# The Impact of Anthropogenic Activities in the Natural Environment Environment and Societies During Contemporary Period

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## Chapter 1.2

## Anthropogenic Impacts in Space: Challenges and Opportunities

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CHAPTER

1.2

# Anthropogenic Impacts in Space: Challenges and Opportunities

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## Introduction

Here we describe some of the significant ways in which human activities are interacting with the space environment to yield anthropogenic impacts. We first describe the atmospheric impact of space launches, then the closely related problem of orbital debris, including its accumulation, mitigation, and remediation. While reentry of spacecraft materials has long-been considered a solution for orbital debris, new data reveals that reentry cannot be ignored, particular given current growth trends in number of spacecraft and mass to orbit. Not only are anthropogenic activities in space impacting our atmosphere, but reentry of space vehicles is beginning to pose a direct risk of casualties on the ground. After reviewing current knowledge of reentry impacts, we review ongoing impairment of scientific endeavors, focusing on astronomy. After this, we briefly review current and future anticipated anthropogenic impacts beyond Earth, including growth in commercial and governmental activities beyond Earth, planetary protection, resource utilization on the Moon and elsewhere, and existential risks such as asteroid redirection. Finally, we highlight current strategies for responsible and sustainable activities in space.

## Space Launch: Overview and Background

The launch of Sputnik in 1957 was quickly followed by a space race between the U.S. and the Soviet Union, culminating in the first lunar landing by U.S. astronauts in 1969 as Apollo 11 and its follow-on missions. Post-Apollo, U.S. launches continued but the rate slowed, with the Soviet Union continuing its high rate of launches as it ventured to the Moon, Venus, and Mars and established orbital space stations. With the end of the Soviet Union in 1991, economic realities reduced the launch cadence of Russia, and launches in the U.S. accelerated. This trend has dramatically accelerated further in the last decade within the U.S. and across the world (Fig. 1A), driven by development of new launch vehicles, especially the dramatic cadence of SpaceX launches and the Starlink megaconstellation (McDowell, 2020). While Starlink aims to provide

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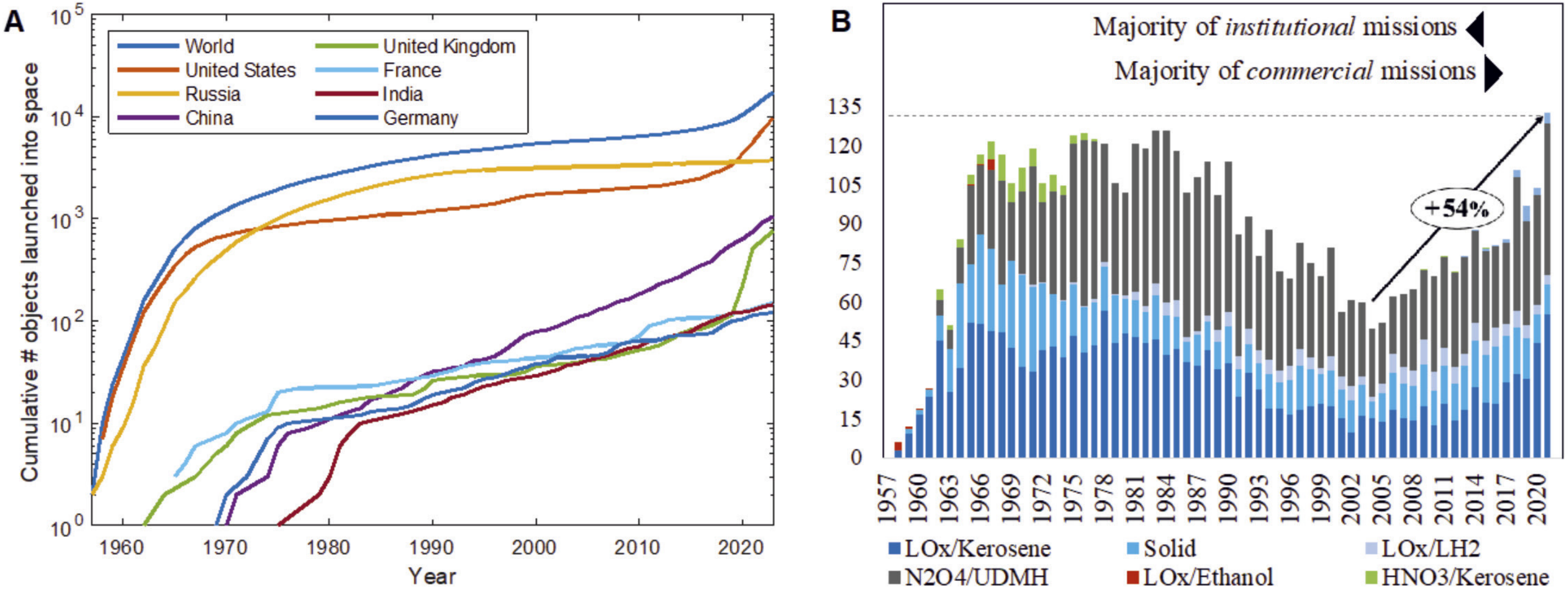

**Fig. 1:** Orbital launches by number and type of rocket propellant used. (A) Cumulative number of objects launched into space, 1957–2023. Launches by the Soviet Union (which existed until 1991) are included in the Russia counts. Adapted under CC BY 4.0 from Edouard Mathieu and Max Roser (2022) - "Space Exploration and Satellites" with data from United Nations Office for Outer Space Affairs (2024); data retrieved from https://ourworldindata.org/grapher/cumulative-number-of-objects-launched-into-outer-space. (B) Total number of successful orbital launches per year worldwide (1957–2021), broken down by main type of propellants used (both first stage and booster(s) are accounted for, cumulatively). Commercial missions primarily drove the 54% growth since 2001. LOx = liquid oxygen, $N_2O_4$ = nitrogen tetroxide, UDMH = unsymmetrical dimethylhydrazine, $LH_2$ = liquid hydrogen, $HNO_3$ = nitric acid. [Source: Data (Krebs, 1996; McDowell, 2022). Reprinted from Fig. 1 of (Sirieys et al., 2022), used under CC BY 4.0 license] ⏎

global low-latency internet, other constellations focus on Earth observation (EO). Data streams from EO total 807 petabytes (PB) and are increasing at >100 PB/year (Wilkinson et al., 2024).

Rockets produce thrust through conservation of momentum by expelling mass at high velocities. For all practical rocket launches from the surface of Earth, this momentum is generated through ejecting gases at high speed enabled by the release of energy through combustion (Fig. 1B), which produces by-products that can impact the atmosphere. For example, combustion of LOx (liquid oxygen, referring to the storage condition of the propellant) and kerosene (a hydrocarbon) produces both $CO_2$ and water, whereas combustion of oxygen and hydrogen (LOx/$LH_2$) produces water. Incomplete combustion results in other non-ideal products. Emissions from rocket launches are determined by (Sirieys et al., 2022) the fuel and oxidizer used, as well as the ratio of oxidizer to fuel (mixture ratio), decomposition during combustion, and afterburning (combustion of excess fuel with atmospheric molecules) (Zhou et al., 2020). For a summary of the main combustion products by fuel and oxidizer type see Sirieys et al. (2022).

To consider the impacts of space activities, we should consider their entire life cycle, including launch, orbital activities, and reentry. In this section and the next, we focus solely on the launch vehicle (Fig. 2) and cover the impacts of spacecraft and in-space activities in other sections. We first discuss the basic math of how rockets deliver spacecraft to orbit.

The required velocity for a circular orbit can be approximated as $v \approx \sqrt{}(GM/(R+h)$ where $G$ is the gravitational constant ($6.674\times10^{-11}$ N·m$^2$·kg$^{-2}$), $M$ is the mass of the planet being orbited (e.g., for Earth, $5.972\times10^{24}$ kg), $R$ is the radius of the planet (e.g., for Earth, $6.378\times10^6$ m), and $h$ is the orbital altitude above the surface (e.g., for example $2.00\times10^5$ m or 200 km). At 200 km, this velocity is 7.78 km/s.

The rocket equation governs the achievable change in velocity, or $\Delta v$, as $\Delta v = v_e \cdot \ln(m_0/m_f)$, where $v_e$ is the effective exhaust velocity, $m_0$ is the initial mass, and $m_f$ is the final mass. Thus, the achievable $\Delta v$ of a rocket depends upon how fast it can eject material ($v_e$) and the fraction of the initial mass that can be expended as propellant, which limits the mass ratio $m_0/m_f$.

An equivalent expression is $\Delta v = I_{sp} \cdot g_0 \cdot \ln(m_0/m_f)$ where $I_{sp}$ is the specific impulse in units of seconds, and $g_0$ is standard gravity, or 9.81 m/s$^2$. $I_{sp}$ is a property of the specific fuel and oxidizer combination along with effects of the propulsion system such as nozzle geometry and its interactions with the atmosphere. For example, the combination of LOx/$LH_2$ can achieve a specific impulse of ~370 s (at sea level) to ~423 s (in vacuum). This is the highest specific impulse of all practical and routinely used propellants for chemical propulsion, e.g., generating thrust via combustion. The differences between sea level and vacuum performance are due to, among other factors, how the presence of an atmosphere and the shape of the rocket engine nozzle interact to change the effective exit velocity.

To achieve orbit from Earth's surface, some velocity is "lost" due to counteracting gravity as a rocket climbs vertically instead of being converted to horizontal velocity (some thrust goes into supporting the rocket, termed gravity loss, and some goes into work done moving the rocket vertically, changing its gravitational potential energy). Movement through the atmosphere also creates drag. In practice, rockets need to achieve about 1.5–2 km/s additional $\Delta v$ to reach low Earth orbit (LEO), or at least 9.3 km/s.

For a rocket to go straight to orbit (so-called single stage to orbit, SSTO), the mass delivered $m_f$ must be small: for the LOx/$LH_2$ example taking $I_{sp}$ as 400 s, achieving 9.3 km/s implies a final-to-initial mass ratio of $m_f/m_i$ of 9.3%. This means the total mass of the payload being delivered and all the non-fuel parts of the rocket can only be a tiny fraction of the initial mass, because over 90% of the initial mass is required to be fuel and oxidizer. For this reason, staging is often used instead of SSTO. In staging, booster rockets or a core stage or both initially carry the upper stage, then separate when their fuel is exhausted, eliminating the need to carry the non-fuel mass from the prior stage(s) (Fig. 2).

The ability for rocket stages to land (Fig. 3), as first demonstrated in 2015, is a major advancement in improving the efficiency of space launch because it enables refurbishment and reuse.

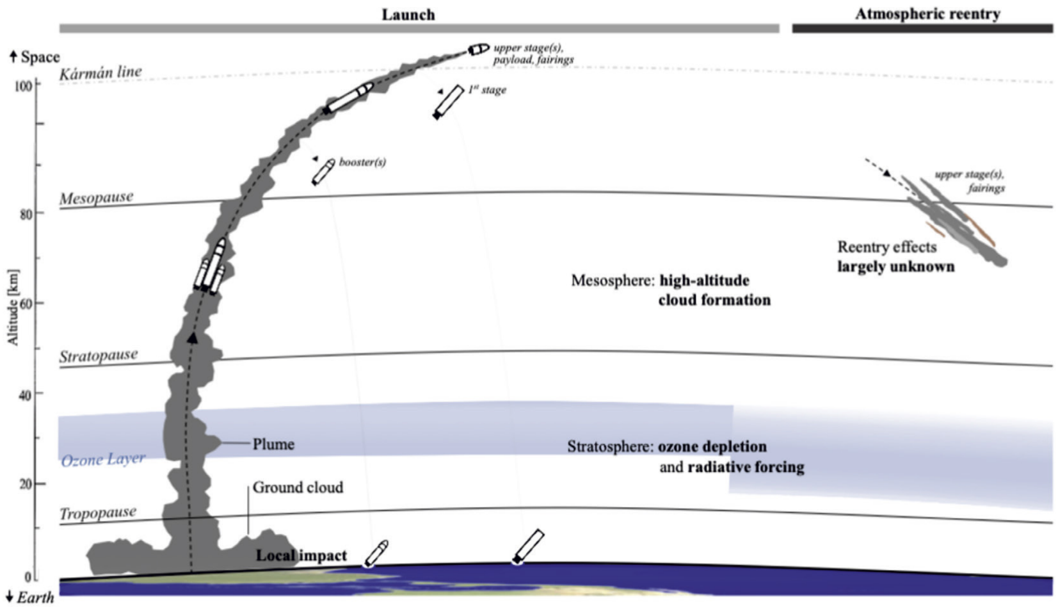

**Fig. 2:** Trajectory of a typical launch vehicle through atmospheric layers during the ascent phase and the atmospheric reentry, with corresponding environmental impacts. The altitude of the various atmospheric layers is indicative and varies with the latitude. Objects are not to scale. Unless the rocket is (partially) reusable, the first stage and boosters are generally discarded in the ocean or on land. Environmental consequences shown above stem from various launch vehicles investigated in the literature. [Reprinted from Fig. 2 of (Sirieys et al., 2022) under CC BY 4.0] ⏎

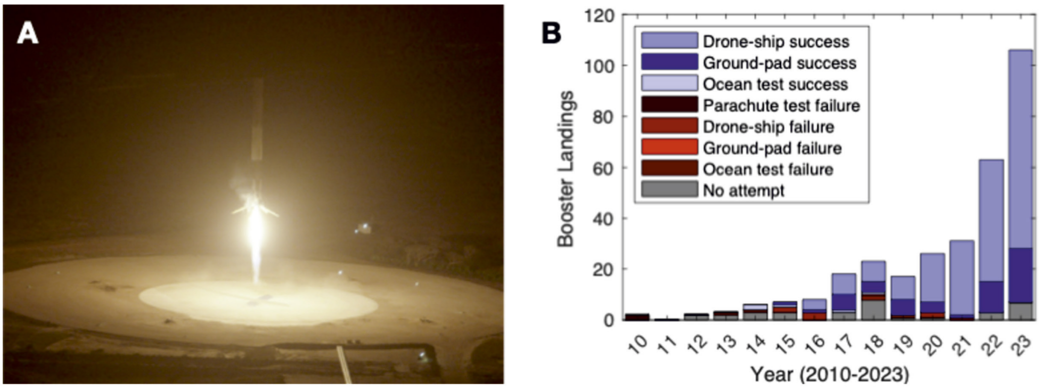

**Fig. 3:** Launch vehicle booster recovery progress by SpaceX. (A) First successful booster landing on December 21, 2015 by SpaceX's Falcon 9. Image credit: SpaceX, CC0. (B) Statistics of booster landings. SpaceX lands boosters on both ground pads and mobile drone-ships (barges) at sea. Ocean tests refer to controlled descents into the ocean with no barge present. No attempt indicates intentional disposal without recovery. [Data from https://en.wikipedia.org/wiki/List_of_Falcon_9_and_Falcon_Heavy_launches] ⏎

Prior to this, every booster or stage launched could not be reused without substantial refurbishment, resulting in enormous waste, and in some cases, outright hazards (Byers et al., 2022). This reuse has also lowered launch costs, leading to more demand for space launches. As of June 2024, the record for number of times a single booster has been reused is 22, for SpaceX Falcon 9 booster B1062.

## Impact of Space Launches

Before launch, a myriad of impacts can accrue including those due to noise, habitat destruction due to industrial activity or pre-launch testing or launch failures, and emissions that in some cases can kill local flora and fauna through acidification or other habitat damage in a launch-vehicle dependent manner (Sirieys et al., 2022). These risks are managed in the U.S. through environmental impact assessments and, when necessary, investigations and corrective actions required to obtain future launch licenses. With a growing number of countries and companies executing space launches, harmonization of launch and reentry regulations is one initiative of many announced by the U.S. executive branch in late 2023.[1]

Launch failures are not uncommon during development of new rocket systems. Static fire tests, in which a rocket fires while held in place to a test stand, are used to assess safety and performance prior to launches. Launch facilities utilize extensive range safety approaches to prevent harm to people and property including flight termination systems (FTS) that can be automatically triggered or remotely commanded. A notable exception was the accidental launch of the Tianlong-3 first stage by Space Pioneer during a static fire test on June 30, 2024, which exploded after impacting the ground 1.5 km from the test stand, near the city of Gongyi, China.

Launch sites are typically located so that rockets can travel east over water after launch, taking advantage of Earth's rotational motion (up to 0.46 km/s at the equator) as they accelerate to orbital speed. Inland launch sites or those without large bodies of water to the east therefore have inherently higher risk of damage to people or property after a launch vehicle failure or during descent and impact of a non-reusable 1st stage. Such impacts are highly visible today through social media. The likely spread of reusable first stage technology beyond SpaceX will mitigate this risk.

Rockets can also cause physical and electrical changes in the atmosphere through production of shock waves that impact the ionosphere (Sirieys et al., 2022). The ionosphere is the region of the Earth's atmosphere from ~48 km to ~1000 km in which the main atmospheric components are electrons and charged atoms and molecules. This charging results from high-energy photons, mainly extreme ultraviolet and x-ray emissions from the sun, as well as galactic cosmic rays (GCRs), which are mainly high energy protons and higher atomic mass charged nuclei from outside the solar system (e.g., supernovas). As an example of a launch impacting the ionosphere, a steep ascent required to deliver the FORMOSAT-5 to its 720 km target orbital altitude resulted in a 1500-km diameter shock acoustic wave that created a 900 km diameter plasma hole with 10-70% depletion of total electron content (TEC) in the ionosphere (Chou et al., 2018). Global Positioning System (GPS) receivers use models of signal propagation through the ionosphere to accurately determine their position from satellite signals; the authors estimate that the ionospheric depletion caused by this event could have induced temporary range errors of ~1 m (Chou et al., 2018). Ionospheric effects appear to be relatively minor but could impact some applications where accurate positioning is required under future scenarios of much higher launch cadences.

One major concern is the impact of rocket emissions on radiative forcing, the balance of heat energy that results in deviations in Earth's temperature. This is especially significant given global warming (IPCC, 2023) and the potential to exacerbate future warming. While rocket $CO_2$ and $H_2O$ emissions have negligible forcing, this is in sharp contrast to black carbon (BC) or soot (Ross and Sheaffer, 2014).

Recently, detailed models have been developed to understand the atmosphere impacts of different launch vehicles, including the venerable SpaceX Falcon 9 (Kokkinakis and Drikakis, 2022), a two-stage rocket utilizing RP-1 (refined kerosene) and liquid oxygen as propellant, whose reusable first stage has reduced costs to orbit and facilitated rapid growth in launch rates

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[1] hhttps://www.whitehouse.gov/briefing-room/statements-releases/2023/12/20/fact-sheet-strengthening-u-s-international-space-partnerships/

(Figs. 1-3). Imperfect combustion results in black carbon (BC), or soot, which can warm the stratosphere, which is particularly sensitive to BC at even ten times 2021 levels (Maloney et al., 2022).

The emission factors of major propellants can be determined and have been used to estimate potential atmospheric and climate impacts assuming 9 years of 5.6% annual growth starting in 2019 (Ryan et al., 2022), although actual growth rates in recent years have been closer to 15%. The simulated atmospheric effects of this included a drop in ozone (–500 ppt, or –0.01%), an increase in total inorganic chlorine and nitrogen oxides, black carbon (BC), and aluminum oxide ($Al_2O_3$). While the NOx impacts are moderate, the BC impacts are substantial, reaching 8 $mW/m^2$ in the upper atmosphere, and representing 6% of total BC radiative forcing globally. For a summary of emission products, their potential atmospheric chemical reactions, and their potential impacts see Brown et al. (2023).

Another study (Larson et al., 2017) modeled high flight rates of $10^5$ per year to evaluate feasibility of space-based solar power, and found that even at this high flight rate, NOx emissions would result in only a 0.5% loss of ozone. These estimates are based on specific launch vehicles with tailored assumptions regarding emission factors and altitudes (e.g., most NOx is generated during reentry of reusable rockets), and given ongoing shifts in the launch marketplace and rapid growth above that modeled in some studies, should be revisited in the future. That said, it is promising that only very moderate effects on ozone are predicted even for extremely high flight rates.

While near-term impacts on ozone may be moderate, in the long term, rocket emission byproducts are expected to negatively impact the ozone layer (Brown et al., 2023). However, there are options for improving sustainability and extending existing frameworks, where relevant, or by analogy (e.g., the Montreal Protocol, an international treaty signed by 197 countries governing protection of the ozone layer). Steps that the aerospace industry and atmospheric research community could take (Brown et al., 2023) include:

- Emissions testing verification during design and testing stages.
- Scientific collaboration on *in-situ* measurements to verify emissions and impacts.
- Explicit assessment of launch profile impacts on emissions, ionosphere, or other atmospheric impacts, and trajectory optimization to minimize adverse impacts.
- Sharing of launch emissions data and improved atmospheric modelling.

## Space Activity and Orbital Debris

### *How much Debris is Present?*

Avoiding or shielding against debris is important in order to facilitate reliable, sustainable growth of space services, which are increasingly economically important and critical for monitoring Earth’s environment. Space activity is most highly concentrated in low earth orbit (LEO), the region below 2000 km altitude. As a consequence, this is also the region with the most space debris, which constitutes 95% of tracked objects (Fig. 4A), including non-functional satellites, upper stages, or other fragments. Geosynchronous orbit (GEO) is a special altitude (~35.785 km) where orbital velocity is matched to Earth’s rotation, so that spacecraft maintain a constant position over a specific equatorial location, useful for providing location-based services, among other applications. Because of this, GEO contains many active spacecraft and debris (Fig. 4B-C).

Earth’s atmosphere extends tenuously into LEO as the thermosphere (80 km to 700-1000 km, the upper limit being significantly modulated by solar activity) and between 200 and 450 km is dominated by atomic oxygen. This produces drag on spacecraft and causes their orbits to degrade, eventually producing reentry. The atomic oxygen also attacks spacecraft materials, resulting in degraded performance, and ultimately failure, turning a once-useful spacecraft into debris.

Thus, while Earth has a "natural cleansing mechanism" at low altitudes, at higher orbits, the atmosphere is too thin, resulting in orbital lifetimes of decades to effectively infinite. To manage the potential for debris accumulation, post-mission lifetime limits of 25 years were proposed to balance the risk of debris persistence with the costs of more rapid reentry, such as extra mass to support a deorbit system.

The ISO 27852:2024 standard covers estimation of orbital lifetime, including assessment of the 25-year threshold. For circular orbits with moderate ballistic coefficient (a measure of an object's ability to overcome atmospheric drag) this corresponds to <500 km altitude; above 800 km, lifetimes will typically be >25 years. Because the actual numbers depend upon many factors (orbital eccentricity—a measure of deviation from a circular orbit—, ballistic coefficient, modulation of the atmosphere by space weather such as solar activity, ability to do a de-orbit burn, risk of impact especially with a LEO-crossing orbit), actual lifetime predictions must be assessed on a case-by-case basis.

Starlink, deployed in LEO, has grown rapidly in recent years, yet Starlink satellites still represent only a small fraction of all tracked objects in space (Fig. 4D). Starlink satellites (>6000 functional as of mid-2024) are designed to have a ~5-year life expectancy; there have been calls to replace the 25-year rule with a 5-year rule (now the law for U.S. licensed operators), which would be substantially easier to accommodate for new spacecraft in very low orbits, but more difficult

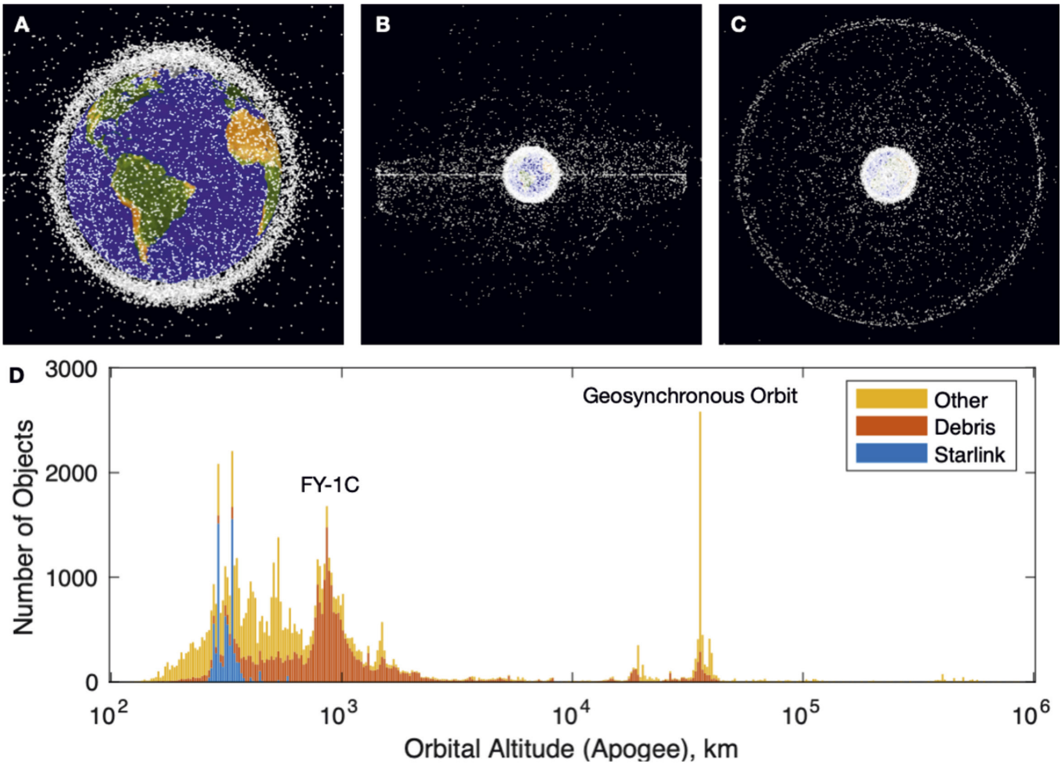

**Fig. 4:** Actively tracked objects around Earth. Each dot represents one object and does not indicate size. (A) Low Earth orbit (LEO). (B) An oblique view of geosynchronous orbit. (C) A polar view of geosynchronous orbit. Image credits: NASA Orbital Debris Program Office (ODPO), https://orbitaldebris.jsc.nasa.gov/photo-gallery/. D) Objects in orbit as a function of orbital altitude (apogee). [Data from (McDowell 2022) data update 2024 Jun 16. FY-1C indicates the orbit of a satellite (at 865 km) prior to its destruction in an anti-satellite test conducted by China in 2007, leading to more than 3000 pieces of trackable (in this case, golf ball sized or larger) debris] ⏎

for spacecraft being deployed to higher orbits. Starlink ultimately plans to expand its constellation to tens of thousands of satellites.

Collisions, intentional or unintentional, have also contributed appreciably to the number of tracked objects in space. For example, in 2007 China conducted an anti-satellite weapon test leading to thousands of tracked pieces of debris (Fig. 4D). In 2009, an active Iridium satellite and a defunct Russian military satellite collided at 789 km altitude, producing 2,296 tracked pieces of debris, around half of which have now reentered or are no longer trackable. In addition, Russia conducted an anti-satellite test in 2021. Together these three events represent 15% of tracked debris and 20% of conjunction warnings.[2]

## *How is Debris Tracked?*

Orbital debris is mainly tracked using ground-based facilities (e.g., radars and telescopes) and detection is dependent upon the size of the object as well as the distance to the object being tracked (Fig. 5). Small particles can still cause extensive damage, but because they cannot be tracked from the ground, our knowledge of size, number, and velocity for this size class is based on limited in space measurements or returned hardware. One source of data (Hyde et al., 2011) was analyses of Space Shuttle surfaces (windows, thermal protection tiles, and other surfaces). Multilayer insulation (MLI) recovered during servicing of the Hubble Space Telescope (HST) was returned to Earth and analyzed to characterize hypervelocity impact damage caused by small particles (Murray et al., 2023). Also analyzed was the HST Wide Field and Planetary Camera 2 (WFPC2), replaced and recovered during the same 2009 mission.

In the future it may be possible to map debris through statistical means by detecting impacts associated with small debris *in situ*. The data gap for 0.2-10 mm can be filled through on-orbit measurements such as the Local Orbital Debris Environment (LODE) detector concept (Gruntman, 2014), which would look for reflected solar photons. There are also proposals for collision-free detection of mm to cm-scale debris *in situ* at distances up to 10 km from the detector (Truitt and Hartzell, 2020). As of 2022, the Intelligence Advanced Research Projects Activity (IARPA) has initiated the Space Debris Identification and Tracking (SINTRA) project,[3] which is focused on tracking the estimated greater than 100 million objects in the 1 mm to 10 cm class from LEO to GEO. *In-situ* measurements can directly detect impacts or detect the consequences of impacts, such as the resulting plasma that can be detected optically or as non-optical electromagnetic emissions (e.g., radio frequency). This may enable detection of impacts for particles as small as 10 μm (personal communication, Nilton Renno). Below this size, minimal shielding can protect spacecraft from damage except inherently sensitive surfaces.

## *What Causes Debris?*

Major causes of debris (summarized from NASA's NASA-HDBK-8719.14) include:

- Mission-related (intentionally-discarded items such as lens caps, tanks, generally no longer permitted under established guidelines),
- Fragmentation (dominated by accidental explosions until the FY-1C event),
- Anomalous or deterioration-related debris (including sub-mm paint flaking and other damage caused by atomic oxygen), and
- Slag (aluminium oxide, $Al_2O_3$, particles produced by solid rocket motor firings), which is especially problematic because of the potential to create >100 μm particles, possibly up to 1 cm.

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[2] https://breakingdefense.com/2023/06/debris-from-asat-tests-creating-bad-neighborhood-in-low-earth-orbit-analyst/

[3] https://www.iarpa.gov/research-programs/sintra

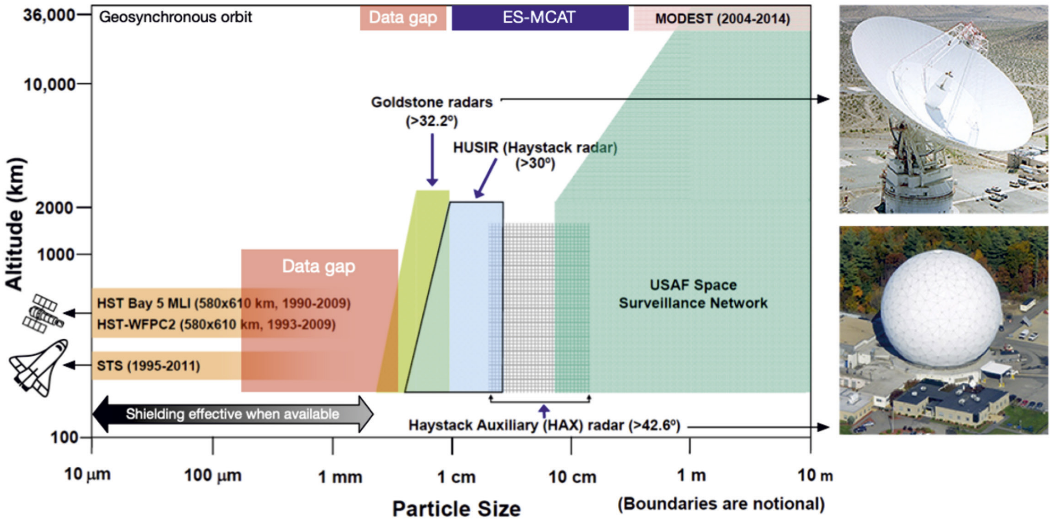

**Fig. 5:** How orbital debris is tracked. Orbital debris is mainly tracked by ground-based radars and telescopes. Historical LEO measurements were also made on returned space hardware from the Hubble Space Telescope (HST) and Space Shuttle (Space Transportation System, STS). For GEO, the Eugene Stansbery Meter Class Autonomous Telescope (ES-MCAT) is a joint NASA-Air Force Research Laboratory project that reached full operational capability in 2021 and can detect ~10 mm and larger objects in GEO (Manis et al. 2023). Prior to this, the Michigan Orbital Debris Survey Telescope (MODEST) enabled tracking of larger meter-class objects in GEO, where spacecraft are often shielded against impactors of up to mm size. Indicated data gaps represent areas of nascent interest for orbital sensing such as via new small spacecraft platforms. [Adapted from the NASA Orbital Debris Program Office (ODPO), https://orbitaldebris.jsc.nasa.gov/measurements/] ⏎

In addition, the Soviets launched a series of Radar Ocean and Reconnaissance Satellite (RORSAT) spacecraft into LEO up until 1988 that contained 2 kW BES-5 fission reactors. Most reactor cores (16) were ejected into “disposal” orbits of 900-950 km (Wiedemann et al., 2005), but several were not successfully transferred to the desired orbit. In addition, a sodium-potassium (Na-K) salt mixture leaked from some reactor cores, producing liquid droplets that subsequently froze. Given the disposal orbital altitude, the debris (~154 kg) will persist for thousands of years. While the small particle population (<1 mm) rapidly dissipated, it is estimated that the large (>7 mm to 5.5 cm) subset of the debris population may number in excess of 45,000 particles as of 2005 (Wiedemann et al., 2011, 2005). In addition to leaky cores, impacts from space debris may puncture intact coolant loops, leading to more release of Na-K debris. The ability for debris to create yet more debris highlights a potential runaway process called the Kessler syndrome (Kessler, 1991; Kessler and Cour-Palais, 1978), which could render at least some orbital altitudes unusable due to expanding debris populations.

In contrast to debris, nuclear materials on orbit represent a comparatively minor but important risk. The U.S. flew the SNAP-10A fission reactor in space in 1965, the first time a fission reactor had been flown in space and the only known time the U.S. has flown a fission reactor. In addition to the RORSAT reactors, the Soviets also developed and twice flew a 6 kW TOPAZ reactor. The U.S. acquired and proposed to fly TOPAZ reactors but ultimately did not. There was concern that the reactors planned orbit could result in interference with gamma ray telescopes.

The U.S. has utilized Radioisotope Thermal Generators (RTGs) in which (most commonly) Plutonium-238 (Pu-238, half-life 87.7 years) oxide pellets generate heat, and the heat is used to generate electricity. RTGs are essential power sources for deep space missions due to their reliability and lack of dependence upon solar power, which is especially important as space missions travel far from the sun. RTGs have been used on the Apollo Lunar Modules (12-17), and robotic missions including Pioneer (10-11), Viking (1-2), Voyager (1-2), Galileo, Ulysses, Cassini, New Horizons, Mars Science Laboratory (Curiosity Rover), Mars 2020 (Perseverance Rover), as well as on a few other U.S. satellites.

The robust RTGs used in spacecraft represent a highly manageable risk that can be balanced with their essentiality for certain applications. In 1964 a failed launch of a Transit satellite with an RTG and 1 kg Pu-238 resulted in atmospheric release of plutonium. However, follow-on systems were designed to withstand reentry and long-term exposure to seawater. For example, when Apollo 13 failed to reach the moon, its RTG was intentionally delivered via targeted reentry to a deep water site (Tonga Trench), and is expected to resist seawater corrosion for ~870 years, or ten half-lives, at which point the remaining radioactivity will be 0.1% of the initial value. The largest mass of Pu-238 carried by a spacecraft to date was Cassini, with a total of 28 kg. In contrast, nuclear testing released about 3.5 t of plutonium into the Earth's atmosphere, and the insoluble nature of Pu-238 oxide means it does not concentrate easily in biological materials. While Pu-238 could be used to make a dirty bomb, this isotope is not used in nuclear bombs, lowering the risk of diversion. More than a thousand RTGs have been used for terrestrial applications, mainly by the Soviets and U.S. for reliable power at remote installations, typically powered by Strontium-90 (90-Sr, half-life 28.8 years). With the collapse of the Soviet Union, some of these RTGs were dismantled, sold for scrap, and in a few cases caused harm due to radiation exposure. The chemical form of 90-Sr used is inert in the environment and so risks to humans occur mainly through mishandling or intentional action with disregard for others. Thus, while rigorous handling, control, and disposal plans are essential, RTGs represent an important tool for planetary exploration, and may find future use within long-lived infrastructure, e.g. on the Moon.

Considering potential environmental impacts of new technology is critical, particularly as LEO space activity expands. Spacecraft thrusters can achieve much higher $I_{sp}$ than chemical propulsion by using electric fields to accelerate ions (e.g., Hall-effect thrusters). This efficiency reduces the mass of propellant that must be carried, but thrust is typically low and the devices require high power to operate, typically 1-100 kW. These thrusters are often used for orientation control or (larger ones) for low-thrust trajectories for medium-sized space vehicles. The efficiency is higher for higher atomic mass elements, with the most comment propellant being xenon, an inert gas. In contrast, one company, the now-acquired Apollo Fusion, developed thrusters that would utilize mercury, with the implication that any widespread usage in LEO could have resulted in significant atmospheric mercury contributions. The U.N. outlawed use of mercury as a propellant in 2022, and the mercury thrusters are no longer under development.

## *What Do We Do About Debris?*

One approach to debris mitigation is to avoid it. While space debris is growing rapidly, the 3-dimensional density of debris remains generally sparse but non-uniform, with some orbits (e.g., 700-1000 km altitude) much riskier than others. Imperfect knowledge of spacecraft positions must be considered to prevent collisions even when nominal orbits suggest no collision will occur. When two spacecraft have a predicted close approach (CA), this is denoted as a conjunction.

The U.S. Space Force 18th Space Defense Squadron (SDS) and 19th SDS are responsible for operating and tasking the U.S. Space Surveillance Network (SSN), not only tracking objects but also performing conjunction assessment[4]. NASA also performs conjunction assessment risk analysis (CARA)[5] in cooperation with the 18th and 19th SDS. For an example of how CAs are determined, see (Y. Zhang et al., 2022). In brief, one must have orbital trajectories for all objects being considered, and an estimate of their size, which may be somewhat different from the radar cross section. Given

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[4] https://www.space-track.org/

[5] https://www.nasa.gov/cara/

assumed position errors, one can compute the probability of a collision. A collision probability larger than $10^{-5}$ or $10^{-4}$ would indicate a need for action, such as a collision avoidance maneuver (Gavin, 2010). For example, in 2022, there were 1,486 conjunctions involving the ISS, of which two were deemed to be a high enough risk to require avoidance maneuvers by the ISS.[6] The number of required CA maneuvers per year is growing rapidly. In filings to the U.S. Federal Communications Commission (FCC), SpaceX disclosed[7] it had made over 25,000 avoidance maneuvers in the six month period of Dec 2022 to May 2023. SpaceX has also implemented additional mechanisms to prevent debris and damage to Starlink satellites, such as changing the solar array configuration in a so-called "duck maneuver"[8] to have the smallest possible cross section in the direction of the CA. SpaceX also uses a $10^{-6}$ threshold for avoidance maneuvers.

Registering a spacecraft with the 18th SDS (e.g., via https://www.space-track.org) provides a means for provisioning of conjunction assessment, with CA notifications. Operators can utilize these services to plan and execute maneuvers to avoid CAs with high impact probability following the guidelines laid out in the 18th and 19th SDS Spaceflight Safety Handbook for Satellite Operators (latest edition, v1.7, April 2023 as of mid-2024[9]). Beyond explicit calculation, long-term orbital evolution (W. Zhang et al., 2023) and machine learning based-approaches (Rodriguez-Fernandez et al., 2024) are being used to predict orbital density and collision risk in the far future for long-term planning. Space traffic management for U.S. commercial entities is expected to be taken over by the U.S. Office of Space Commerce via the (under-development) Traffic Coordination System for Space (TraCSS) program.[10]

Perhaps the most important approach to mitigating debris is not producing it in the first place. A study by the NASA Inspector General found that growth of debris in LEO "can be slowed" if >90% of spacecraft are "removed from orbit within 25 years of the end of their mission, and at least five defunct spacecraft (that will not deorbit on their own) are actively removed from orbit every year." (NASA, 2021) However, the industry itself has advocated for more stringent measures such as deorbiting within one to five years.

In 2022, Iriudum, OneWeb, SpaceX, and the American Institute for Aeronautics and Astronautics (AIAA) released the Satellite Orbital Safety Best Practices 2.0 guide (AIAA, 2022). This work advocates for best practices for sustainable use of space and minimizing debris and orbital impacts (Table 1).

There is currently no mechanism to enforce such guidelines, although it is promising that major commercial players have taken leadership in establishing best practices. In 2022, the FCC adopted a five-year deorbit rule for U.S. licensed launches.[11] An alternative approach is to issue fines for non-compliance: In 2023, the FCC issued its first fine,[12] to Dish Network, for failing to move a satellite to a previously agreed-upon "graveyard orbit." It seems likely that a combination of carrot-and-stick measures may be needed to encourage reasonable and sustainable use of space.

In contrast, all NASA missions must comply with agency-specific rules: the NASA Procedural Requirements (NPR) standard on orbital debris mitigation (NPR 8715.6E, active April 18, 2024 to April 18, 2029; and NASA-STD-8719.14C[13] and its accompanying handbook NASA-HDBK-8719.14[14]). For example, new flight missions, even for planetary exploration well beyond

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[6] https://breakingdefense.com/2023/06/debris-from-asat-tests-creating-bad-neighborhood-in-low-earth-orbit-analyst/

[7] https://www.space.com/starlink-satellite-conjunction-increase-threatens-space-sustainability

[8] https://www.spacex.com/updates/#sustainability

[9] https://www.space-track.org/documents/SFS_Handbook_For_Operators_V1.7.pdf

[10] https://www.space.commerce.gov/traffic-coordination-system-for-space-tracss/

[11] https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites

[12] https://docs.fcc.gov/public/attachments/DOC-397412A1.pdf

[13] https://standards.nasa.gov/standard/NASA/NASA-STD-871914

[14] https://standards.nasa.gov/standard/NASA/NASA-HDBK-871914

**Table 1:** Selected recommendations from the Satellite Orbital Safety Best Practices 2.0 guide (AIAA 2022) ⏎

| Spacecraft design | Mission design |
|---|---|
| Make your spacecraft large enough (radar cross section) to be tracked | Analyze trajectory from launch to delivery in "final orbit" for active spacecraft and debris |
| Use security measures for uplink and downlink to avoid "hostile commandeering" | Identify and eliminate systematic conjunctions (close approaches) between multiple spacecraft (preexisting or newly expected in the target orbit) |
| If the spacecraft will not deorbit through passive means within 5 years, install an interface for active removal once such a standard exists | Plan propulsion reserves to enable collision avoidance maneuvers that may be required |

Earth, must incorporate conjunction CARA into their launch planning (e.g., New Frontiers 5 program[15]). This is because *space debris can constrain spacecraft launch windows.* Spacecraft launch windows are set by orbital dynamics and trajectory constraints. Launch windows can be constrained by many other factors such as coordinating exclusion zones, communication, tracking, and so often, weather. Based on these constraints, launch windows may be minutes or hours or have other complicated dynamics. Due to the increase in space debris and incorporation of debris avoidance predictions for launch systems, launch windows for key missions are now often considered instantaneous. One example is the NASA mission Psyche.[16] This increases the risk that a launch, whether for human or robotic exploration or for commercial or military purposes, will not take place due to a temporary issue that previously could have been addressed within what previously would have been a broader launch window. Future efforts to address this may involve computing more extensive debris avoidance windows and improved knowledge of debris and spacecraft trajectories.

For larger debris, active removal (Mark and Kamath, 2019) is under consideration, including use of robotic spacecraft to approach and deorbit large structures. One challenge is that attempting to deorbit a defunct spacecraft, which may be tumbling randomly, itself poses a significant risk of generating debris. Another approach is not to deorbit debris, but to adjust its orbit slightly to avoid high-risk CAs, which could be accomplished using ground-based lasers to provide light pressure and/or ablate spacecraft material that would, over time, perturb the orbit of the target (Scharring et al., 2021). NASA's Office of Technology, Policy, and Strategy reviewed the cost and benefits of different debris removal methods and found that the most promising methods for small debris are use of ground- or space-based laser, which would offer a return on investment within 5-10 years (Colvin et al., 2023). For large debris, a just-in-time laser or rocket-based (launch a vehicle to actively remove an object) collision avoidance approach would offer an immediate return on investment (Colvin et al., 2023). Finally, one challenge to widespread use of active debris removal technologies is that they can be dual use, e.g., also applied as anti-satellite weapons.

Harmonization of standards is an important process that will contribute to sustainable commercial, governmental, and scientific use of space. Consistent with this, the World Economic Forum adopted recommendations for debris mitigation including a 5-year post-mission deorbit limit, and a mission success rate of 95-99%, along with a host of other suggestions.[17] However, obstacles remain that will require additional international coordination. One report (Silverstein, 2023) identified three areas where international cooperation can enhance collision avoidance: (1) improved information sharing to address unforeseen incidents that could not be predicted due to lack of shared knowledge, (2) incompatible CA analyses that generate different impact probabilities prevent systematic decision making around maneuvering, and (3) different risk postures around

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[15] https://newfrontiers.larc.nasa.gov/NF5/

[16] https://twitter.com/ltelkins/status/1643783498438934528?s=46&t=kLtP3H_0Rwz4_sEaS9A__g

[17] https://www3.weforum.org/docs/WEF_Space_Industry_Debris_Mitigation_Recommendations_2023.pdf

when maneuvers are warranted can lead to conflict. In one example, China maneuvered its space station in July and October 2021 to avoid impacts with two Starlink satellites, despite the U.S. stating that there was no significant risk of impact (Silverstein, 2023).

## *New Frontiers in Space Debris*

New hazards will come into play as governmental and commercial use of space grows. For example, NASA-HDBK-8719.14 documents that the most frequent cause of spacecraft fragmentation are propulsion-related events (88 as of February 2007, representing 45% of those analyzed). Future space exploration efforts plan to utilize on-orbit propellant depots. It is well known that thermal loading leading to fatigue, micrometeoroid damage, maintenance, docking and other activities that could result in propellant leakage and create explosion hazards (Bahr 1992). SpaceX's Starship vehicle successfully completed an inter-ship cryogenic propellant transfer during the 3rd Starship integrated flight test on March 14, 2024. Future testing will involve on orbit cryogenic propellant transfers in support of sending U.S. astronauts back to the Moon as part of the Artemis program,[18] and future missions to send humans to Mars. The biggest risks of such transfers creating on-orbit debris will likely be during early testing, although aging hardware could also pose risks in the long-term.

Another emerging threat are space weapons. The Outer Space Treaty[19] of 1967, of which all major spacefaring nations are signatories, declares that space "shall be free for exploration and use", is not subject to claims of sovereignty, no state shall place nuclear weapons or weapons of mass destruction in space, and states "shall avoid harmful contamination of space and celestial bodies" among other things. These statements are being tested by recent anti-satellite weapon tests by China, India, and Russia. It must be acknowledged that the U.S. carried out anti-satellite weapon tests prior to the Outer Space Treaty, including nuclear weapons tests in space, the largest of which was the 1962 Starfish Prime detonation at 400 km altitude, which caused an electromagnetic pulse (EMP) larger than expected, resulting in electrical grid damage over 1400 km away in Hawaii, and the failure of six satellites. In late 2022, a U.N. resolution led by the U.S. was passed, banning direct-ascent anti-satellite missiles. U.S. assessments of a Russian launch in early 2024 suggested Russia may have launched an anti-satellite weapon into space into the same orbit as a U.S. government satellite. Earlier in 2024, reports emerged that the U.S. had privately warned Russia not to launch a new nuclear-armed satellite weapon, raising questions over whether there is now a nuclear armed spacecraft orbiting Earth. In the current political environment, it seems likely that the treaty provisions will be tested in the 21st century (West, 2024).

With multiple countries now exploring the moon and NASA planning a human return to the Moon with Project Artemis, orbital debris problems will not be limited to Earth orbit. But unlike Earth orbit, the Moon's extremely tenuous atmosphere will not offer any significant orbital decay. However, the moon has mass concentrations (mascons) that make most orbits below 100 km unstable, except for stable "frozen" orbits at 27°, 50°, 76°, and 86° inclinations. These orbits may therefore be of interest for spacecraft and may also accumulate debris. Orbits beyond ~690 km are unstable due to the influence of the Earth. Other locations of importance are the Lagrange points, which are points of gravitational equilibrium that occur when in space near two large bodies (e.g., Earth and Moon; or sun and Earth).

Debris hazards in lunar orbit can arise from both natural and human-caused processes. Because of the relatively smaller mass of the moon, orbital velocity is only 1.6 km/s and escape velocity is 2.4 km/s. A full description of lunar dust properties and migration is beyond our scope, but is

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[18] https://www.nasa.gov/news-release/nasa-announces-partners-to-advance-tipping-point-technologies-for-the-moon-mars/

[19] https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

well-covered in (Jin et al., 2024). Dust particle bombardment is 800 particles/cm$^2$/yr for particles >1 µm (Zakharov et al., 2020) and this incoming dust can generate ejecta. Early evidence of scattering above the lunar horizon suggested possible lofting of electrostatically-charged dust to 100 km altitudes at least in certain places under certain conditions. However, later modeling failed to explain observations of scattering near the terminator (Hartzell and Scheeres, 2011). Remote sensing measurements by the Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission found "no evidence of electrostatically lofted grains in the altitude range of 3-250 km above the lunar terminator." However, later evidence for local dust fountains were observed in LDEX data at five craters, confirming the local nature of enhanced lunar dust events (Xie et al., 2020).

Lunar dust gets everywhere due to electrostatic interactions, and spacecraft structures are no exception. Spacecraft can thus carry lunar dust into orbit, where dust may subsequently separate from the spacecraft structure (due to vibration, charging, or other mechanisms) and be released into orbit. Perhaps more significantly, because rocket plumes can accelerate lunar dust to speeds above orbital velocity, risks to orbiting spacecraft can be generated by arriving and departing spacecraft (Barker and Alred, 2020). Recent analysis shows that the damage to spacecraft orbiting the Moon at low altitude could be quite substantial: on the order of millions of tiny impacts per square meter for a spacecraft passing through an ejecta sheet caused by a 40 t lander (Metzger and Mantovani, 2021). Such damage can be avoided by careful timing of launches and landings. In short, with growing interest in lunar exploration, commerce, and cis-lunar activity, planning is urgently needed to address future lunar orbit congestion and orbital debris.

Many different complex orbits are possible when considering gravitational dynamics of three bodies (e.g., a spacecraft orbiting in the Earth-Moon system). This suggests that the future debris problem will become much more complex than at present, where debris trajectories are more straightforward.

## Natural vs. Anthropogenic Atmospheric Contributions from Space

Earth receives 28 ± 16 tons (t) of material daily from outer space (Carrillo-Sánchez et al., 2020), mainly composed of interplanetary dust particles (99%) and other meteoritic material (Plane et al., 2017). The mass distribution of this material (Schulz and Glassmeier, 2021) is dominated by dust particles with infrequent significant contributions from large impactors (Fig. 6A). In comparison to this ~10,000 t/yr input, anthropogenic contributions by spacecraft (Pardini and Anselmo, 2019), at ~101 t/yr between 2008 and 2017, are tiny (Fig. 6A, orange line), representing only 1% of natural contributions. A more recent but unpublished (conference presentation) estimate puts the number at 130 t/yr for spacecraft (Pardini, 2024), highlighting recent growth in spacecraft reentry mass. However, this mass neglects the contribution from rockets and core stages of launch vehicles; taking these into account, the annual anthropogenic contribution to the atmosphere has been estimated to be 890 tons/year (as of 2019) of which 110 tons/year were estimated to result from spacecraft (Schulz and Glassmeier, 2021) in concordance with other estimates (Pardini, 2024; Pardini and Anselmo, 2019).

Ablation of reentering material can result in formation of plasma (individual atoms), aerosols (nanometer to micron sized particles), and larger fragments or chunks of material that reach the ground (Fig. 6B). As a consequence, ablation of meteoroidal material results in the formation of metal layers in the upper atmosphere (75 km to 200 km) as well as other phenomena such as meteoritic smoke particles, thought to result in nucleation of polar mesospheric clouds and stratospheric clouds (Plane et al., 2017).

Orbital velocity at 200 km is 7.6 km/s, compared to an Earth escape velocity of ~11 km/s. As a consequence, meteoroidal material typically has a higher entry velocity (11-74 km/s, Fig. 7A) compared to spacecraft (E. Drolshagen et al., 2020). This has implications for disposition of

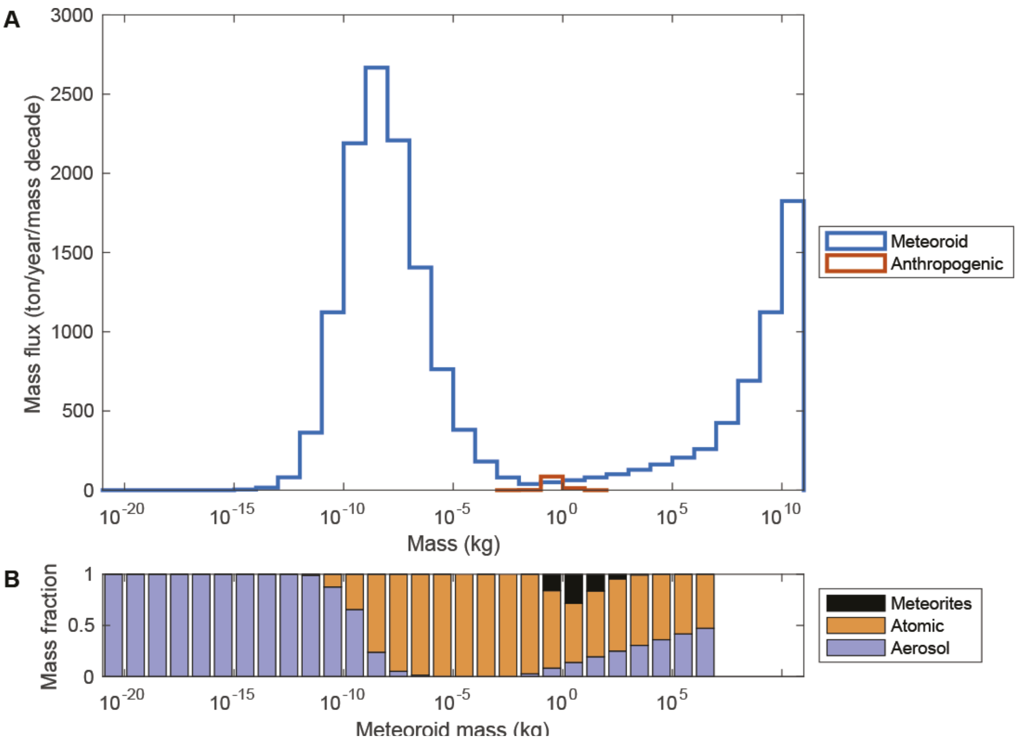

**Fig. 6:** Yearly Influx and disposition of meteoroid mass into the Earth's atmosphere. (A) Yearly influx of meteoroids as a function of meteoroid mass as calculated by Schulz and Glassmeier (2021). Based on dust data from Grün et al. (1985), P. Brown et al. (2002) and Stokes (2003) as given in (G. Drolshagen et al., 2017). (B) Estimated fractional mass ablation of meteoroids as a function of mass. [Data from Figures 1 and 4 of (Schulz and Glassmeier 2021) respectively. Panels A and B are co-aligned to facilitate comparison. In (A), anthropogenic contributions from uncontrolled reentry of spacecraft and rockets have been overlaid as estimated by Pardini and Anselmo (2019)] ⏎

meteoroidal material during reentry: Smaller dust particles are light enough they can decelerate quickly, reducing peak temperatures and yielding aerosols (Fig. 6B). In contrast, larger dust particles and meteoroids in the range of 1 microgram to 100 g are mostly ablated into their constitutive atomic components (Fig. 6B), most strongly within 75 to 110 km altitude (Fig. 7B). This means that large dust particles dominate the atomic deposition mode, even while larger mass meteoroids and rare large impactors also contribute. For spacecraft, it is estimated that of ~130 tons/year, 80 tons/year disintegrates in the atmosphere and 50 tons/year reaches the ground intact (Pardini, 2024).

To date, reentry of spacecraft has largely been treated as an innocuous disposal method. However, recent estimates show that even a single mega-constellation, e.g. Starlink, is likely to result in spacecraft reentry contributing more aluminum to Earth's upper atmosphere than natural sources (Boley and Byers, 2021). Despite the comparatively low anthropogenic mass fraction, spacecraft now significantly contribute through ablation to Earth's atmosphere due to the high abundance of metals, especially aluminum, in spacecraft structures. Direct measurements of stratospheric aerosols, which are dominated by sulfuric acid, have demonstrated that around 10% of stratospheric aerosols contain evidence of contamination by spacecraft and rocket metals (Fig. 8, compare panel A, derived from a meteoric stratospheric particle, to panel B, a particle showing signs of spacecraft metals) including aluminum, copper, lithium, niobium, hafnium, and lead (Murphy et al., 2023).

Re-entry survival modeling (Park et al., 2021; Vondrak et al., 2008) can be used to predict ablation products and their altitude distribution as well as the mass reaching the surface of Earth. Compared to the predominant source of meteoric material, which is dominated by small dust particles

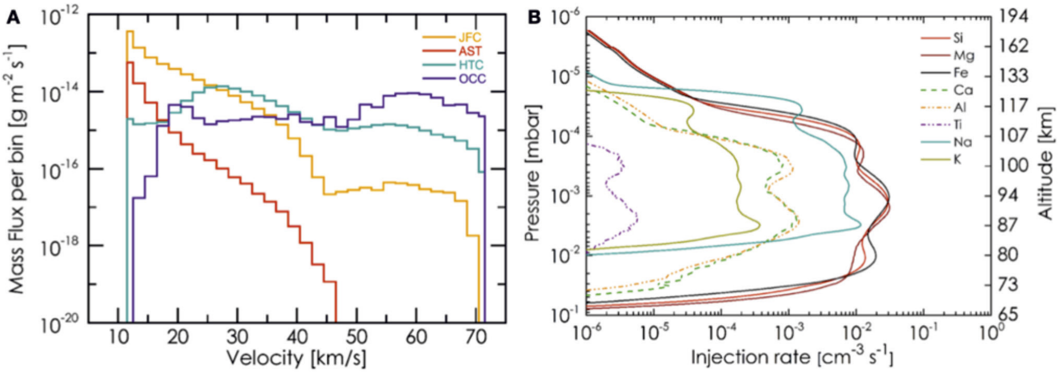

**Fig. 7:** Injection of atomic ablation products into Earth's atmosphere by interplanetary dust. (A) Mass flux as a function of entry velocity for interplanetary dust from Jupiter-Family comets (JFC, in yellow), Asteroid belt (AST, in red), Halley-Type comets (HTC, in cyan), and Oort-Cloud comets (OCC, in blue) for Earth. (B) Overall ablation rate profiles of individual elements, integrated and weighted for the JFC, AST and HTC particle populations (Carrillo-Sánchez et al., 2016). [Reprinted from (Plane et al., 2017) under CC 4.0 license] ⏎

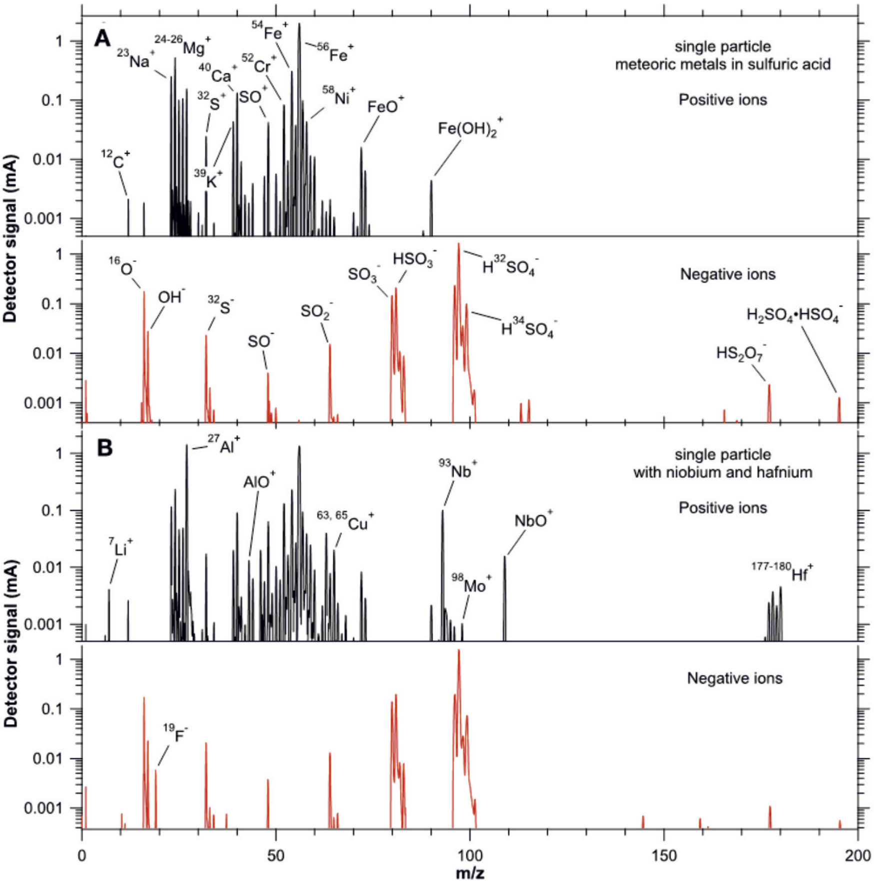

**Fig. 8:** Examples of mass spectra of single particles in the stratosphere. These spectra were chosen to be representative of a typical sulfuric acid particle with meteoric metals (A) and a particle with both meteoric metals and metals from spacecraft reentry including niobium and hafnium (B). In (B), only peaks that are significantly enhanced are tagged. [Reprinted from Murphy et al. (2023). Proceedings of the National Academy of Sciences 120.43: e2313374120, Fig. 2 under CC BY 4.0 license] ⏎

(Fig. 6A) that ablate above 75 km, anthropogenic debris ablates at lower altitudes (40 to 70 km) (Park et al., 2021) and at lower velocities (Murphy et al., 2023). Measurements obtained by (Murphy et al., 2023) suggest incomplete mixing from products of rocket nozzles and satellites, and concentration of both natural and anthropogenic products in polar regions owing to global circulation patterns.

The effects of these anthropogenic contributions is unknown. One hypothesis (Murphy et al., 2023) is that aluminum and other associated elements could impact ice nucleation or contribute to the formation of a greater number of smaller sulfuric acid particles, influencing their overall size distribution, with unknown downstream impacts. While the current relative contribution of anthropogenic input is small (Fig. 6A, orange line), with significant growth there is concern that reentry metals could impact the ionosphere (Solter-Hunt, 2023).

These concerns are hypothetical, yet it is important to recognize that the current situation is an uncontrolled long-term experiment in Earth upper atmosphere chemistry, the effects of which are not certain. This points to the need for future tracking, improving our understanding of downstream consequences and their implications, and potential regulation of re-entry materials. If it is determined that the impacts of increased delivery of aluminum to the upper atmosphere are negative, one option is replacement of aluminum with alternative materials, such as densified wood (Cabral et al., 2022), a high performance material with strength in some cases similar to aluminum and steel. However, it is not yet known if densified wood can provide adequate thermal performance and meet other (e.g., outgassing) requirements to be used for spacecraft structures. Such a solution assumes that ablation of densified wood, mainly composed of carbon, oxygen, and hydrogen, would be more benign from an atmospheric chemistry standpoint than aluminum. This is a reasonable supposition given the much higher abundance of these elements in the Earth's atmosphere, but remains an untested assumption.

While most spacecraft or debris burns up completely upon reentry, there are also physical risks from larger objects (Byers et al., 2022). Standards for all U.S. licensed launches require that "risk of a casualty from a reentering rocket body is below a 1-in-10,000 threshold" (Byers et al., 2022). Current records (as of June 19, 2024)[20] of space object reentries have catalogued 31,488 "good disposals" consistent with U.S. Orbital Debris Mitigation Standard Practices (ODMSP), whereas 7024 reentries did not meet these standards.

Despite numerous recorded incidents of people being injured indirectly or directly by falling debris, there are no known deaths yet from falling debris as of mid-2024. Calculations of risk align with this experience: An FAA commissioned study[21] found that in 2021, the total risk of a casualty worldwide was a 7% chance of one person being severely injured or killed, and this number is expected to increase to 61% by 2035. Another study noted that uncontrolled reentries of orbital stages are dominated by China (>50% mass) whereas for spacecraft reentries, U.S.-associated objects accounted for 2/3 of the mass (Pardini and Anselmo, 2024). In addition to contributing to casualty risk, reentering space objects may also harm the environment, for example through release of toxic hypergolic (capable of igniting spontaneously) propellants.

Without limiting uncontrolled reentries, space object reentry will begin to kill people on the ground in the near future. Fortunately, "allowing rocket bodies to reenter in an uncontrolled manner is increasingly becoming a choice rather than a technological limitation" (Byers et al., 2022). For example, reusable boosters can dramatically reduce the risk of harm due to uncontrolled entry of spent boosters and 1st stages, and spacecraft can be designed for intentional ablation. The answer seems simple: standards should evolve to reduce the casualty risk, including through controlled reentry. The Montreal Recommendations[22] provide a set of guidelines to avoid uncontrolled reentry and reduce the risk of casualties from reentering space objects.

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[20] https://planet4589.org/space/reentry/index.html

[21] https://www.faa.gov/sites/faa.gov/files/Report_to_Congress_Reentry_Disposal_of_Satellites.pdf

[22] https://outerspaceinstitute.ca/osisite/wp-content/uploads/Montreal-Recommendations-on-Aviation-Safety-and-Uncontrolled-Space-Object-Reentries.pdf

## Impairment of Astronomy

One of the most notable impacts of rapid increases in LEO satellites has been our changed view of the night sky: while spotting a satellite may be an exciting moment for a casual stargazer, to professional astronomers this light pollution, caused by solar illumination of orbiting satellites, has scientific impacts. While a dark period of ~6 hours is expected in winter for low latitude observatories, at latitudes of 45-55° hundreds of satellites may be visible to the naked eye around twilight (McDowell, 2020). The impacts are most acute for wide-field-of-view surveys in the optical and infrared (e.g., wavelengths emitted by the sun that can be reflected by spacecraft *and* propagate through the atmosphere). One such study is the Zwicky Transient Facility (ZTF) at the Palomar Observatory in California; an analysis of ZTF twilight images revealed an increase in streaks from 0.5% in 2019 to 18% in 2021 (Mróz et al., 2022). The study also highlighted that as of 2021, the streaks were not strongly affecting science return, but if a LEO mega-constellation (e.g., Starlink) reaches 10,000 satellites, nearly 100% of images would be affected. Scheduling of observations can partially mitigate the impacts (Hu et al., 2022). Beyond ground-based astronomy, one study analyzed Hubble Space Telescope images from 2002-2021 and found that 2.7% of individual exposures with typical exposure times (~11 min) are negatively impacted by satellite trails and that the impact is increasing with time (Kruk et al., 2023).

Astronomers also monitor radio frequency (RF) emissions; orbiting mega-constellations emit RF for communications but can also reflect RF signals from ground-based radar monitoring or emit RF outside communication bands (Vruno et al., 2023). This highlights the need for controlling unintended emissions and balancing the needs of different communities for the mutual benefit of all stakeholders.

Numerous mitigations are possible and have been effective in reducing brightness of LEO satellites. In mid-2020 it was announced that SpaceX would add visors to reduce illumination and reflection by Starlink satellites. One study of the so-called VisorSats (Horiuchi et al., 2023) stated that while effective, new countermeasures remained necessary. Another study (Halferty et al., 2022) found that VisorSats were 2.3 times fainter than the initial Starlink satellites, and that a earlier test of a DarkSat with anti-reflective coating was at least 7.6 times fainter (Halferty et al., 2022; Tregloan-Reed et al., 2020, 2021), but was not put into further production due to thermal issues. SpaceX found that the sun visors, while effective, also created drag and interfered with laser links[23]; they subsequently explored multiple techniques to darken the satellites using dielectric mirror film, solar array mitigations such as non-optimal-power pointing of the array near the terminator, and low-reflectivity black paint. In early 2023, the National Science Foundation (NSF) and SpaceX announced a joint agreement on astronomy coordination[24] that aims to reduce the brightness of Starlink satellites, as well as collaboration with the radio astronomy community to facilitate surveys beyond required international protection in the 10.6-10.7 GHz band, among other activities.

To address impairment of Earth-based astronomy due to orbiting satellites, telescopes and other astronomical facilities are being considered for the Moon (Silk, 2018). However, there is already concern that cis-lunar activities could impair the quiet electromagnetic environment that would enable radio-astronomy (Castelvecchi, 2023). Beyond astronomy, many animal species use stars for orientation during migration and foraging, and the impacts of satellite motion and brightness on these activities is unknown (Lawrence et al., 2022). It seems likely that some impairment is here to stay but that it can continue to be mitigated and managed to balance competing interests. Further study is needed to assess potential impacts on and beyond astronomy.

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[23] https://api.starlink.com/public-files/BrightnessMitigationBestPracticesSatelliteOperators.pdf

[24] https://new.nsf.gov/news/statement-nsf-astronomy-coordination-agreement

# A Future in Space, Near Earth and Far Beyond

## *Chemical Propulsion is Here to Stay*

Rockets powered by chemical propulsion are with us for the foreseeable future. There are other approaches to generating thrust that can achieve higher exhaust velocities, such as nuclear thermal propulsion, in which nuclear fission is used to heat and accelerate propellant, or electrical propulsion, in which electric and/or magnetic fields are used to accelerate propellant. However, these technologies cannot provide or are not being considered for safety reasons (nuclear fission), the required thrust to overcome gravity and get to orbit.

## *Reusable Launch Systems will Proliferate*

Today's launch systems can be expected to evolve towards increased reusability due to both cost and sustainability considerations. One nascent possibility is to use staging but have the first stage launch like an aircraft: in the turbofan engines in passenger aircraft the reaction mass that generates thrust comes almost entirely from the atmosphere ($I_{sp}$ of 3000-6000 in large commercial aircraft), compared to rockets where it comes entirely from the propellant ($I_{sp} < 450$). Aircraft launches have been performed before, with one example being the Pegasus rocket by Northrop Grumman. However, the Pegasus is a rocket launched from a conventional aircraft. In the future, it may be possible for rocket first stage to utilize engines that operate across a wide range of speeds, first operating like a turbofan, then at higher velocities and altitudes, like a ramjet, in which the vehicle's motion is used to compress even thin atmosphere into an inlet, brought to below the speed of sound, and combusted, or a scramjet, which operates on a similar principle but under a state of supersonic airflow. This would require a new type of engine design as well as an aircraft/rocket hybrid able to operate across a wide range of conditions, and able to carry large rocket upper stages. One example of development in this area is the Hermeus Chimera,[25] an engine which has demonstrated the ability to transition from turbofan to ramjet operations. If successful, such a technology—an aircraft-like first stage that could transition from turbofan to ramjet to scramjet—could improve launch efficiency. For reference, the heaviest aircraft ever built is the Antonov An-225, with a maximum take-off weight of 640 t, and payload of 232 t. In comparison, the second stage of SpaceX's Starship system, the Starship spacecraft, weights 200 t when empty but 3600 t when fully fueled. This suggests that large rockets will outcompete such a technology for large payloads.

There is also a nascent surge in activity and interest in hypersonic passenger aircraft.[26] The relative inefficiency of flying at hypersonic speeds could result in increased fuel usage and increased primary $CO_2$ emissions, although in some cases these could be offset through use of green fuels produced through $CO_2$ fixation (e.g., biofuels). Due to drag at lower altitudes, flights would be conducted in the stratosphere and would result in NOx and water vapor emission that could produce warming and under some assumptions reduce ozone by 0.046% (D. Eastham et al., 2022).

## *More Mass will be Delivered to Orbit and Commercial Activity will Grow*

The global space industry is expected to triple in size by 2040 (Shutler et al., 2022). With the advent of reusable heavy-lift rocket systems, such as SpaceX's Falcon Heavy or nascent Starship with Super Heavy Booster first stage, it is likely that the total mass to orbit will continue its

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[25] https://www.hermeus.com/chimera

[26] https://aerospaceamerica.aiaa.org/features/supersonic-travel-dead-on-arrival/

dramatic climb. In addition, we can expect continued growth in the “smallsats” class, or satellites under 1200 kg, due to advancing technologies leading to increasingly capable satellites at low mass.[27] This interest also extends to national governments seeking to leverage smallsats for national security applications.[28] Their increasing capabilities, including orbital maneuvering, will make tracking them more complex.

There is also increasing commercial interest for in-space activity. With the designation of the ISS as a National Laboratory, incorporation of commercially-provided cargo and astronaut delivery to and from the space station, and a wide range of commercial partners assisting with or conducting research in space, commercial activity in space is growing in response to government investments. With the current planned retirement of the ISS by 2030, several commercial space stations have been proposed by Vast, Axiom, Orbital Reef (a partnership including Blue Origin and Sierra Space), and Starlab.

## *Cis-lunar Activity will Grow and Humans will Make Plans for Mars*

Several nations plan to send humans to the Moon, including the U.S., China, and Japan, the latter via the U.S. Artemis program. We can envision a future where economic activity takes place on the moon (U.S. Cislunar Technology Interagency Working Group, 2022). If lunar resources such as water ice are identified in permanently shadowed craters, they may be mined and used to establish propellant depots and a broader lunar economy, which might ultimately include datacenters or use of the moon as a base of operations to journey to other worlds, such as Mars—the low escape velocity means that it is relatively low cost energetically to go from the Moon to many planetary bodies.

To reduce the transfer time to Mars, which averages 8 months or more using a minimum energy transfer, NASA and the Defense Advanced Research Projects Agency (DARPA) are partnering[29] on a test of the Demonstration Rocket for Agile Cislunar Operations (DRACO) as soon as 2027. This nuclear thermal rocket (NTR) would utilize a fission reactor to heat a working fluid (e.g., hydrogen) to high temperatures to achieve a high exit velocity, instead of using chemical propulsion. This would result in both high thrust and higher propulsion efficiency, enabling shorter transfer times to Mars and other destinations. While the U.S. developed and tested NTRs on the ground from 1955 to 1973, none have been flown to date.

Even so, SpaceX has plans to go to Mars using chemical propulsion using more traditional transfer times. SpaceX has repeatedly demonstrated supersonic retropropulsion (thrust in the direction of motion to slow down) through reusable boosters on Earth, and is now poised to take that technology to Mars. Starship’s potential ability to land up to 100 tons on Mars could dramatically upend traditional modes of exploration on that world, which have been limited in mass and without a rocket-based deceleration system. Future human missions to Mars will test current *planetary protection* policies, the topic of the next section.

## *Planetary Protection will Evolve*

Planetary protection encompasses both limiting the contamination of other worlds by Earth biology or organic material (forward contamination) as well as keeping Earth safe from life or harmful agents from other worlds (back contamination). Planetary protection policies apply to space missions to all planetary bodies. The legal framework for planetary protection comes from

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[27] https://brycetech.com/reports/report-documents/Bryce_Smallsats_2024.pdf

[28] https://eos.org/articles/earths-orbit-is-about-to-get-more-crowded

[29] https://www.nasa.gov/news-release/nasa-darpa-will-test-nuclear-engine-for-future-mars-missions/

the 1967 Outer Space Treaty,[30] which requires that states avoid harmful contamination of other worlds and also "adverse changes in the environment of Earth resulting from the introduction of extraterrestrial matter." The Committee on Space Research (COSPAR) Panel on Planetary Protection (PPP)[31] maintains policies which are interpreted and implemented by states. NASA's office of Planetary Protection,[32] part of the Office of Safety & Mission Assurance, promulgates rules for U.S. missions. Planetary protection rules (e.g., NASA NPR 8715.24) are specific to the target body being explored as well as whether a round trip (e.g., sample return) is being considered. Currently planetary protection for the moon is quite limited, with the main objectives being preserving lunar polar volatiles for scientific study.

On Mars, due to the potential for life (Carr, 2022), planetary protection is much more complex. The current guidelines for Mars robotic missions have recently been reviewed by (Olsson-Francis et al., 2023). One of the major challenges is that wherever humans go, we will bring with us our trillions of microbes that make up our gut, skin, and other microbiomes. While guidelines for human exploration are in an interim status (NASA NID 8715.129), a proposed roadmap has been reviewed by (Siegel et al., 2023). This is an evolving area that will be tested by technical challenges, cost, and lack of environmental knowledge as humans venture further into space with our robotic vehicles and ultimately ourselves, as we seek to live, work, and prosper on multiple worlds.

## *Long-term Opportunities and Existential Risks*

The extension of human activity to the moon and beyond will bring new opportunities and risks. For example, space exploration may be a driver of sustainability (closed loop life support, recycling, bioproduction, manufacturing) (Averesch et al., 2023; Santomartino et al., 2023; Berliner et al., 2022; Soundararajan et al., 2023; Vengerova et al., 2024) due to the high costs of importing or transporting goods to space or planetary destinations. Space also offers new opportunities for resource extraction, such as lunar helium 3 (a potential fusion fuel) or asteroid mining—which contrary to popular belief is not likely to result in mass return of raw materials or goods to Earth, but is more likely to contribute to in-space manufacturing. This future requires a capability to move and control large masses in space.

On February 15, 2023, an 18 m diameter meteoroid exploded at ~23 km altitude over Chelyabinsk, Russia. Traveling at 19 km/s, it's explosive power was ~30 times greater than the Hiroshima atomic bomb (Emel'yanenko et al., 2013; Popova et al., 2013). Despite damaging 7,200 buildings and injuring 1,491 people, no deaths were reported. But a bigger meteoroid could have ended civilization as we know it.

NASA's recent Double Asteroid Redirection Test (DART), in which a spacecraft intentionally impacted an asteroid moon of another asteroid, demonstrated the ability to deflect the body's trajectory (Chabot et al., 2024). This capability is essential for long-term survival of humans so that civilization-ending impactors (upper mass range in Fig. 6A) can be redirected, if detected early enough. While necessary to ensure our survival, the capability to manipulate large masses in space also brings with it the capability to use large masses as a weapon. Monitoring in an increasingly dynamic environment will be critical. More near-term threats also include the risk of conflict in space. Cooperation and the establishment of norms will be essential as humans venture further into the cosmos.

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[30] https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

[31] https://cosparhq.cnes.fr/scientific-structure/panels/panel-on-planetary-protection-ppp/

[32] https://sma.nasa.gov/sma-disciplines/planetary-protection

## The "Natural Environment" Beyond Earth

Anthropogenic impacts on the space environment and their impact on Earth are complex and yet this diagram (Fig. 9) only captures near-Earth aspects of space exploration. As humans continue to venture into space, the domain of human activity and awareness will truly encompass not only Earth, but the Moon, and perhaps one day Mars and other worlds. Our self-awareness of anthropogenic impacts must also expand to include all impacted parts of the natural world.

To mitigate anthropogenic impacts in space will require coordinated action to address both accidental and intentional acts (Guoyu, 2024), and will play out amid a very complex landscape of space security (Pekkanen and Blount, 2024). As is often the case, the regulatory environment lags behind current space activities. For example, international regulations do not currently cover rocket emissions (Sirieys et al., 2022). Sustainability metrics encompassing the entire lifecycle of space vehicles are required in order to incentivize development and adoption of sustainable practices in the commercial sector (Sirieys et al., 2022). One proposal includes the development of a Space Sustainability Rating (SSR) to incentivize good behavior (Rathnasabapathy and David, 2023). The space environment does share several features that make sustainable use challenging (Lawrence et al., 2022): (1) observed and predicted damage is incremental and complex; and (2) global exploitation of this "free" resource externalizes true costs. Some proposed steps that can be taken (Archinard, 2024) include: (1) improving implementation of existing international instruments, (2) refining common interpretation of international space law, (3) involving all stakeholders in standardization and rule-making, (4) where possible, setting realistic common objectives as a way to start addressing urgent issues and emerging challenges.

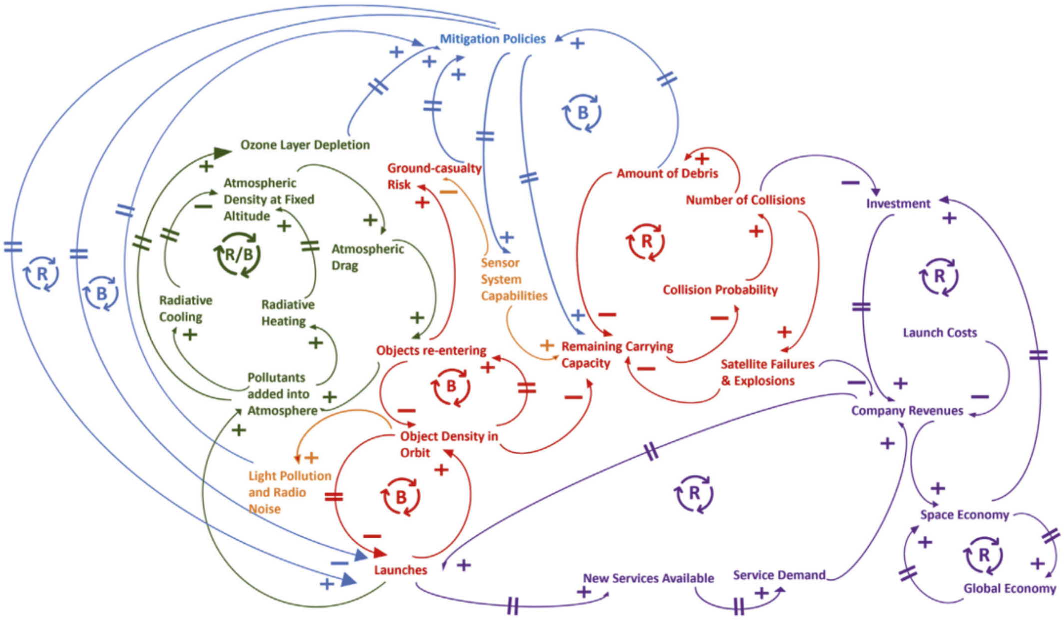

**Fig. 9:** Causal loop diagram outlining the connections and polarity of relationships between a wide variety of factors linked to the space environment. Color coding in this figure signifies the predominant grouping for the connections shown. Red signifies the space environment, green signifies the atmospheric environment, purple signifies economics, blue signifies polices and orange signifies sensor systems. Positive polarity indicates a reinforcing relationship whereas negative polarity indicates inhibition. R indicates closed reinforcing loops; B indicates balancing feedback, where one or many factors may limit growth. [Reprinted from (Perks et al., 2024) Fig. 1 under CC BY 4.0 license] ⏎

Balancing “technological advancement, protection of space environments, and our capacity to explore the Universe” will require adaptive governance “that swiftly responds to environmental changes, incorporating new information and adapting to evolving conditions” (Williams et al., 2024) Such a system, integrating “regulatory and policy measures and incentives at national and international levels” seems at odds with current political realities, which is all the more reason to advocate strongly for collaborative management of our shared near-Earth environment and collective interests. Our past failures to consider long-term consequences do not doom us to repeat them.

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