere are also testing removal technologies [10]. But these solutions are costly and difficult to scale, said Darren McKnight, a senior technical fellow at LeoLabs, a Menlo Park, CA, USA-based company that tracks space debris.

Another concern emerging as the size of constellations mushrooms is pollution released when satellites re-enter the atmosphere and burn up. One study published in 2023 found chemicals such as niobium and hafnium, which do not occur in the atmosphere naturally but are used in satellites and rocket boosters, embedded within roughly 10% of the most common aerosol particles in the stratosphere [27]. Another study published in 2024 used an atomic-scale molecular dynamics simulation to estimate that airborne aluminum oxide pollution from satellites increased eightfold between 2016 and 2022 [28]. Aluminum oxide nanoparticle compounds generated by all the satellites re-entering the atmosphere in 2022 were calculated to weigh in at around 17 t. That number is expected to rise to 360 t annually as planned megaconstellations expand to their projected numbers in the near future, which could result in significant ozone depletion [28].

There are still many unknowns regarding these chemicals, McDowell said. "We do not know the distribution of these particles in the atmosphere, whether it is a localized effect or a global effect," he said. "We do not know what altitudes the particles settle in, and we do not know how long the particles remain."

The potential threat of the pollution from satellites burning up in the atmosphere is underscored by the fact that newer satellites are built with a "design-for-demise" approach to specifically burn up in the atmosphere [9,10]. "Operators are quite confused because it seems like environmentalists and academics are conflicted," McKnight said. "They are saying, 'Hey, you should do design-for-demise, so things do not hit the ground. Oh wait, do design-for-reentry, so things do not burn up in the atmosphere.'"

In addition to satellite re-entries, rocket launches produce their own atmospheric pollution. Rocket engines release black carbon, NO_x, CO_2, chlorine, CO, and aluminum oxides, with impacts varying by fuel type and altitude. Research published by Barker and colleagues in 2024 suggests that black carbon injected into the upper atmosphere has 500 times more warming potential than at the surface [3]. They found that from 2020 to 2022, emissions from megaconstellation launches accounted for nearly 40% of black carbon and CO_2 emitted across all space activities [3]. Other studies in the past few years have also indicated that pollutants released during rocket launches and those created during space debris reentry may be slowly shredding the planet's delicate ozone layer [4–6].

Even "clean" fuels like hydrogen produce NO_x through atmospheric heating during ascent, Barker said. And while the liquid methane burned by SpaceX's Starship is not directly toxic to the environment, unlike the kerosene used in other rockets such as the Atlas V and Saturn V and SpaceX's Falcon 9 and Falcon Heavy [29], each Starship launch releases 76 000 t of CO_2 equivalent [30]. Barker said this puts Starship and the Falcon Heavy on roughly equal footing regarding emissions per launch. "Even though you have switched to this slightly cleaner fuel, you are still launching such a big rocket that you are going to have the same emissions or even greater."

As the orbital space becomes more crowded and less forgiving, the intersection of environmental impacts and space policy seems to be a needed focus for greater concern. It is well established that GHG emissions have consequences like rising sea levels and deadly heatwaves on Earth. It now appears they could also threaten the long-term viability of today's space-based infrastructure. In the coming years, satellite operators, environmental scientists, and regulators will need to work together—across industries and borders—to ensure that the Earth's newest commons remain optimally usable and safe. The emerging findings beg the question, said Barker: "What does sustainability mean in the space industry?"

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