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Proliferating Satellite Constellations Pose Astronomical and Environmental Challenges

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On 6 October 2023, Amazon (Seattle, WA, USA) launched two prototype satellites into low-Earth orbit [1], the inaugural orbiters of Project Kuiper, a constellation of 3236 satellites that will work together to eventually deliver internet to tens of millions of customers worldwide. While Kuiper, named for the belt of ice, rock, and dwarf planets beyond Neptune, is smaller in number than the so-called mega-constellations built by SpaceX (Hawthorne, CA, USA), OneWeb (London, UK), and others, Amazon plans to loft its Kuiper satellites into orbit at a historic pace over the next few years.

Such ambitions for space-based communication networks are raising fresh concerns about the negative consequences of the proliferation of satellites buzzing above Earth, where they disrupt astronomical observations and contribute to atmospheric pollution. While astronomers, environmentalists, and others point to these concerns, they also note that regulators seem unable to set limits on the industry.

The constellations promise to provide internet access anywhere in the world. "Nobody can possibly lay enough fiber to do that," said Darren McKnight, a senior technical fellow at LeoLabs, a Menlo Park, CA, USA-based company that tracks space debris. "This does not mean that industry should get a pass to do anything they want. They need to be responsive and really understand the potential negative consequences."

A decade ago, there were fewer than 1000 active satellites in orbit. As of June 2023, there are more than 11 000 [2]. SpaceX's Starlink constellation, which now provides internet to two million customers [3], accounts for more than 5400 [4]. The total number across companies is set to increase rapidly (Fig. 1).

In April 2022, to begin to build its Kuiper constellation, Amazon purchased up to 83 rocket launches, the largest-ever commercial purchase of launches, including 27 from its space-focused subsidiary, Blue Origin (Kent, WA, USA) [1]. The US Federal Communications Commission (FCC), which regulates satellite communications to the ground, approved Amazon's Kuiper network in 2020. The FCC gave the company a deadline to launch half of its planned 3236 satellites by July 2026, with the remainder to be deployed by July 2029 [1].

Satellite constellations communicate with each other and the ground through radio signals. Between 2017 and 2022, filings for radio spectrum allocations with the International Telecommunication Union (ITU) indicate that more than one million satellites—including 90 constellations exceeding 1000 satellites each—are already on the schedule to come online [5]. About a third of the filings came from French company E-Space, which submitted for a constellation of 337 320 satellites named Cinnamon-937 in September 2021 through the Rwanda Space Agency. The company submitted another large filing for 116 640 satellites in June 2023 [6]. While this seems like enormous numbers of satellites, many experts expect only a fraction of them to actually launch. In addition, the technology has advanced enough that each satellite packs sufficient functionality that some may be no larger than a shoebox; this, in turn, makes such large constellations financially feasible, greatly reducing the costs of building, launching, and replacing them.

Not surprisingly, however, these numbers have astronomers concerned [7]. While satellites do not produce light, they reflect sunlight down to Earth. Some do so with such intensity that they etch bright trails across images astronomers gather when their telescopes capture light from the sky over prolonged exposure times (Fig. 2). These trails of light often render the data unreadable.

"Satellites are everywhere," said Meredith Rawls, an astronomy research scientist at the University of Washington in Seattle, WA, USA, who works with the Vera C. Rubin Observatory. "You cannot go to the most remote isolated mountaintop and have a prayer of escaping them because they are intentionally blanketing the whole globe."

The global coverage of satellites is not just a problem for light-based observations. Radio-based observations are also at risk. "Radio observatories are usually placed in remote areas, surrounded by protected quiet zones," said Aaron Boley, associate professor of physics and astronomy at the University of British Columbia in Vancouver, BC, Canada. "While there are coordination agreements to help ensure satellite operators are not transmitting directly at radio facilities, just the operation of satellites creates radio noise. And now with so many satellites going up, that noise is becoming much more of a problem."

Satellites do not just make astronomical observations more difficult. They can outright fool astronomers. In December 2020, US

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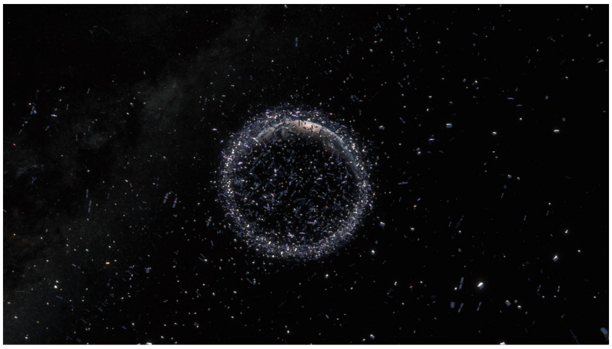

Fig. 1. The space around Earth is already very crowded. Existing satellites and planned constellations will join the throng shown in this illustration of the larger pieces of space debris—old, defunct satellites and other assorted flotsam related to the space industry—being tracked by the US Space Surveillance Network. Credit: European Space Agency/ID&Sense/ONiRiXEL (CC BY-SA 3.0 IGO).

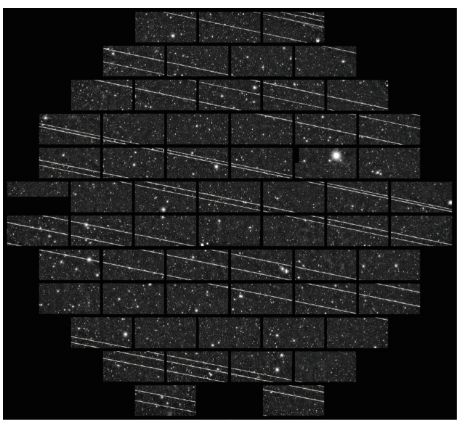

Fig. 2. Satellites streak through this 333-second exposure image taken from the Blanco four-meter optical telescope at the Cerro Tololo Inter-American Observatory in Chile in November 2019. Credit: US National Science Foundation National Optical-Infrared Astronomy Research Laboratory/CTIO/AURA/DELVE (CC BY 4.0).

and Chinese astronomers reported what they thought was a burst of highly energetic light from one of the most distant galaxies ever observed [8]. But other scientists have since presented evidence that the burst was merely a passing satellite [9]. Such mistakes could have important consequences. "Astronomy is one of the ways that we test fundamental theories about new physics," Boley said. "Interfering with it compromises our capacity to better understand the universe."

Having an unvarnished view of the night sky has also become fundamental to planetary defense systems that hunt for objects on a collision course with Earth. "Time is crucial for those type of observations," Boley said. "And when you start talking about missing data, and delaying observations, you could be delaying critical reactions to existential threats."

Astronomers are not entirely helpless, though. They have developed a few tricks to work around satellite interference. "To some degree, we know where these satellites are going to be and how bright they are," Rawls said. But to plan observations around the streaking satellites requires significant time and energy, she said.

Astronomers can also deploy software to filter out light reflected off satellites. Rawls said some observatories have even started building secondary, all-sky telescopes that can follow along and take a low-quality image of the same area of sky the primary telescope is pointing at. "They can then go back and say, 'Do we need to throw any data out?' " she said, citing the time-intensive nature of data processing and the utility of not wasting time on corrupted observations. "But that is a huge added expense."

Another expensive, though not foolproof, workaround is swapping out the slow charge-coupled device (CCD) sensors found in most telescopes with newer complementary metal–oxide–semiconductor (CMOS) detectors that can obtain images a few orders of magnitude faster, reducing the chance that a traversing satellite spoils the data [10]. Rawls said that the swap may work for smaller telescopes but not larger ones like the Vera C. Rubin Observatory in Chile. The car-sized, mammoth CCD sensors such telescopes typically rely on would be very difficult to replace.

In any case, while astronomers have found industry a somewhat willing partner in seeking ways to darken satellites, they are also trying to persuade regulators to hold manufacturers accountable for the negative consequences of their constellations. So far, the results have been mixed.

SpaceX has tested several methods for making its satellites less reflective. A painted-black Starlink prototype named DarkSat flew to orbit in 2020, but it overheated and failed [11]. Unfortunately, black satellites absorb more heat. "One of the best ways to kill a satellite is to have it absorb too much heat," McKnight said.

The company also tried installing shades over its satellites that prevent sunlight reflecting off the crafts' white antennae, an idea quickly abandoned because the shades did little to make the satellites less bright, and they blocked the satellites' laser communications links [11,12]. SpaceX also began rotating its satellites so their solar panels, their most reflective part, pointed away from Earth at twilight when many astronomical observations are made [13]. To compensate for the resulting loss in solar power, the company outfitted its satellites with larger solar panels at an extra cost. Initial data indicate that this intervention may be working [10,14].

In 2022, the US National Science Foundation (NSF) announced a formal agreement with SpaceX to maintain Starlink orbital elevations of 700 km or lower [15]. The FCC has since required other satellite providers, including Amazon, to coordinate with the NSF on similar protections [16]. "It is a somewhat counterintuitive requirement because you would think that if the satellite is closer to you, it is brighter and you would be correct," Rawls said. "But at lower altitudes, it orbits more quickly and so it moves out of the way faster and does not linger as long in any given pixel." Rawls also pointed out that putting satellites at lower orbits means companies need to launch more satellites to get full global coverage because each one has a reduced line of sight to Earth. "There are a lot of interesting trade-offs," she said.

More satellites in lower orbit also increase the likelihood of collisions. "I am not particularly worried about the space traffic management challenges within a company," said Chris Johnson, director of Legal Affairs and Space Law for the Secure World Foundation, a Washington, DC, USA-based think tank focused on peaceful uses of outer space. "The real challenge will be when different operators all have traffic on the same road."

Starlink's traffic management system was put to the test in 2021, when Russia destroyed a defunct Soviet-era satellite at an orbit of 470 km by slamming a missile into it [17]. The explosion created at least 1500 pieces of debris large enough to track from the ground. "That event put a lot of pressure on Starlink to maneuver around the debris for nine months or so," McKnight said. "But they came through unscathed."

Another trade-off with placing satellites in lower orbits is gravity drags them back to Earth more quickly than when they are at higher orbits, meaning shorter lifespans. Newer satellites are being built with a "design-to-demise" approach, purposely made to burn up in the atmosphere. "It is considered a good space sustainability practice to have your spacecraft intentionally burn up rather than crash to the ground and hurt someone," Boley said. However, in addition to increased replacement costs for operators, lower orbits mean more frequent occurrences of the optical flares of satellites burning up in re-entry that also mar astronomic observations.

Dying satellites also create another problem: As they disintegrate in the upper atmosphere, they leave behind a stream of pollutants [18]. Niobium and hafnium, for example, do not occur in the atmosphere naturally, but are used in satellites and rocket boosters. These metals, along with aluminum and lithium and other distinct elements used in spacecraft, have been found embedded within roughly 10% of the most common aerosol particles in the stratosphere [19]. What the consequences of adding these metals to the atmosphere might be is unknown. "We are basically doing a real-time experiment with our atmosphere," Rawls said. "In the meantime, we are treating it like an infinite garbage dump."

In addition to dying satellites, the exhaust emitted from the rockets bringing satellites to orbit also contributes to atmospheric pollution. While the quantity of pollution is dwarfed by that generated by the aviation industry, rocket exhaust may be more harmful because it is released at higher altitudes. Researchers recently reported that rocket exhaust soot at high altitudes has nearly 500 times as much global warming potential as soot released from airplanes flying closer to the Earth's surface [20]. They determined that a ten-fold increase in the rate of rocket launches could cause temperatures in parts of the stratosphere to rise as much as 2 °C [21]. They additionally postulated that a temperature rise of that magnitude could degrade the ozone layer over most of North America, Europe, and large swaths of Asia, greatly increasing exposure on the ground to harmful ultraviolet radiation [21].

But finding ways to regulate pollution related to satellites is not straightforward. Nearly every regulation around the globe related to the space industry revolves around launch safety and little else, leaving problems like space industry-related atmospheric pollution unaddressed [19]. And this makes it difficult to compel the industry to account for the potential negative consequences related to its satellites.

The United States, for example, has no law that unambiguously protects the space environment. A dispute is ongoing about whether the National Environmental Policy Act (NEPA) could and should apply to private commercial satellite launches and operations licensed by the federal government [22]. If NEPA applied, federal agencies like the FCC would be required to prepare environmental impact statements for the licensing of large constellations. Such regulations could, for instance, mandate using less toxic materials in the construction of satellites.

In the end, some wonder if regulators should consider if all these constellations are needed in the first place. "I wish we could just be happy with a few geosynchronous satellites for all of our telecom needs and a little bit of lag," said Rawls. "But that is not where we are at." Astronomers are not against satellites, Boley said. "We are against the unmitigated proliferation of satellites—we really need better coordination among regulators to address the global-scale impacts."

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