Waste of Space

The Environmental Cost of Human Activities in Space

Space Watch UK investigates and challenges the militarisation and corporate exploitation of space, focusing in particular on the UK's military space programme. Space Watch UK is a project of Drone Wars UK.

We undertake education work with the public, parliamentarians and NGOs to raise awareness of the risks of militarising space; support local and international efforts to control the environmental and security impact of military space programmes; and engage in networking and advocacy in support of ensuring the peaceful use of space.

We are an affiliate of the international Global Network Against Weapons and Nuclear Power in Space and we support the Global Network's call to stop the arms race in space.

We work to support local groups campaigning against space-related developments that harm environment or contribute to the militarisation of space, and undertake research, education, and advocacy work in support of our aims.

We do not accept funding from governments or private companies. This study has been supported by grants from the Edith M Ellis Charitable Trust and the Sir James Reckitt Charity. The Network for Social Change provided funding to establish the Space Watch UK project.

Space Watch UK would like to thank Dave Webb and Wuhu Feng for assistance in preparing this report.

Published by Space Watch UK, July 2026

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Cover image: Illustration of space junk orbiting the Earth. **Credit:** Mark Garlick/Science Photo Library

"Given the mess we've made of things down here on Planet Earth, it's no surprise we're now doing exactly the same up there in space. But this is the first time I've seen all the details of that "space-trashing" laid out so clearly – and so disturbingly.

However, for every problem, 'Waste of Space' suggests a better way forward, with constructive recommendations regarding regulation and ethical ground rules.

This is an extremely significant and timely contribution to a debate that is becoming more and more crucial".

Jonathon Porritt
Sustainability campaigner and author

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Executive Summary

The Earth's environment and climate are changing as a result of human activity. Human activity in space may now be playing an increasing role in contributing to global environmental change – possibly in ways that we do not yet fully understand. Although small in scale when compared with many industries, the space industry is growing rapidly. For decades the small numbers of annual rocket launches into space meant that the industry's impacts were thought to be limited and local, but as the number of launches grows this is no longer the case. 'Waste of Space' identifies in detail the environmental impacts of the space sector and sets out some ways forward for controlling these impacts.

Terrestrial impacts

Ground infrastructure such as spaceports (launch sites) and satellite ground infrastructure may have impacts on the local environment as they are frequently situated in remote locations, often with unspoilt and possibly rare ecosystems. Infrastructure development or secondary development around a spaceport hub may add to the impacts. Spaceport developments can also present a challenge to established ways of life and erode cultural identity and can also have a divisive impact on local communities.

Launch and rocket test operations at spaceports as well as accidents, spills and leaks can cause pollution, while rocket debris may be discarded into the sea during a launch. The planning process provides weak protections for local communities and the environment from significant development projects such as spaceports.

Atmospheric impacts

Rocket emissions and debris falling out of orbit are having increasingly detrimental effects on global atmospheric chemistry. The impact depends upon the type of pollutants released and whereabouts in the atmosphere they are released. Atmospheric science has developed rapidly in recent years but we still have much to learn about the ramifications of introducing unfamiliar chemicals into the atmosphere.

Space rockets release gases and particles directly into the atmosphere and are the only anthropogenic source of pollution in the middle and upper atmosphere. The stratosphere is the location of the ozone layer, which absorbs most of the sun's ultra-violet radiation and protects living organisms from its harmful effects.

There is evidence that some emissions from the burn-up of rocket components, space debris, and redundant satellites reentering the atmosphere are damaging the ozone layer.

The four most commonly used rocket fuels are kerosene, hypergolic fuels, liquid hydrogen, and solid fuels. Combustion emissions created by all propellants include water vapour and nitrogen oxides. Other pollutants include black carbon (soot) from kerosene fuels, and alumina particles (aluminium oxide) and gaseous chlorine and hydrochloric acid from solid fuels. All of these substances have impacts on the atmosphere, with possible global implications.

All rocket fuels generate substances which contribute to global climate change. Water vapour released from rocket engines can act as a greenhouse gas, absorbing heat radiated from Earth and preventing it from escaping into space. The quantity of greenhouse gases emitted directly by rockets is currently low compared to that of other industrial sectors, but other substances released during rocket launches can have far more significant implications for the climate. Black carbon – soot from rocket fuels which is a solid form of mostly pure carbon – absorbs solar radiation at all wavelengths and warms the atmosphere. It is produced by the combustion of any carbon-based fuel and can account for several per cent of rocket emissions. Alumina is another particulate material emitted during rocket launches. The climate impacts of alumina are more complex than those of black carbon, but modelling suggests that its overall effect is to generate net positive radiative forcing, adding to the greenhouse effect. In addition to direct contributions to climate change, rocket launches may indirectly give rise to an increase in the generation of greenhouse gases as a result of closure of air traffic corridors, causing flights to divert.

Both rocket launches and the reentry of spent satellites and space debris can impact upon the ozone layer. Rockets emit persistent ozone-destroying compounds directly into the stratosphere. The intense heat generated during a launch, as well as the burn-up of satellites and components which enter the atmosphere at the end of their life, causes atmospheric nitrogen to be converted into ozone-destroying nitrogen oxides. Reactive radicals produced by combustion such as oxides of chlorine, nitrogen, bromine, hydrogen, and aluminium also destroy ozone. Aluminium oxides and metallic pollution resulting from the reentry of satellites and space debris act as catalysts triggering chemical reactions which destroy ozone but are not consumed during chemical reactions, potentially continuing to destroy ozone for decades.

Space debris

Space debris poses a catastrophic collision hazard to functional satellites. As the debris population grows more collisions can be expected to occur, with risks increasing geometrically. This may give rise to a self-sustaining chain of collisions known as the 'Kessler syndrome', threatening the use of certain orbits. Even without an increase in the number of launches the number of objects in space is expected to continue to grow because of fragmentation events, and the risk of collision is increasing dramatically.

Items of space debris which are too large to burn up in the atmosphere are brought to Earth in a controlled descent so that they land in a remote area of the South Pacific Ocean where they will cause little harm. While this may be the least worst disposal option, this location is a pristine area largely unspoilt by human activity, hosting unexplored and probably vulnerable ecosystems.

Dark and quiet skies

Light pollution of the night sky has the potential to erode and damage human cultural heritage and may also have unforeseen effects on wildlife and human health. Large satellite constellations can reduce the visibility of the night sky by reflecting sunlight down to Earth and generating light trails and radio signals which interfere with astronomical observations.

The magnetosphere

There is a possibility that deposition of material originating from space hardware in the atmosphere may also be adding a 'magnetospheric loading' onto the planet. The accumulation of conductive, electrically charged material in the atmosphere could theoretically alter or weaken the Earth's magnetosphere, possibly reducing the protection it provides from cosmic radiation.

Reversing the trends

The second section of the report looks at approaches which might allow the environmental impacts of the space sector to be controlled.

Planetary boundaries

The planetary boundaries framework sets quantitative limits for human pressure on critical environmental processes which affect how global systems function and define a 'safe operating space' for humanity. The concept of planetary boundaries could be extended to cover the proliferation of objects in orbit and night sky brightness to encourage action to keep these measures within sustainable limits.

Regulation of the space sector

Scientific uncertainty and the rapid growth of the sector mean that space policies based on the assumption that environmental impacts are minimal and no longer appropriate. Since the end of the Cold War few new international rules or guidelines have been established to regulate conduct in space. Existing treaties need to be supported and new instruments need to be developed to prevent the further deterioration of space commons and protect them from encroachment. However, powerful interests are opposed to such measures and are actively working to dismantle existing protections.

An ethical approach to space policy

Blockages which are preventing space law from being updated to meet modern needs suggest that a fresh approach is needed to deal with shortfalls in space governance. Efforts to build a consensus among scientists and policymakers on a responsible, ethical approach to space issues have an important role to play in moving things forward. An increased focus on space ethics from civil society, media, and citizens may help to create a climate where meaningful negotiation on space governance can take place. An ethical approach to technology development and the responsible use of space, based around education, public awareness-raising, and adoption of ethical guardrails can act as a 'moral compass' in the absence of regulation and serve as a foundation for developing new law and policy.

Decoupling space from the military

The military use of space has become an increasingly important part of modern warfare. Nowadays space is fundamental to military operations and underpins the ability to undertake the majority of military tasks. The military is a major driver for the space sector and the sector is substantially funded by the military. Space is becoming a competitive and increasingly dangerous domain. It is in everyone's interests to move towards the demilitarisation of space.

Decoupling space from the military will be a complex, long term project, centred on reducing and managing risks arising from space militarisation through space technology control, arms control negotiations, and separating military and civil interests in space. An important step towards the peaceful use of space would be an international treaty on the Prevention of an Arms Race in Outer Space (PAROS) to prevent any nation from placing objects carrying any type of weapon into orbit.

Citizen action

Public opinion can influence government and corporate policies. The top space priorities for most citizens are related to activities that have benefits on Earth, such as climate monitoring. Citizens do not support steps to militarise space and want their own nations to comply with international space law. Public interest in space science can be marshalled through social movements to successfully influence government funding and decisions on space policy. Citizen push-back can force corporates and governments to adopt a sustainable approach to space, and may currently be the best hope of achieving positive change.

If worst case scenarios are correct, the space industry may already be having a significant impact on atmospheric chemistry, with implications for global climate change and the health of the ozone layer. This means we must slow down or pause certain activities in space until we have a greater understanding of how our presence in space is affecting the atmosphere and other commons. Environmental change is often irreversible, and it is in humanity's interests to take a precautionary approach to prevent lasting harm to the global environment.

“Облетев Землю в корабле-спутнике, я увидел, как прекрасна наша планета. Люди, будем хранить и преумножать эту красоту, а не разрушать её!”

Юрий Гагарин

Translation:

“Orbiting Earth in the spaceship, I saw how beautiful our planet is. People, let us preserve and increase this beauty, not destroy it!”

Yuri Gagarin, first human to travel into outer space.[1]

“I realized up there that our planet is not infinite. It’s fragile. That may not be obvious to a lot of folks, and it’s tough that people are fighting each other here on Earth instead of trying to get together and live on this planet. We look pretty vulnerable in the darkness of space.”

Alan Shepard, second human to travel into space and fifth human to walk on the Moon.[2]

1 Quoted in Lev Aleksandrovich Lebedev, Boris Borisovich Luk' ianov & Aleksandr Romanov: ‘Sons of the Blue Planet’. National Aeronautics and Space Administration and the National Science Foundation, Washington, 1973.

2 Alan Shepard, Deke Slayton, Jay Barbree, Neil Armstrong, & Howard Benedict: ‘Moon Shot: The Inside Story of America’s Race to the Moon’. Turner Publishing, 1994.

1 Introduction

For many astronauts, the most memorable experience during space flight is the awe and wonder of seeing the fragile blue globe of planet Earth beneath their spaceship. The breathtaking privilege of observing the beauty of our home planet from space is often a transformative experience. Astronauts return to Earth with an understanding of the unity of humanity, a unique awareness of the interconnectedness of ecological systems, and a determination to protect and preserve the planet.[3] Astronaut Jessica Meir, who commanded the February 2026 Crew-12 flight to the International Space Station described this striking perception during her mission's launch. "Looking at our planet from above it is immediately clear that everything is interconnected," she said. "The vast oceans, the continuing landmasses... we are one humankind. We know it is utterly unique, fragile and must be protected."[4]

However, the Earth's environment and climate are changing as a result of human activity. Space technologies have helped us monitor such changes, but may now be playing an increasing role in contributing to environmental change – possibly in ways that we do not yet fully understand. Space based operations affect many aspects of modern life and commerce. The global economy relies heavily on satellites in orbit to provide communication services for a variety of services including mobile phones, the internet, television, and financial trading systems. Global positioning system (GPS) satellites play a key role in transport networks, while Earth observation satellites provide information for weather forecasting, climate monitoring, and crop observation. Space is also a key domain for military operations and is becoming increasingly militarised.

Although small in scale when compared with many industries, the global space industry is growing rapidly. Satellite launch costs have fallen dramatically over recent years and are far less than in the space shuttle era of the 1980s. Costs continue to drop, and are expected to drop further as technology development leads to advances in manufacturing, miniaturisation, and reusable launch systems, and as competition increases.[5] This is driving a new 'race for space', with commercial and government sectors keen to capitalise on the economic and strategic advantages offered by the exploitation of space. The space sector

3 Charles Perring: '10 Astronaut Quotes on the Overview Effect'. EarthScapeVR, 27 March 2023. https://www.earthscapevr.com/10-astronaut-quotes-on-the-overview-effect

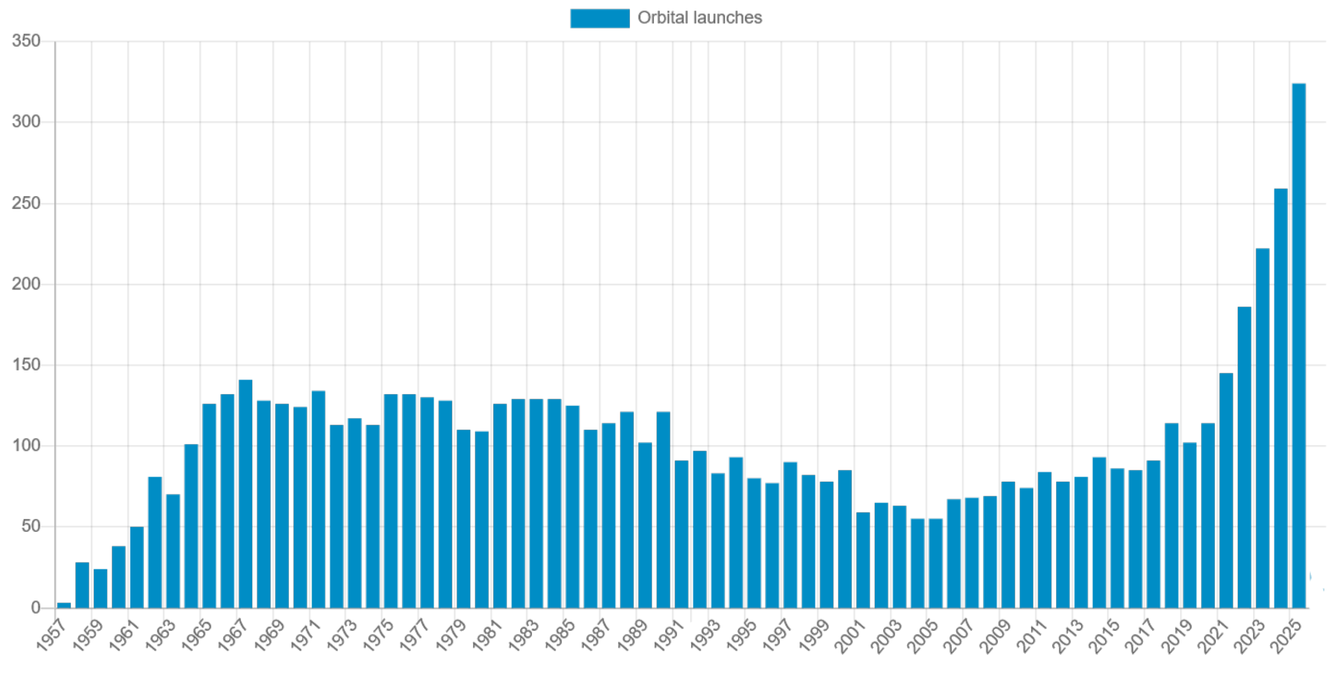
4 'Astronauts in awe at 'utterly unique, fragile' Earth as they blast off to ISS'. BBC News, 13 February 2026. https://www.bbc.co.uk/news/live/c5yjrz5rlejt

5 Nodir Adilov, Peter Alexander, Brendan Cunningham & Nikolas Albertson: An Analysis of Launch Cost Reductions for Low Earth Orbit Satellites. Economics Bulletin V42(3), p1561-1574. 2022. https://www.researchgate.net/publication/379335390_An_Analysis_of_Launch_Cost_Reductions_for_Low_Earth_Orbit_Satellites_accepted_for_publication_Economics_Bulletin_2022

itself is undergoing transformation and is moving from traditional government-led investment to a 'NewSpace' sector funded by entrepreneurs and private companies, focused on developing products for commercial markets.[6] As a result, rapidly increasing activity in space is now creating pressure on both the global environment and international arrangements for the governance of space. Many of the environmental problems caused by the space sector are a consequence of its single use, throwaway approach to business.

The number of space launches is increasing significantly, and more satellites have been launched in the last five years than in the preceding 60 years combined. Between the mid 1960s and the mid 1990s the number of world-wide orbital launches fluctuated between around 100 – 140 launches per year. This fell in the 2000s and dropped to a low of 55 launches per year in 2004 and 2005, but has since grown exponentially (see Image 1). With 114 launches in 2020, the number of launches has been growing at a minimum rate of 12 per cent per year since then, and reached 324 in 2025.[7] The US Federal Aviation Administration expects the number of launches from the US over the period 2024 – 2028 to increase between 45 and 117 per cent – more than doubling at the highest estimate.[8] As the space sector grows and increasing numbers of satellites are launched, its environmental impacts will at the same time rapidly accelerate from the relatively modest levels they are at today.

Image 1. Numbers of orbital launches into space, 2000–2025



Credit: SpaceStatsOnline.Com

6 Robert Murray: 'The NewSpace market: Capital, control, and commercialization'. Atlantic Council Scowcroft Centre for Strategy and Security, 27 April 2023. https://www.atlanticcouncil.org/wp-content/uploads/2023/04/The-NewSpace-market-Capital-control-and-commercialization.pdf

7 'Orbital launches by year'. Space Stats. https://spacestatsonline.com/launches/

8 'FAA Aerospace Forecast Fiscal Years 2024–2044: Commercial Space'. Federal Aviation Administration. https://www.faa.gov/dataresearch/aviation/aerospaceforecasts/commercial-space.pdf

Agencies and industries in the space sector often talk about 'sustainability', but sustainability means different things to different people. The concept of sustainability was largely formulated in the 1980s through the work of the United Nations' World Commission on Environment and Development (the Brundtland Commission) and the subsequent United Nations Conference on Environment and Development – the 1992 Rio 'Earth Summit'. Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.[9] It is based around meeting human needs, rather than the demands of the market or the desires of the wealthy, and the understanding that there are environmental, social, and technological limitations to the planet's ability to meet those needs. The concept of sustainability requires taking a wide-ranging, holistic view of how human activity is affecting the environment. Both the US National Aeronautics And Space Administration[10] and the UK Space Agency[11] have web pages on space sustainability, but their view of sustainability is focused solely on dealing with the problem of space debris, which is posing a threat to continued operations in space (see section 4 below). This does not address other important impacts from the space industry, such as its effects on the atmosphere, the night sky, and the terrestrial environment. The European Space Agency takes a broader view and has published a set of principles intended to allow the agency to undertake its mission with a high sense of ethics to minimise environmental impact and maximise social impact.[12] Different understandings of sustainability, however, allow governments and industry to 'spacewash'[13] their space programmes by describing them as sustainable when, from a broader environmental viewpoint, they are no such thing.

Space Watch UK has undertaken this study to review the environmental impacts of the space sector and identify risks that these impacts may pose to local and global ecosystems. We have examined the impacts the space sector has on global commons such as pristine ecosystems on Earth, sensitive regions of the atmosphere, and the night sky, and look at the consequences of abandoning debris in space. We explore potential ways of tackling some of these issues and set out a number of recommendations.

Environmental and ethical issues relating to the space industry are seldom discussed in the mainstream media, and there is little awareness among the general public and political decision-makers about the impact that the industry is beginning to have on global environmental systems. "I think we are at a stage in the space industry that we were at many decades ago in a number of our terrestrial environments," says space executive Tim Maclay, chief strategy officer for Switzerland's ClearSpace orbital servicing company. "We see the prospect of development and we tend to race into it without a tremendous amount of forethought on the environmental consequences."[14] For decades the tiny numbers of annual rocket launches into space meant that the industry's impacts

9 United Nations General Assembly: 'Report of the World Commission on Environment and Development: Our Common Future'. Annex to document A/42/427 – Development and International Co-operation: Environment; Our Common Future: Chapter 2: Towards Sustainable Development; Paragraph 1. 20 March 1987. **http://www.un-documents.net/ocf-02.htm**

10 'NASA's Space Sustainability Strategy'. NASA. **https://www.nasa.gov/spacesustainability/**

11 'Case study: Space sustainability'. UK Space Agency, 7 October 2023. **https://www.gov.uk/government/case-studies/space-sustainability**

12 'ESA Sustainability Principles'. European Space Agency. **https://www.esa.int/About_Us/Climate_and_Sustainability/ESA_Sustainability_Principles**

13 The space sector's equivalent of greenwash: public relations that uses marketing to deceptively persuade the public that its operations are environmentally friendly. See section 3.3.

14 Shannon Hall: 'The New Space Race Is Causing New Pollution Problems'. 9 January 2024. **https://www.nytimes.com/2024/01/09/science/rocket-pollution-spacex-satellites.html**

were thought to be limited and local, but as the number of launches grows this is no longer the case. Space corporations and governments invariably present space programmes in terms of their economic and technical benefits, and this approach is almost always regurgitated by the mainstream media, describing projects as “sustainable” even through they may pose significant environmental hazards.

We wanted to investigate these hazards further and challenge the spacewashing of environmentally harmful and ethically suspect programmes. The ‘Waste of Space’ study aims to start a debate about how humans are treating the space environment and mobilise scientists, communities, and science writers to take action at a critical point in time. It is still not too late to prevent irreparable harm from being done to global commons such as the atmosphere, the night sky, and access to satellite orbits, but if we hesitate for much longer it may be.

2 Terrestrial impacts

2.1 Resource extraction

Satellites and space rocket bodies are made from lightweight and strong metals such as aluminium and titanium alloys and / or stainless steel. Aluminium can typically comprise up to 40 per cent of a satellite's mass. Other metals, such as cadmium, gold, lithium, and gallium are also present in satellites and their electrical components. The mining, extraction, and smelting of these metals have a number of significant impacts on the environment and are highly carbon intensive processes consuming large quantities of energy. Cadmium in particular is toxic and can accumulate in food chains. Satellites and metallic space debris will be left to deorbit and burn up in the atmosphere at the end of their life, and metal residues from end-of-life space components become distributed in the atmosphere (see section 3.5 below). However, in terms of resource extraction the quantity of metals consumed by the space sector is likely to be considerably lower than quantities used in other industrial sectors such as the consumer electronics, automotive, aviation, and energy sectors.[15]

2.2 Spaceports and launches

Spaceports – launch sites for placing satellites into orbit – are usually based in remote locations to minimise hazards to human populations from launch accidents and falling debris following a rocket launch. These locations are often considered by government and business to be uninhabited and of little value: remote, distanced from cities and townships and ripe for development. They are often relatively unspoilt, rich, and possibly also rare ecosystems. The planned Sutherland Spaceport in Scotland is intended to be located on a site in peatland,[16] an internationally important habitat and carbon store (see Image 2). Launch pads at the SaxaVord Spaceport are situated on open coastal/upland habitat characterised by peatland and grassland.[17] The eventual impacts of spaceport development on these locations is not yet known.

15 Kevin J Gaston, Karen Anderson, Jamie D Shutler, Robert JW Brewin, Xiaoyu Yan: 'Environmental impacts of increasing numbers of artificial space objects'. Frontiers in Ecology And The Environment, Vol 21(6), p289-296. 5 April 2023. https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/fee.2624

16 Tom Pashby: ''Floating road' and bridge installed at Sutherland Spaceport'. New Civil Engineer, 13 May 2024. https://www.newcivilengineer.com/latest/floating-road-and-bridge-installed-at-sutherland-spaceport-13-05-2024/

17 'SaxaVord Spaceport AEE V3. Assessment of Environmental Effects'. ITPEnergised, 30 June 2023. Para 6.4.15, p6-9. https://www.caa.co.uk/publication/download/21052

Image 2. The Sutherland Spaceport site is located in an area of valuable peatland habitat. **Credit:** Orbex

Spaceports are often built at repurposed airports or military bases, where a certain amount of infrastructure is already present. However, this will often need refurbishing or upgrading. Roads and transport infrastructure, fuel storage, water supply and sewage systems, electrical supply and broadband connections are all required to service a spaceport, and sometimes more substantial development also takes place as part of a wider spaceport infrastructure project, such as construction of wharves or bridges. In other cases spaceports may require a significant element of new build, with potential for disturbing the local ecosystem.

As well as being operational sites for space launches, spaceports are usually planned to act as catalysts for further economic development in the locality and wider region – 'economic powerhouses' intended to drive the creation of spin-off and secondary businesses. In fact, a number of successful 'spaceports' in the US, such as Houston Spaceport at Ellington Airport, have not actually hosted rocket launches or landings, but have thrived by acting as hubs for the space sector.[18]

Other spin-off developments may relate to the potential of the spaceport to attract tourists, and centre around the hotel and restaurant and hospitality sectors. SaxaVord Spaceport operates alongside a gin distillery, and there have been proposals for a tourism-related hotel nearby as part of the spaceport project.[19] Because spaceports are secure facilities and are often located in remote locations they are attractive sites for military and security-related activities.[20]

18 Jeff Foust: 'The spaceport conundrum'. The Space Review, 10 February 2025. https://www.thespacereview.com/article/4934/1

19 Chris Cope: 'Plans could be submitted for '£60m to £70m' Saxa Vord hotel by end of the year'. Shetland News, 20 May 2022. https://www.shetnews.co.uk/2022/05/20/plans-could-be-submitted-for-60m-to-70m-saxa-vord-hotel-by-end-of-the-year/

20 Jeff Foust: 'The spaceport conundrum'. The Space Review, ibid.

Spaceport developments can also present a challenge to established ways of life and erode cultural identity, especially for those living close to the spaceport, and can also have a divisive impact on local communities. This is particularly the case if some parties, for example landowners, stand to gain financially as a result of the development while others feel they may lose out. Divisions can be exacerbated if the developer makes over-inflated promises about benefits the spaceport could bring to the community. In more remote locations, spaceport development on indigenous lands may result in the displacement of indigenous peoples or raise issues about the cultural and spiritual significance of land, sky, or celestial bodies such as the Moon and Sun, in ways which are not immediately obvious to outsiders. Both land and celestial bodies in the heavens hold a sacred position in many indigenous cultures and are part of their spiritual heritage, deserving reverence and respect.[21]

Launch and rocket test operations at spaceports can give rise to local environmental impacts and pollution of watercourses. During a rocket firing a 'deluge' system of water jets is used to blanket the launchpad to suppress noise and energy and act as a fire suppression system. This can consume large quantities of water, much of which is vaporised, but some of which, contaminated by fuel residues, may be released to the environment. Fuel residues and combustion products released during the rocket launch may also drift back to the ground and cause contamination. Releases during launch of the propellant unsymmetrical dimethylhydrazine (UDMH), which is toxic, highly carcinogenic, and persistent in the environment, have reportedly heavily contaminated large areas of steppe around the Baikonur Cosmodrome in Kazakhstan, used by Russia for rocket launches.[22]

Accidents, spills and leaks are another potential hazard to the water environment. A fire at the Pacific Spaceport Complex-Alaska on Kodiak Island, Alaska, in July 2024 during a rocket ground test resulted in a spill of 1,800 gallons of aviation fuel and other contaminants. Clean-up costs arising from the incident totalled $US3 million.[23] Per- and polyfluoroalkyl substances (PFAS) used in spaceport fire-fighting foams are persistent organic pollutants which do not easily degrade in the environment and accumulate in tissue in fish, wildlife and humans.

Depending on the type of launch vehicle, rocket debris may be discarded during a launch. This will usually fall into the sea and is rarely recovered. Other businesses, particularly in the maritime and fisheries sector, view this practice with disfavour as most other industries are not permitted to abandon waste at sea.[24] Rocket debris remains on the sea bottom and may damage fishing gear, as well as eventually corroding and releasing contaminants into the ocean. Fishing communities may also be disadvantaged by closure of fishing grounds during launches.[25]

21 Michael J. Listner: 'The intersection of cultural beliefs and mythos with non-governmental space activities and its potential impact to national interests and great power competition'. The Space Review, 2 September 2025. **https://www.thespacereview.com/article/5048/1**

22 Mark Piesing: 'The pollution caused by rocket launches'. BBC Future, 15th July 2022. **https://www.bbc.co.uk/future/article/20220713-how-to-make-rocket-launches-less-polluting** Russia no longer uses UDMH but China does.

23 Davis Hovey: 'Alaska Aerospace sues insurance group over cleanup costs at Kodiak Island spaceport'. KMXT, 18 February 2025. **https://www.kmxt.org/news/2025-02-18/alaska-aerospace-sues-insurance-group-over-cleanup-costs-at-kodiak-island-spaceport**

24 'UK Space Expansion: Benefits for All? Local Perceptions of the SaxaVord Spaceport'. Space Watch UK, 22 September 2025. P14. **https://spacewatch.uk/wp-content/uploads/2025/09/DW-Saxavord-portrait-w_links.pdf**

25 'Rick Neale: 'Nets torn 'all to hell': Port Canaveral fishermen worry about increasing rocket launches, debris'. Florida Today, 27 July 2025. **https://eu.floridatoday.com/story/tech/science/space/2025/07/27/port-canaveral-fishermen-say-frequent-cape-canaveral-rocket-launches-reduce-fishing-time-ruin-nets/84287108007/**

Industry sources have claimed that the negative impacts of collecting rocket debris are currently higher than the impact of the debris itself.[26] Space Watch UK has been unable to find any evidence or analysis supporting this assertion. It is sometimes also claimed that, over time, rocket debris abandoned at sea will act as artificial reefs, with benefits for marine life. Such claims are an example of spacewashing intended to justify the dumping of waste at sea. Good practice guidance on the construction of artificial reefs requires them to be made from inert, durable, structurally sound materials, secured to the sea bottom, and sited in appropriate locations.[27] Rocket debris may not meet these criteria and may contain toxic components. It is not possible to pre-position debris at a selected location. Artificial reefs are not necessarily an enhancement to the environment: poorly planned and built reefs may pose risks by disrupting existing patterns of marine life.[28]

Abandoning rocket debris in the ocean may render it 'out of sight and out of mind', but it is a symptom of a throwaway mindset which treats the seas as a dustbin. As we will see throughout this study, the space sector often fails to plan for the end of life for its projects and components, and this has environmental consequences. The space sector and individual spaceports should develop action plans to minimise ocean-bound rocket debris, recover and recycle debris from the sea, provide compensation for damaged fishing gear, and develop reuseable launchers.

Authorisations and permits from various government agencies are intended to regulate environmental impacts and limit them to within acceptable levels. Our discussions with members of communities living close to the location of proposed spaceports in Scotland have indicated a number of anecdotal concerns about the planning and approval process governing spaceport development.[29] The licencing process for opening and operating a spaceport in the UK is complex, but before construction can commence the operator will need to have secured planning permission from the local planning authority and been granted a spaceport licence from the Civil Aviation Authority (CAA).[30] For both applications an environmental impact assessment (EIA) or assessment of environmental effects (AEE) is required. Local residents living near spaceports have identified the following issues with permitting processes from their point of view as members of the public:

- There may be conflicts of interest in the local authority planning process: either institutional, in cases such as the Spaceport 1 development in North Uist, where the local authority is applying to itself for planning permission as the developer, or individual, where members of the planning committee may be perceived to have split loyalties.
- Planning and licencing process can be long-winded, but there are only relatively short windows for public consultation and the lodging of comments and objections.

26 'Launch Our Future'. Spaceport Cornwall. https://spaceportcornwall.com/wp-content/uploads/2022/07/spaceport-impact-highlights.pdf

27 'National artificial reef guidelines. Version 1.0 (2023)'. Australian Government Department of Climate Change, Energy, the Environment and Water. P63. https://www.dcceew.gov.au/sites/default/files/documents/national-artificial-reef-guidelines-version-1-2023.pdf

28 Ariane Easton, Valeriya Komyakova & Tom Coughlin: 'Evaluating ecological risk in artificial habitat failure: A systematic review and risk assessment considering noise and light pollution in the marine environment'. Environmental Impact Assessment Review Vol 107, July 2024. https://doi.org/10.1016/j.eiar.2024.107560
'Unpacking the Risks Associated with Artificial Reefs: What Lies Beneath?' DRAR Diving and Watersports, 31 August 2025. https://drardiving.com/unpacking-the-risks-associated-with-artificial-reefs-what-lies-beneath/

29 Spacewatch UK online meeting with spaceport community members, 23 July 2025.

30 'Space licensing in the UK'. UK Civil Aviation Authority. https://www.caa.co.uk/media/kbfjgbx0/space-licensing-in-the-uk.pdf

- In general local authorities are seen to be under-resourced and their determination of planning applications was felt to be hurried and amateurish:
  - Errors flagged up by members of the public in planning applications are not subsequently addressed.
  - Technical matters, such as safety zones, need careful scrutiny and are probably not given enough attention by local authorities.
  - Local authorities are seen to be averse to challenging developers or upholding objections from local residents.
- Environmental impact studies are conducted by consultants selected and paid by the developer. They may lack local knowledge, present a best-case view of impacts, and draw conclusions which are not supported by survey data.
- After planning permission has been granted developers will do whatever they want at the site, regardless of whether permission has been given or planning conditions intended to reduce impacts. Residents do not have confidence that the planning authority will enforce planning conditions.
- In cases where local authorities are acting as developers in their own right to open a spaceport, they may not have adequate skills to manage the scale and technicality of the development and over-reach their capacity.

These will be familiar concerns to anyone who has encountered the UK's development planning system, as they are critiques which can be applied to any development of scale and any local authority in the country. Bond et al. argue that environmental impact studies support neoliberal agendas by facilitating economic development and that the political nature of the EIA system undermines attempts to use evidence objectively.[31] A response by the CAA to comments received from members of the public in response to consultation on the Assessment of Environmental Effects submitted by Virgin Orbit and Spaceport Cornwall for launches from Spaceport Cornwall supports this finding. In every case, the CAA responded by merely reasserting comments in the original submission from the developers, or with rebuttals provided by the developers. No effort was made to critique the developers' assertions and none of the comments submitted by the public resulted in any change to the proposals made by the developers.[32] The planning process and EIA system therefore result in weak protections for local communities and the environment from significant development projects such as spaceports. Intended changes to the planning system in the UK aimed at watering down controls to accelerate the pace of development can only weaken these protections further.[33]

31 Alan Bond, Jenny Pope, Monica Fundingsland, Angus Morrison-Saunders, Francois Retief, and Morgan Hauptfleisch: 'Explaining the political nature of environmental impact assessment (EIA): A neo-Gramscian perspective'. Journal of Cleaner Production, Vol 244. 20 January 2020. https://doi.org/10.1016/j.jclepro.2019.118694

32 Virgin Orbit and Spaceport Cornwall Joint Assessment of Environmental Effects Public Consultation Responses. Civil Aviation Authority. https://consultations.caa.co.uk/corporate-communications/aee-consultation-virgin-orbit-spaceport-cornwall/results/virginorbitandspaceportcornwalljointassessmentofenvironmentaleffectspublicconsultationresponses.pdf

33 'Environmental reforms to break planning system gridlock'. Department for Environment, Food & Rural Affairs, 19 August 2025. https://www.gov.uk/government/news/environmental-reforms-to-break-planning-system-gridlock

2.3 Satellite ground infrastructure

A system of ground infrastructure is needed to monitor, track, and control satellites and spacecraft in orbit. This includes a network of ground stations to provide a radio communication interface with satellites for transmitting and receiving data; operations and control centres; and data centres and data distribution networks. Depending on the orbits serviced, ground stations may be in remote and often pristine locations. Data centres contain hardware to process, distribute, and archive data downloaded from satellites. Gaston et al have highlighted the impacts associated with Google Earth Engine, a cloud computing platform for processing satellite imagery and other Earth observation data used principally by researchers.[34] Storage and use of this data has a carbon cost equating to hundreds of millions of tons of carbon dioxide equivalent emissions annually, and globally data centres were estimated to consume around 1 per cent of global energy use in 2018[35] – roughly the same as Australia's total annual energy use.[36]

Satellite ground stations communicate with satellites through radio waves, a form of electromagnetic radiation. Radio waves are a non-ionising form of radiation, which means they do not have enough energy to damage cells or DNA directly. The health effects of radiofrequencey radiation are not well understood, but they may have impacts depending upon the frequency and field strength of the radio signal, length and proximity of exposure, and parts of the body exposed to radiation. Prolonged exposure to radio waves, especially at higher frequencies, may cause heating of internal tissue resulting in a sensation of warmth and possible skin redness, burning, or damage to tissue. The lens of the eye is sensitive to heat, and thermal effects from overexposure to radio waves may be a risk factor for the development of cataracts. Electromagnetic fields also have the potential to interfere with active implanted medical devices such as pacemakers, and can also heat passive surgical implants in the body. Anecdotally, persistent neurological symptoms such as headache, nausea, dizziness, and fatigue have been reported following overexposure to radio waves but as yet there is no definitive data to show whether these are related to exposure.[37] In 2011 the World Health Organization classified radiofrequency electromagnetic fields (including microwave and millimeter waves) as "possibly carcinogenic to humans", meaning there "could be some risk of carcinogenicity", but also noted that further research is required to establish whether there is a causal relationship and that to date adverse health effects have not been observed.[38]

Satellite ground stations may pose electromagnetic radiation hazards from the signals they transmit and receive. These hazards include potential interference with other nearby electronic systems as well as possible health impacts. In general, electromagnetic radiation hazards are more of a concern in terms of workplace safety rather than through any risks they may pose to the public or

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34 Kevin J Gaston, Karen Anderson, Jamie D Shutler, Robert JW Brewin, Xiaoyu Yan: 'Environmental impacts of increasing numbers of artificial space objects', op cit.

35 Jones N. 2018. How to stop data centres from gobbling up the world's electricity. Nature 561: 163–66. Cited in Kevin J Gaston, Karen Anderson, Jamie D Shutler, Robert JW Brewin, Xiaoyu Yan: 'Environmental impacts of increasing numbers of artificial space objects', op cit.

36 Calculation by Space Watch UK on the basis of figures at Worldometer 'World Energy Statistics': https://www.worldometers.info/energy/

37 Judith Eisenberg, David Sylvain, Srinivas Durgam: 'Nonionzing [sic] Radiation Exposure to Technicians at a Satellite Communications Facility'. National Institute for Occupational Safety and Health. Health Hazard Evaluation Report HETA 2007-0095-3063, p5. June 2008. https://www.cdc.gov/niosh/hhe/reports/pdfs/2007-0095-3063.pdf

38 'Cancer and Radiofrequency Radiation'. Physicians for Safe Technology. 20 January 2023. https://mdsafetech.org/cancer/

environment. They can be adequately controlled by measures to ensure that on-site safety guidelines and procedures are followed, shielding to protect personnel and equipment from high levels of radiation, and planning and siting controls to protect the public.

Environmental impacts from spaceports and space-related ground infrastructure are strictly local in their effect. In the following chapters we will examine how the space sector is beginning to have global-scale impacts on the atmosphere and in space itself.

Case study 1 SpaceX and Starbase: good neighbour or local menace?

The giant SpaceX 'Starbase' spaceport at Boca Chica, Texas, is situated on the coast of the Gulf of Mexico and adjacent to the Lower Rio Grande Valley National Wildlife Refuge (see Image 3). The area is one of the most sacred sites for the Carrizo-Comecrudo indigenous people who traditionally lived along the Rio Grande delta. The Carrizo-Comecrudo are gradually being displaced from the region, squeezed between the SpaceX development, Trump's border wall, and petrochemical facilities.

Boca Chica town is a relatively deprived area with low income workers, attractive to SpaceX as a cheap workforce. As well as paying low wages, SpaceX is not unionised and also has a poor company safety record – six times worse than anywhere else in the US space industry. Many local residents work at the spaceport, and because of a SpaceX policy of buying property locally, the company is their landlord as well as their employer. The spaceport is close to populated areas and on occasions windows have been broken, homes damaged, and soot deposited over the area when launches have gone wrong.[39]

Image 3. Location of SpaceX's Starbase on the Gulf of Mexico

39 'We Went To The Town Elon Musk Took Hostage'. More Perfect Union, 19 Feb 2025. https://www.youtube.com/watch?v=5cZEZoa8rW0

The spaceport is surrounded by state parks and wildlife refuges which are home to 18 vulnerable and critically endangered species, including the critically endangered Kemp's ridley sea-turtle. SpaceX's "move fast and break things" philosophy has seen fires, leaks, explosions and other accidents causing littering and damage to habitat, release of toxic particulates, and fire damage across the Boca Chica Park.[40]

Government agencies have found that the spaceport has violated environmental regulations by repeatedly releasing pollutants into nearby bodies of water. The Environmental Protection Agency and the Texas Commission on Environmental Quality have both notified SpaceX that discharges of waste water from deluge systems at the spaceport had not been authorised by the agencies. The discharges were reported to have contained high levels of the toxic metal mercury.[41]

SpaceX has recently been granted permission to double its launch rate from Vandenberg Space Force Base in California, and is currently preparing an environmental impact statement for launches of its huge new 'Starship' launcher – the largest rocket ever built – from the Kennedy Space Centre at Cape Canaveral. If accepted, the company will be able to perform 120 launches a year from Cape Canaveral, in contrast to 25 launches a year currently from Starbase.

Other operators using the complex have expressed concern that the scale of SpaceX operations could affect other launch providers, and there is also the potential that there may be significant impacts on commercial aviation resulting from flight diversions during launches.

A public meeting set up to allow local residents to give their views on the proposal heard concerns about launches causing frequent closures of a popular beach, noise from launches, and damage to property from vibration.

"Launch sites of the future need to be fully operationalized like an airport," according to a statement from SpaceX. "That means multiple launches a day from multiple providers, able to launch when ready to support a variety of vehicles and missions."[42]

40 Peter Howson: 'Elon Musk's SpaceX Fantasies Come with Huge Costs for the Rest of Us. Deceleration, 6 June 2024. https://deceleration.news/spacex-elon-musk-fantasies/ 'The Hidden Problems of Rocket Launch Sites'. GNspace4peace, 19 June 2022. https://www.youtube.com/watch?v=lU5Tex6Aw80

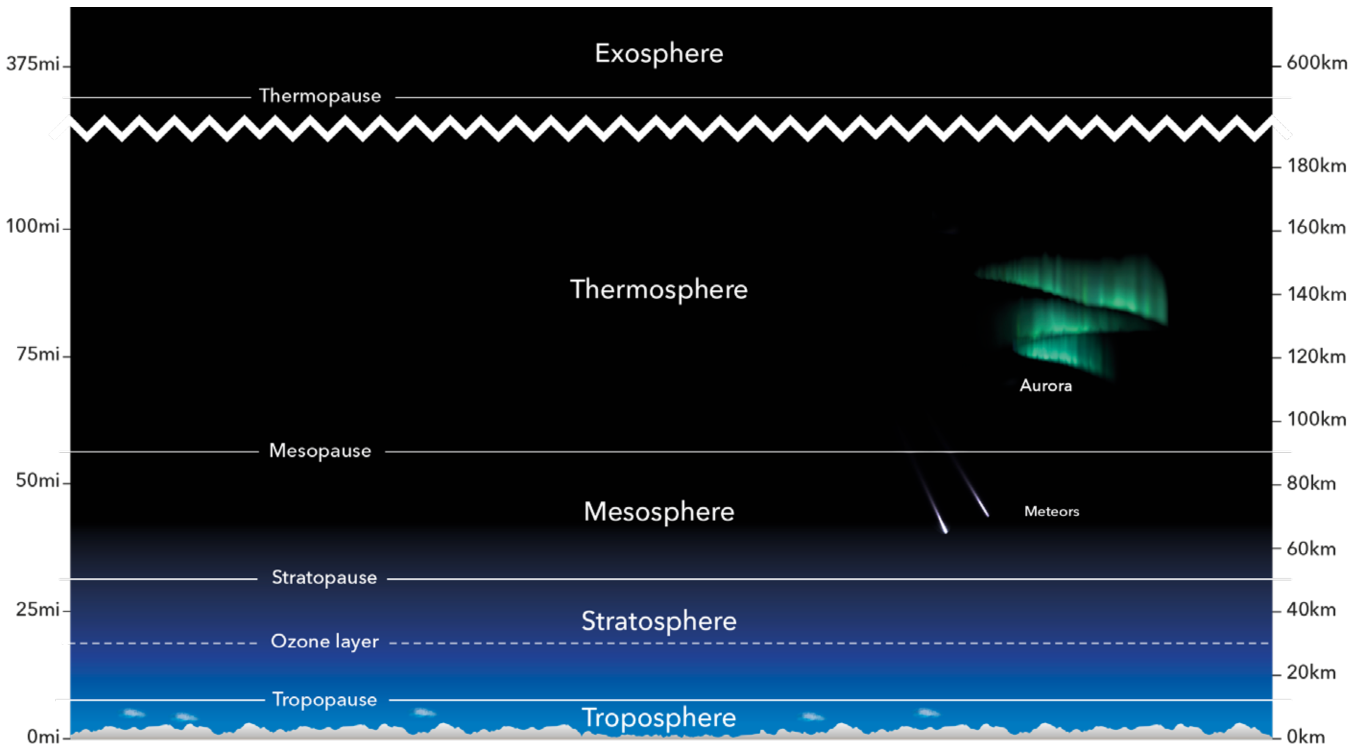
41 Lora Kolodny: 'SpaceX repeatedly polluted waters in Texas this year, regulators found'. NBC News, 12 August 2024. https://www.nbcnews.com/science/environment/spacex-polluted-waters-texas-regulators-rcna166283

42 Jeff Foust: 'Promising to be a good neighbor'. The Space Review, 13 October 2025. https://www.thespacereview.com/article/5080/1

3 Atmospheric impacts

Pollutants from the space industry affect the atmosphere in a number of ways. The nature of their impact depends upon the type of pollutants released and whereabouts in the atmosphere they are released. As atmospheric science is still a relatively young scientific discipline we still have much to learn about the ramifications of introducing unfamiliar chemicals into the atmosphere. There is considerable uncertainty about what pollutants are being emitted into which parts of the atmosphere, in what quantities, and what the longer term consequences of atmospheric pollution caused by the space sector may be. Nevertheless, it is becoming apparent that rocket emissions and debris falling out of orbit are having increasingly detrimental effects on global atmospheric chemistry. By the time a rocket enters orbit it will have deposited up to two-thirds of its exhaust in the middle and upper layers of the atmosphere (see Images 4 and 5). Rocket emissions pollute at high altitudes – all the way up to 80 km – where they are the only direct cause of human pollution.

Image 4. Schematic diagram showing the basic layers of the atmosphere



In due course these pollutants will accumulate in the stratosphere: the lower part of the middle atmosphere. Chemicals released during the launch of space rockets can contribute to climate change, despite the use of rocket fuels marketed by the space industry as 'environmentally friendly'. Space rockets release gases and particles directly into the atmosphere and are the only anthropogenic source of pollution in the middle and upper atmosphere (above 15 km). Emissions into the troposphere (the lower layer of the atmosphere) are relatively transient and have local impacts, but impacts into the layer above – the stratosphere – can persist and accumulate over several years. The stratosphere is also the location of the ozone layer, which absorbs most of the sun's ultra-violet radiation and protects living organisms from its harmful effects. There is evidence that some emissions from the burn-up of rocket components, space debris, and redundant satellites are damaging the ozone layer.[43] [44]

3.1 Rocket fuels

To understand fully the impacts that emissions from space rockets can have on the atmosphere, we need to know about the types of fuel used in rockets. Chemical rockets are powered by chemical reactions of the propellant (usually an oxidation-reduction reaction, i.e. combustion) which produce large quantities of exhaust gas which generate thrust when expelled through a nozzle. For most rocket types both an oxidising agent and reducing agent must be present in the fuel mix. These substances are highly energetic and reactive and are usually toxic. The effects of rocket emissions on the atmosphere vary significantly depending on the type of propellant used. We will consider here only chemical propellants which are currently in use, rather than inert propellant methods such as ion thrusters which have not yet been commercially applied in the space sector.[45]

Solid-fuel rockets use propellant in a solid state and are commonly used in military rockets and boosters as they provide a high energy density during lift-off. Systems using solid fuel propellants include Ariane 5 booster rockets and space shuttle booster rockets. They consist of composite mixtures of particles of solid oxidiser bound into a polymer with granules of fuel compounds. Other compounds such as plasticisers, stabilisers and burn rate modifiers (iron oxide or copper oxide) are also present in the propellant. Oxidisers commonly used in solid rocket fuels are ammonium nitrate, ammonium dinitramide, ammonium perchlorate, and potassium nitrate. Reducing agents include nitroamine compounds such as RDX,[46] HMX,[47] aluminium or beryllium, although the chemicals in the fuel can play multiple roles in reactions. Solid fuels have traditionally been used to power older rockets and are generally dirtier than modern fuels. Since the retirement of the space shuttle, solid rocket fuel use has declined by about 60 per cent globally.

43 Loïs Miraux: 'Environmental limits to the space sector's growth'. Science of the Total Environment Vol 806(4), 1 February 2022. **https://doi.org/10.1016/j.scitotenv.2021.150862**

44 Jamie D. Shutler, Xiaoyu Yan, Ingrid Cnossen, Leonard Schulz, Andrew J. Watson, Karl-Heinz Glaßmeier, Naomi Hawkins & Hitoshi Nasu: 'Atmospheric impacts of the space industry require oversight'. 4 August 2022. Nature Geoscience, V15 p598–600. **https://www.nature.com/articles/s41561-022-01001-5**

45 'Rocket fuels 101'. Space Agency, 31 July 2023. **https://space.agency/blog/rocket-fuels-101/** 'Understanding The Different Types of Rocket Fuel & Propellants'. Spacecraft & Vehicles. **https://spacecraftandvehicles.com/articles/types-of-rocket-fuel/**

46 'Research Department Explosive', 'Royal Demolition Explosive' or hexogen.

47 'High Melting Explosive', 'High-velocity Military Explosive', 'High-Molecular-weight RDX' or octogen.

Liquid rocket engines (LREs) use propellants in a liquid state fed from tanks. This allows the use of high performance liquid oxidisers such as liquid oxygen, nitric acid, dinitrogen tetroxide, and hydrogen peroxide. Some of these propellants, such as liquid oxygen, must be kept at low temperature and are known as cryogenic propellants. Liquid oxygen and highly refined kerosene is a commonly used combination for lift-off boosters and has been used in the first stages of the Atlas V, Falcon 9, Falcon Heavy, Soyuz, and Long March 6 rockets. Liquid oxygen and liquid hydrogen have been used for most stages of the Ariane 5 and the Delta IV rockets, and liquid oxygen and methane are used for China's ZhuQue-2 rocket and SpaceX's Starship.

Image 5. Earth's night-side upper atmosphere, appearing from the bottom as bands of afterglow illuminating the troposphere in orange with silhouettes of clouds, the stratosphere in white and blue, and the mesosphere (pink area) extending to the edge of space and the lower edge of the thermosphere (invisible). **Credit:** Alexander Gerst / ESA.

Hypergolic rocket propellants are combinations of propellants which will spontaneously ignite when they are brought into contact. Such substances are highly corrosive and toxic. Hypergolic propellants were used in the US Titan II intercontinental ballistic missile (ICBM) and in many Soviet ICBMs, and also as fuel for the descent and ascent rocket engines in the Lunar Module for the Apollo space missions. The most commonly used hypergolic propellant combination is dinitrogen tetroxide and hydrazine, historically used in US rockets. Although hypergolic propellants are still used in the upper stage rockets of some spacecraft, there has been a trend away from their use because of the risks and difficulties in handling them.

Monopropellant fuels consist of a single, storable propellant which decomposes when passed over a catalyst, generating thrust from high pressure gas created during the decomposition reaction. Such propellants generate less thrust than other types of rocket fuel but are simple and reliable and are usually used for altitude control and station-keeping for satellites in orbit. Monopropellant rocket fuels include hydrazine, hydrogen peroxide, and nitrous oxide, and the catalyst is often alumina / iridium pellets.

Finally, **hybrid rockets** use a solid propellant to which a second liquid or gas oxidiser is added to generate combustion. These are generally safer than liquid rocket engines and have been used by Virgin Galactic on their 'SpaceShipTwo' launcher for space tourism purposes. SpaceShipTwo has operated using thermoplastic polyamide and hydroxyl-terminated polybutadiene (HTPB) fuels and nitrous oxide oxidiser.

The four most commonly used rocket fuels are kerosene, hypergolic fuels, liquid hydrogen, and solid fuels. Combustion emissions created by all propellants include water vapour and nitrogen oxides. Other pollutants include black carbon (soot) from kerosene and carbon-based solid and hypergolic fuels, and alumina particles (Al_2O_3), gaseous chlorine and hydrochloric acid from solid fuels. All of these substances have potential impacts on the atmosphere, with global implications for climate change and the ozone layer.[48]

3.2 Climate impacts

Rockets uniquely emit gases and particles directly into the middle and upper atmosphere where exhaust from hundreds of launches accumulates, with the potential to change atmospheric radiation patterns (the way in which electromagnetic energy is distributed and varies as it travels from the sun through the Earth's atmosphere).

Most rocket fuels contain carbon, and all rocket fuels generate gases which contribute to global climate change. Space rockets do not release large quantities of carbon dioxide, the gas which is the main driver of climate change, and pollution from rocket launches does not yet contribute significantly to climate change. In comparison with the aviation sector, carbon dioxide emissions from the space industry are currently very low. There are millions more aircraft flights than rocket launches and the aviation industry burns the fossil fuel equivalent of a year's worth of rocket launches in mere hours, releasing tons of carbon dioxide into the lower atmosphere.[49] This may not remain the case looking to the long term, however, as the number of launches into space each year is increasing rapidly. In less than ten months, SpaceX's Falcon 9 rocket conducted more launches than the space shuttle did in its entire thirty year flight history. The total amount of rocket propellant consumed by launches has more than tripled over the period from 2019 – 2025, and will continue to increase as more and larger launch vehicles enter service.[50]

Water vapour released from rocket engines can also act as a greenhouse gas, absorbing heat radiated from Earth and preventing it from escaping into space. Because it is present in the atmosphere in relatively high concentrations, water is the most important greenhouse gas in the global climate system and is estimated to account for around half of the total greenhouse effect. Clouds also contribute to roughly a further quarter of the greenhouse effect, acting as

48 Jaela Bernstien, Nicole Mortillaro and Aloysius Wong: 'How bad is rocket pollution? Depends what part of the atmosphere you look at'. CBC News, 2023. https://newsinteractives.cbc.ca/features/2023/rocket-pollution/; Tyler F M Brown, Michele T Bannister & Laura E Revell: 'Envisioning a sustainable future for space launches: A review of current research and policy'. Journal of the Royal Society of New Zealand, Vol 54(3), p1-17. 2 February 2023. https://doi.org/10.1080/03036758.2022.2152467 Connor R Barker, Eloise A Marais & Jonathan C McDowell: 'Global 3D rocket launch and re-entry air pollutant and CO2 emissions at the onset of the megaconstellation era'. Scientific Data, Vol 11, 1079. 3 OCtober 2024. https://doi.org/10.1038/s41597-024-03910-z ; Laura E. Revell, Michele T. Bannister, Tyler F. M. Brown, Timofei Sukhodolov, Sandro Vattioni, John Dykema, David J. Frame, John Cater, Gabriel Chiodo & Eugene Rozanov: 'Near-future rocket launches could slow ozone recovery'. NPJ Climate and Atmospheric Science, Vol 8, 212. 9 June 2025. https://doi.org/10.1038/s41612-025-01098-6

49 Jaela Bernstien, Nicole Mortillaro and Aloysius Wong: 'How bad is rocket pollution? Depends what part of the atmosphere you look at', op cit.

50 Jeff Foust:'Space sustainability comes down to Earth'. Space Review, 27 October 2025. https://www.thespacereview.com/article/5090/1

a blanket and trapping thermal radiation, although they may also reflect sunlight and have a cooling effect.[51] A study by Stevens et al. found that water vapour emissions from the final space shuttle launch in 2011 generated about 350 tons of water vapour which spread out in horizontal plume over a distance of 3000 to 4000 km and caused the formation of polar mesospheric clouds: noctilucent clouds in the upper atmosphere which shine brightly at night.[52] Such clouds can make a significant contribution to the heat balance of the upper atmosphere[53] although as yet their climate impacts are not fully understood and are not well represented in climate modelling.[54]

Atmospheric circulation in the stratosphere and troposphere is sensitive to the quantity of water vapour in the lower stratosphere. As a result, an increase in stratospheric water vapour can be expected to have regional climate impacts. Modelling experiments have shown that water vapour in the lowermost part of the stratosphere can decrease local temperatures and cause an upward and poleward shift of subtropical jets; strengthening of stratospheric circulation; a poleward shift of the tropospheric eddy-driven jet and regional climate impacts.[55]

While the quantity of greenhouse gases emitted by rockets is currently low compared to that of other industrial sectors, other substances released during rocket launches can have far more significant implications for the climate. The effect of submicrometer-sized particles of black carbon and alumina released by rockets is a cause of concern to scientists. Black carbon – soot from rocket fuels which is a solid form of mostly pure carbon – absorbs solar radiation at all wavelengths and warms the atmosphere. It is produced by the combustion of any carbon-based fuel and can account for several per cent of rocket emissions.[56]

Black carbon particles released by rockets accumulate in the stratosphere and can linger there for three to four years. Rockets can emit up to 10,000 times more black carbon particles than turbine engines from modern aircraft[57], which release particles lower in the atmosphere where they break down within weeks. Although the amount of black carbon released overall from rockets is a fraction of the total produced by traditional sources such as the transport and energy sectors, the quantity released directly into the stratosphere is significant – an estimated 225 tons in 2018, comparable to the annual amount emitted by the entire global aviation sector.[58] Scenarios modelled by Ryan et al. showed that black carbon directly injected to the upper atmosphere has a greater climate forcing efficiency than other sources, and the warming efficiency of black carbon particles from rockets is almost five hundred times that of all other sources of

51 Kevin Trenberth: 'How rising water vapour in the atmosphere is amplifying warming and making extreme weather worse'. The Conversation, 13 September 2023. https://theconversation.com/how-rising-water-vapour-in-the-atmosphere-is-amplifying-warming-and-making-extreme-weather-worse-213347

52 Michael H. Stevens et al.: 'Bright polar mesospheric clouds formed by main engine exhaust from the space shuttle's final launch' Journal of Geophysical Research – Atmospheres, Vol 117(D19), 16 October 2012. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012JD017638

53 Arseniy Sokolov, Elena Savenkova, Andrey Koval, Nikolai Gavrilov, Karina Kravtsova, Kseniia Didenko and Tatiana Ermakova: 'Quantifying Polar Mesospheric Clouds Thermal Impact on Mesopause'. Atmosphere Vol 16(8) p922. 30 July 2025. https://www.mdpi.com/2073-4433/16/8/922

54 'How clouds in polar regions impact climate'. Knut and Alice Wallenberg Foundation, 2024. https://kaw.wallenberg.org/en/research/how-clouds-polar-regions-impact-climate

55 Edward Charlesworth et al.: 'Stratospheric water vapor affecting atmospheric circulation'. Nature Communications Vol 14. 3 July 2023. https://www.nature.com/articles/s41467-023-39559-2

56 Frederick Simmons: 'Rocket Exhaust Plume Phenomenology'. Aerospace Press, 2000, cited in M N Ross and D W Toohey: 'The Coming Surge of Rocket Emissions'. Eos, 24 September 2019. https://eos.org/features/the-coming-surge-of-rocket-emissions

57 Martin N. Ross and Patti M. Sheaffer: 'Radiative forcing caused by rocket engine emissions'. Earth's Future, Vol 2(4), P177-196. 23 January 2014. https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2013EF000160

58 M N Ross and D W Toohey: 'The Coming Surge of Rocket Emissions', op cit.

soot combined.[59] This is enough to contribute to an estimated three per cent of global warming caused by soot emissions, meaning that the space sector is having a disproportionate impact on this contributor to global warming even if it is smaller than other industries.[60]

Modelling studies by Maloney et al. have examined the impact of a possible future emission rate of 10,000 tons per year of black carbon from rocket launches, which is roughly an order of magnitude larger than current emissions but, they consider, plausible within the next two decades based upon recent trends in space traffic growth. They found that black carbon emissions increased stratospheric temperatures by up to 1.5 C and reduced jet wind speeds, weakening global atmospheric circulation by 10-20 per cent. The results show that this form of climate response increases in a near linear fashion to the quantity of black carbon emitted and that the stratosphere is sensitive to relatively modest black carbon injections.[61] The German aerospace centre Deutsches Zentrum fur Luft- und Raumfahrt has modelled emissions from rocket launches during 2025 and estimates that black carbon emissions were between 10 and 40 per cent of those from the aviation sector two decades ago. The impact of this needs to be confirmed by climate modelling, but if black carbon emissions from launches are hundreds of times more damaging than those from air travel, they could already be having a significant impact even though only around 250 launches took place during the year.[62]

Most black carbon from rocket launches comes from kerosene-fuels used by rockets such as SpaceX's Falcon 9 (the most frequently lunched rocket in the US), SpaceX's Falcon Heavy, Rocket Lab's Electron and Russia's Soyuz rocket (the most-launched rocket in history). Other launcher companies are developing new types of fuel that may produce less black carbon. SpaceX's Starship burns liquid natural gas, which is almost pure methane, creating less black carbon residues and making it easier to reuse engines, and Blue Origin's BE-4 rocket also runs on liquefied natural gas. Orbex planned to power its Prime launcher with bio-propane gas, made from "sustainable resources, such as plant and vegetable waste".[63] Cryogenic rockets using liquid hydrogen and liquid oxygen as fuel have far less direct climate impact in the stratosphere than kerosene-fuelled rockets or solid fuels. These rockets do not generate carbon dioxide or soot, although they produce water vapour. Ross and Sheaffer estimate that a kerosene-fuelled rocket generates radiative forcing (a measure of the difference in the quantity of energy entering the Earth's atmosphere and the energy leaving it, which affects the planet's temperature) at a level about 30 times that of a cryogenic rocket, and therefore cryogenic hydrogen fuel should be preferred for extensive space projects in future.[64] However, the liquification process for hydrogen and oxygen fuels takes place at temperatures below -253°C at normal atmospheric pressure, which means that very energy-intensive processes are required to create the fuel and store it at these low temperatures. For each ton of liquid hydrogen used it has

59 Robert G. Ryan, Eloise A. Marais, Chloe J. Balhatchet, and Sebastian D. Eastham: 'Impact of Rocket Launch and Space Debris Air Pollutant Emissions on Stratospheric Ozone and Global Climate'. Earth's Future, Vol 10(6), 9 June 2022. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021EF002612

60 Jaela Bernstien, Nicole Mortillaro and Aloysius Wong: 'How bad is rocket pollution? Depends what part of the atmosphere you look at', op cit.

61 Christopher M Maloney, Robert W Portmann, Martin N Ross, and Karen H Rosenlof: 'The Climate and Ozone Impacts of Black Carbon Emissions From Global Rocket Launches'. Journal of Geophysical Research: Atmospheres, Vol 127(12), 27 June 2022. https://doi.org/10.1029/2021JD036373

62 Jeff Foust:'Space sustainability comes down to Earth', op cit.

63 'Boosting greener rockets with Orbex'. European Space Agency, 13 December 2023. https://www.esa.int/Enabling_Support/Space_Transportation/Boost/Boosting_greener_rockets_with_Orbex

64 'Martin N. Ross, Patti M. Sheaffer'. Radiative forcing caused by rocket engine emissions', op cit.

been estimated that around 25 tons of carbon dioxide equivalent are emitted, compared with about 3 tons for aviation fuel.[65]

Although novel carbon-based rocket fuels may produce less climate-harming substances than traditional rocket fuels, they still produce some soot, and they also produce water vapour, carbon dioxide, and nitrogen oxides. Compression of gases into liquid for use as rocket fuels is also an energy intensive process which contributes to carbon emissions. Gains in environmental performance may be largely offset if these rockets burn more propellant and contribute to an increase in launch rates. It is not yet clear whether rocket fuels promoted as cleaner will reduce environmental impacts or cause different ones. As Aaron Boley, an astronomer at the University of British Columbia and co-director of the Outer Space Institute points out: "You can't take what's green in the troposphere and necessarily think of it being green in the upper atmosphere. There is no such thing as a totally neutral propellant. They all have different impacts."[66]

Aluminium powders are a component of solid rocket fuels added to enable an improved burning rate. Aluminium oxide (alumina) is therefore another particulate material emitted during rocket launches. Writing in 2019, Ross and Toohey stated that solid-fuelled rockets emitted about 1,400 tons of alumina particles into the stratosphere,[67] and sub-micron sized particles will remain suspended in this region. The climate impacts of alumina are more complex than those of black carbon. Whereas darker black carbon particles absorb solar radiation and slightly reduce Earth's albedo (a measure of how much sunlight is reflected), lighter alumina particles reflect solar radiation and so increase the albedo slightly. Alumina thus reflects incoming radiation into space and absorbs outgoing radiation from the Earth's surface. Modelling suggests that the overall effect, though, is to generate net positive radiative forcing, adding to the greenhouse effect. Alumina has been estimated to contribute to 28 per cent of the radiative forcing resulting from rocket emissions, compared with 70 per cent from black carbon and the remainder mainly from water vapour. However, given uncertainties in climate modelling, there is limited confidence that alumina has a net positive radiative forcing effect, and even less confidence in the magnitude of the effect.[68]

In addition to direct contributions to climate change, rocket launches may indirectly give rise to an increase in the generation of greenhouse gases as a result of conflict over airspace use. In order to protect aircraft from the risk of an accident during a rocket launch, air traffic controllers must restrict flights through large areas of airspace. This can disrupt dozens of flights. During one routine Delta II rocket launch from Cape Canaveral, for example, 56 flights had to be rerouted by roughly 65 nautical miles each, adding over 3,600 miles in flight as a result of detours. This results in increases in flight time, fuel consumption, and greenhouse gas emissions as aircraft are forced to fly on longer and less optimum routes.[69] The risks are not fanciful: on 16 January 2025 flights across the Caribbean were hastily diverted following the explosion of a SpaceX Starship rocket during a test flight. Airspace around the incident area was closed and at least 20 flights appear to have been delayed or diverted by the incident, with at least 16 of those flights having to divert to a different airport

65 Robert Rapier: 'Estimating the Carbon Footprint of Hydrogen Production', Forbes, 6 June 2020. https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/?sh=6722565424bd

66 Shannon Hall: 'The New Space Race Is Causing New Pollution Problems'. New York Times, 9 January 2024. https://www.nytimes.com/2024/01/09/science/rocket-pollution-spacex-satellites.html

67 M N Ross and D W Toohey: 'The Coming Surge of Rocket Emissions', op cit.

68 Martin N. Ross and Patti M. Sheaffer: 'Radiative forcing caused by rocket engine emissions', op cit.

69 Mathew Lewallen ' No man's airspace: Why our skies aren't ready for the space boom'. Space News, April 2025. https://spacenews.com/no-mans-airspace-why-our-skies-arent-ready-for-the-space-boom/

as a result of suspension of air traffic at four major Florida airports. A second Starship exploded on the next test launch on 6 March, when disruption affected about 240 flights, forcing 28 aircraft to divert and 40 flights to circle in holding patterns.[70]

In the UK, consultation over airspace reservation requirements during launches from SaxaVord Spaceport has raised concern that the implications of closure of air traffic corridors could be "huge". Iceland's air traffic control airspace area commences just 12 nautical miles out to sea from SaxaVord – an area crossed by 25 per cent of all transatlantic flights. Up to 76 flights a day would need to be rerouted during launches, according to Isavia, Iceland's air traffic control agency, with up to 30 launches each year eventually planned from SaxaVord. Adam Baker, technical director of UK Launch Services Ltd, has observed that "to thread a launch vehicle flight through that very small needle and not disrupt hundreds of transatlantic flights is harder than anyone cares to admit."[71]

With launches now planned to take place two or three times a week from busy spaceports in the USA, the climate implications of airspace closures are considerable. Diversions and disruption could be reduced if rocket launches are brought under the auspices of air traffic controllers, with real-time tracking and flight plans which controllers can monitor continuously and use to alert aircraft in the event of an emergency.

Case study 2 'Spacewashing': Spaceport Cornwall's green credentials

Spaceport Cornwall, owned by Cornwall Council, was opened in September 2022 as a base for horizontal launches into space, with rockets being launched from under the wing of an aircraft flying from the spaceport. In January 2023 Virgin Orbit conducted an unsuccessful attempt to launch its LauncherOne rocket into space from underneath the wing of a converted Boeing 747 aircraft flying from Spaceport Cornwall (see Image 6). Following the subsequent collapse of Virgin Orbit the spaceport has been in discussions with "an established horizontal launch provider" over future launches.[72] Spaceport Cornwall seeks to be a "new kind of spaceport" championing "space for good" and seeks to be the most sustainable spaceport in the world, challenging the space launch industry to overhaul its practices.[73] Despite this, the spaceport has attracted criticism locally over its environmental impacts.[74]

The Spaceport Cornwall website highlights a number of laudable initiatives which the spaceport is undertaking to improve its environmental performance. These include building energy-efficient buildings and using electric vehicles for on-site transport, setting up wildflower meadows across the site, and opening a Centre for Space Technologies to undertake research and development into

70 Geoff Brumfiel: 'Air traffic controllers rush to divert aircraft after Elon Musk's rocket explodes'. NPR, 17 January 2025. https://www.npr.org/2025/01/17/nx-s1-5266013/elon-musk-rocket-exploded

71 Rob Edwards: 'Alarm at Shetland spaceport climate pollution'. The Ferret, 6 July 2023. https://theferret.scot/climate-pollution-shetland-spaceport/
Susan Walton: 'The Gap Is Back and UK Space Ambitions Will Be The First Casualty'. Geopolitical Monitor, 4 May 2025. https://www.geopoliticalmonitor.com/the-gap-is-back-and-uk-space-ambitions-will-be-the-first-casualty/

72 'Looking Back: A Year of Inspiration and Innovation'. Spaceport Cornwall, 20 December 2023. https://spaceportcornwall.com/looking-back-a-year-of-inspiration-and-innovation/

73 'Launch Our Future'. Spaceport Cornwall. https://spaceportcornwall.com/

74 ARE Taylor: 'Spaceport Cornwall: Scaling environmentally responsible space futures in South West England'. Environment and Planning D: Society and Space, Vol 43(2). 6 January 2025. https://doi.org/10.1177/02637758241307

Image 6. Virgin Orbit's 'Cosmic Girl' launch aircraft at Spaceport Cornwall in January 2023. **Credit:** Virgin Orbit.

rocket reuseability, space debris recovery, and the use of biofuels and cleaner launch methods.[75] Other measures have proved more controversial, particularly those relating to carbon emissions and climate change.

Cornwall Council has committed to the Spaceport being carbon neutral by 2030, and the spaceport aspires to be the first Net-Zero Spaceport in the world. As a step towards achieving this goal, the spaceport emphasises that it is the first spaceport to have carried out a full carbon impact assessment of its operations. However, the spaceport does not publicly report its carbon emissions or set out how its actions have reduced its carbon footprint

The carbon impact study appears to considerably under-estimate the climate impacts of launches from the spaceport.[76] The methodology uses recommendations for the calculation of the global warming potential of aviation emissions, rather than the space sector,[77] and is based around applying an assumed radiative forcing index for the higher atmosphere to direct carbon dioxide emissions from the LauncherOne rocket. However, as we have seen, carbon dioxide emissions from rockets do not have a significant climate impact and discussions of the climate impact of space transport should not focus on carbon dioxide emissions.[78] LauncherOne used the kerosene fuel formulation RP-1, generating black carbon in the stratosphere which has considerable warming potential. This contribution to warming is omitted from the carbon impact study.

Information on the spaceport's expected carbon consumption given in the carbon impact report is not presented in a clear and straightforward way, but in a way which plays down its scale. The report describes the scale of annual life cycle emissions associated with launches at Spaceport Cornwall as representing 0.057 (2022) and 0.071 per cent (2023 onwards) of total territorial greenhouse

75 'Our five main impacts'. Spaceport Cornwall. https://spaceportcornwall.com/our-five-main-impacts/

76 'Spaceport Operator Carbon Impact – A Life Cycle Analysis'. University of Exeter Consulting, July 2022, p8. https://spaceportcornwall.com/wp-content/uploads/2022/07/Spaceport-Cornwall-Carbon-Impact-report_UoE-2022_final-draft-2022-07-19.pdf

77 Niels Jungbluth & Christoph Meili: 'Recommendations for calculation of the global warming potential of aviation including the radiative forcing index'. International Journal of Life Cycle Assessment, Vol 24 p404–411. 19 November 2018. https://link.springer.com/article/10.1007/s11367-018-1556-3

78 Martin N. Ross and Patti M. Sheaffer: 'Radiative forcing caused by rocket engine emissions', op cit.

gas emissions for Cornwall and the Isles of Scilly.[79] These figures, presented as tiny percentages, suggest that the spaceport's carbon impact is negligible. An alternative way of quantifying this impact could use more accessible comparisons based on everyday experiences, for example by describing the spaceport's annual impact as the equivalent of:

- The carbon footprint of an average UK citizen for 170 years.
- Driving a car 3.9 million miles.
- Having your household central heating on at full temperature non-stop for 37 years.[80]

Controversially, the spaceport and Virgin Orbit undertook to offset carbon emissions from launches with the purchase of carbon credits. Carbon offsetting – attempting to trade off contributions to global warming in one place or time against reductions elsewhere – is sometimes proposed as a mechanism for addressing climate impacts. Common types of carbon offsetting schemes include reforestation and renewable energy projects, intended to 'cancel out' emissions from other activities.

A recent study reviewing over ten years of data showed that carbon offsetting schemes have not significantly slowed global warming and do not work in most cases. The study found that most offsets are tied to projects that would have occurred regardless, and do not represent genuine emission reductions. Less than 10 per cent of offsets on the market deliver genuine, measurable, and lasting emission cuts. The most widely used offset programmes greatly overestimate their probable climate impact and overcrediting in carbon offsets is "an intractable problem". The study recommends that carbon offsets should no longer be used as a substitute for direct emission cuts.[81]

Carbon offsetting is based on sleight of hand and acts to create a financial market in 'carbon credits' rather than deliver real benefits to the environment. Within a hierarchy for mitigating greenhouse gas emissions, carbon offsets are usually considered as a last resort and should not substitute for other measures to tackle climate change.

As part of its strategy to mitigate carbon emissions, Spaceport Cornwall presents satellite data as an essential tool for monitoring climate change. Spaceport Cornwall's publicity material emphasises plans for the launch of the Kernow Sat 1: a locally designed and built environmental monitoring satellite which will monitor the sea around Cornwall to identify areas for sea grass restoration, monitor kelp forests, and monitor pollution levels. The satellite is intended to "positively influence the Blue Carbon market" – in other words, enable the trading of carbon credits generated from coastal and marine ecosystems.

79 'Spaceport Operator Carbon Impact – A Life Cycle Analysis'. University of Exeter Consulting, op cit. P3.

80 Based on the estimate by University of Exeter Consulting that Spaceport Cornwall's carbon emissions in 2022 (including radiative forcing) would be the equivalent of 2164 tons. Calculations by Space Watch UK using assumptions for the UK average carbon footprint and equivalents published by The Eco Experts: Tamara Birch: 'What's the average carbon footprint in the UK?' The Eco Experts, 10 December 2024. **https://www.theecoexperts.co.uk/news/average-carbon-footprint-uk**

81 Joseph Romm1, Stephen Lezak and Amna Alshamsi: 'Are Carbon Offsets Fixable?' Annual Review of Environment and Resources, Vol 50 p649-680, October 2025. **https://doi.org/10.1146/annurev-environ-112823-064813**

Spaceport Cornwall is not alone in talking about satellites which monitor the environment as a substitute for discussing climate change impacts. A September 2025 press release from the UK Space Agency claimed that "space projects" funded by the Agency will "use satellite technology" to "transform how Britain tackles climate change" and "reduce carbon emissions". On closer examination, the projects receiving funding from the agency were revealed to be computing applications for the financial sector which used satellite imagery and data to help investors assess environmental risks.[82] The space sector and mainstream media and educational institutes frequently play up the role of satellites in monitoring climate change,[83] while other less palatable applications such as their military uses are downplayed. Inconvenient issues such as the climate impact of space launches and the fact that action, rather than yet more monitoring, is needed to tackle the climate crisis are simply sidestepped. This process has been described as "spacewashing": the highlighting of romantic and humanitarian space applications to deflect attention from negative uses and impacts.[84]

While Spaceport Cornwall's recognition of its environmental responsibilities and its sustainability ambitions are to be applauded, it is difficult to see how they represent a genuine change of direction away from 'business as usual'. Rather than taking an approach to operations which is fundamentally centred on preventing harm to the environment – an approach which would seriously constrain, and possibly even totally eliminate, business opportunities for the spaceport – Spaceport Cornwall has focused on efforts to mitigate and reduce its impacts instead of abolishing them, while at the same time heavily promoting these efforts as 'eco-friendly'. Government licensing requirements have been met, but fundamental problems such as greenhouse gas production, expanding consumption, and over-exploitation of the space commons have not been addressed.

3.3 Ozone depletion

The stratosphere is home to the ozone layer, which contains a relatively high concentration of ozone in comparison to other parts of the atmosphere. Ozone is formed here by the action of ultraviolet light from the sun on atmospheric oxygen. The ozone layer is vital to life on Earth because it absorbs most of the sun's medium-frequency ultraviolet light, which is harmful to living organisms. The Montreal Protocol on Substances That Deplete the Ozone Layer was agreed in 1987 to protect the ozone layer by phasing out the production of industrial chemicals that cause ozone depletion. Both rocket launches and the reentry of spent satellites and space debris can potentially impact upon the ozone layer. The impacts of launches are discussed in this section of the report, and the impact of reentry is discussed in the following section.

82 'Space projects unlock climate and transport innovations'. UK Space Agency, 15 September 2025'. https://www.gov.uk/government/news/space-projects-unlock-climate-and-transport-innovations

83 See, for example: Andrea Willige: '6 ways satellites are helping to monitor our changing planet from space'. World Economic Forum, 16 May 2024. https://www.weforum.org/stories/2024/05/earth-observation-satellites-climate-change-research/
'How space science can help us combat climate change'. UK Research And Innovation, 4 October 2021. https://www.ukri.org/who-we-are/how-we-are-doing/research-outcomes-and-impact/stfc/how-space-science-can-help-us-combat-climate-change/
Rob Banino: 'How Earth-orbiting satellites monitor climate change'. BBC Sky At Night Magazine, 21 February 2024. https://www.skyatnightmagazine.com/space-science/climate-change-satellites-earth
'How satellites help us understand climate change'. Science Museum, 18 March 2021. https://www.sciencemuseum.org.uk/objects-and-stories/our-environment/how-satellites-help-us-understand-climate-change
Tom Slater: 'All eyes on Earth'. Royal Museums Greenwich. https://www.rmg.co.uk/stories/space-astronomy/why-satellites-are-critical-fighting-climate-change

84 'Palestine Space Institute's Post'. Linkedin, March 2025. https://www.linkedin.com/posts/palestinespaceinstitute_palestinespaceinstitute-spaceethics-decolonizingspace-activity-7308143420164694016-Qa3G

The impact of rocket launches on stratospheric ozone can be more significant when compared to other industrial activities because rockets uniquely emit persistent ozone-destroying compounds directly into the stratosphere. Both solid and liquid fuelled rockets cause ozone depletion, although exhaust from liquid fuelled rockets contains fewer reactive chemicals and particles and is estimated to be an order of magnitude less destructive than solid fuel exhaust. The intense heat generated during a launch, as well as the burn-up of satellites and components which enter the atmosphere at the end of their life, causes atmospheric nitrogen to be converted into ozone-destroying nitrogen oxides. Other highly reactive radicals produced by combustion, such as oxides of chlorine, bromine, hydrogen, and aluminium, also destroy ozone, with a single radical molecule of one of these elements emitted into the stratosphere able to destroy up to 100,000 ozone molecules.[85] In addition, water vapour and black carbon from exhaust emissions can absorb and block the sun's rays, slowing the replacement of ozone and regeneration of the ozone layer. Natural levels of water vapour in the stratosphere are low, and increased water vapour in this region can contribute to formation of polar stratospheric clouds which lead to ozone loss at high latitudes.[86]

Studies during the 1980s and 1990s showed that rocket exhausts can destroy 100 per cent of the ozone in the immediate wake of plumes from kerosene and solid fuel rockets, though this effect was localised and temporary.[87] Voigt et al. have estimated regional losses of ozone caused by launches across the globe to be in the order of several per cent, with total global loss between 0.01 and 0.1 per cent and impacts highest in northern high latitudes.[88] Ozone-depleting substances banned by the Montreal Protocol are thought to have caused loss of 3 per cent of atmospheric ozone, so the contribution of rocket launches to ozone depletion is small at the current time. However, the space sector is unregulated by the Montreal Protocol. Continued growth in rocket launches could see an increase in the sector's impact on stratospheric ozone levels and undermine the progress made on ozone recovery since the Montreal Protocol came into force.[89] These impacts would be most severe over polar latitudes.

85 Martin Ross, Darin Toohey, Manfred Peinemann & Patrick Ross: 'Limits on the Space Launch Market Related to Stratospheric Ozone Depletion'. International Journal of Space Politics & Policy, Vol 7(1), p50-82. 11 March 2009. **https://doi.org/10.1080/14777620902768867**

86 Daniel B Kirk-Davidoff, Eric J Hintsa, James G Anderson & David W Keith: 'The effect of climate change on ozone depletion through changes in stratospheric water vapor'. Nature, Vol 402, p399–401. 25 November 1999. **https://www.nature.com/articles/46521**

87 M. N. Ross, D. W. Toohey, W. T. Rawlins, E. C. Richard, K. K. Kelly, A. F. Tuck, M. H. Proffitt, D. E. Hagen, A. R. Hopkins, P. D. Whitefield, J. R. Benbrook, W. R. Sheldon: 'Observation of stratospheric ozone depletion associated with Delta II rocket emissions'. Geophysical Research Letters, Vol 27(15), p2209-2212. 1 August 2000. **https://doi.org/10.1029/1999GL011159**

88 Ch. Voigt, U. Schumann, K. Graf and K.-D. Gottschaldt: 'Impact of rocket exhaust plumes on atmospheric composition and climate ' an overview'. Progress in Propulsion Physics Vol 4, p657-670. 5 March 2013. **https://doi.org/10.1051/eucass/201304657**

89 Laura E. Revell, Michele T. Bannister, Tyler F. M. Brown, Timofei Sukhodolov, Sandro Vattioni, John Dykema, David J. Frame, John Cater, Gabriel Chiodo & Eugene Rozanov: 'Near-future rocket launches could slow ozone recovery', op cit.; Yuwen Li, Wuhu Feng, John M. C. Plane, Tijian Wang, and Martyn P. Chipperfield: 'The impact of rocket-emitted chlorine on stratospheric ozone'. Atmospheric Chemistry and Physics, Vol 26(5), p3621–3635. 11 March 2026. **https://doi.org/10.5194/acp-26-3621-2026**

3.4 Impacts from reentry

As well as emissions from rocket launches, the space industry also causes pollution of the atmosphere as a result of the reentry and burn-up of satellites and space objects. As a result of natural orbital decay, objects in low Earth orbit eventually fall to Earth and burn up when reentering the atmosphere. This includes rocket sections from high altitudes, redundant satellites, and space debris which, unlike natural meteorites consisting mainly of silicon with some iron, are made of aluminium and other metals which may have impacts on the atmosphere.

As is the case during launch, the acceleration and heating of both space debris and reusable rockets as they pass through the atmosphere during reentry generates thermal nitrogen oxides which contribute to ozone loss. Larson et al. have calculated that 100,000 launches per year of reusable rockets would be needed to generate enough nitrogen oxides from the reentry of reusable sections to cause global stratospheric ozone levels to drop by 0.5 per cent. This is far more – three or four orders of magnitude more – than the number of annual reentries by SpaceX's Falcon 9 reusable boosters[90], suggesting that launch impacts are of limited concern in this respect.

Of greater concern are satellites which have reached the end of their useful life. Redundant satellites are commonly deorbited into the atmosphere when they reach the end of their operational life in order to reduce the accumulation of space debris in orbit. Most satellites are constructed from aluminium alloys, titanium alloys, or stainless steel, with aluminium alloys typically constituting up to 40 per cent of a satellite's mass. Among the oxides they produce as they disintegrate and burn up are aluminium oxides. These are known to act as catalysts for chlorine activation that depletes ozone in the stratosphere. An investigation by Ferreira et al into the oxidation process of satellite aluminium structures during reentry into the mesosphere found that the demise of a typical 250-kg satellite can generate around 30 kg of aluminium oxide nanoparticles (tiny particles of between 1-100 nanometers in size), which may endure for decades in the atmosphere.[91] The total quantity of aluminium oxide compounds generated by all the satellites which reentered the atmosphere in 2022 was estimated to be around 17 metric tons – an increase of aluminium in the atmosphere above the natural level of 29.5 per cent – and in 2024 the mass of aluminium deposited annually in the atmosphere from satellite reentries exceeded that from natural sources like meteors for the first time. There is now evidence that, as a result of atmospheric conditions and circulation patterns, metallic material from spacecraft is being deposited in the polar regions.[92]

The quantity of aluminium oxide compounds deposited in the atmosphere by the space industry looks set to increase dramatically in future years. Commercial opportunities for providing global cellphone and broadband internet coverage are causing a rapid increase in the numbers of small communication satellites in low Earth orbit. More than half of active satellites are now part of a megaconstellation – a network of many small satellites that work together for the purpose of delivering internet access. As of January 2026 SpaceX had placed

90 Erik J. L. Larson, Robert W. Portmann, Karen H. Rosenlof, David W. Fahey, John S. Daniel, & Martin N. Ross: 'Global atmospheric response to emissions from a proposed reusable space launch system'. Earth's Future, Vol 5(1) p37-48. 16 November 2016. https://doi.org/10.1002/2016EF000399

91 José P. Ferreira, Ziyu Huang, Ken-ichi Nomura, Joseph Wang: 'Potential Ozone Depletion From Satellite Demise During Atmospheric Reentry in the Era of Mega-Constellations'. Geophysical Research Letters Vol 51(11). 16 June 2024. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL109280

92 Jeff Foust: 'Space sustainability comes down to Earth', op cit.

9,422 Starlink satellites into low Earth orbit, with plans to eventually launch a total of 42,000 satellites.[93] Blue Origin has plans to launch over 5,400 satellites in its TeraWave network and Amazon also plans to launch 3,232 satellites in its 'Project Kuiper' network.[94] The Chinese government is developing the Guowang megaconstellation and has filed to launch 12,992 satellites with the International Telecommunication Union.[95] The Chinese company Shanghai Spacecom Satellite Technology has also launched the first satellites for its Qianfan megaconstellation which is eventually intended to comprise of 14,000 satellites. In the longer term there are plans for satellite constellations at scales which would dwarf existing projects. SpaceX has filed proposals with the US Federal Communications Commission for a constellation of over a million satellites functioning as an orbital data centre, while China has filed plans with the International Telecommunication Union for two constellations totalling nearly 200,000 satellites.[96]

Internet satellites like these in low Earth orbit have short-lives of around 5-10 years because atmospheric drag is significant at the relatively low altitudes at which they orbit, causing their orbits to decay. Although SpaceX has launched more than 10,000 Starlink satellites, more than 1,300 of them have since reentered the atmosphere. Owners of megaconstellations must continually launch new satellites to replace those that have deorbited. As established practice, satellite operators usually deorbit satellites in a controlled manner at the end of their lives to prevent the accumulation of space debris (see section 4.1 below) and aim to ensure they completely burn up during reentry to remove the risk of debris causing harm or damage when they hit the Earth below.[97]

Ferreira and his team have calculated that if current plans to develop satellite megaconstellations come to fruition, over 360 tons of aluminium oxides could be deposited in the atmosphere every year – an increase of 646 per cent over natural atmospheric levels. Because aluminium oxides act as catalysts triggering chemical reactions which destroy ozone, they are not consumed by these chemical reactions and can continue to destroy ozone for decades as they drift down through the stratosphere. The long term accumulation of aluminium oxides nanoparticles from reentering satellites, which may remain in the atmosphere for decades, could cause significant ozone depletion, halting progress in stabilising the ozone layer which has been made through the Montreal Protocol.[98]

Scientists from the US National Oceanic and Atmospheric Administration (NOAA) have recently found that the stratosphere is peppered with particles containing metals vaporized from the reentry of satellites and space debris. As yet, it is not clear how this may influence atmospheric chemistry and the Earth's environment. The NOAA research team used a special high altitude aircraft to sample particles from the stratosphere. As well as naturally occurring particles from meteorites, they found aluminium and exotic metals embedded in about

93 Tereza Pultarova: 'Starlink satellites: Facts, tracking and impact on astronomy'. Space.Com, September 25, 2025. https://www.space.com/spacex-starlink-satellites.html

94 Jason Rainbow: 'Blue Origin plans bespoke high-speed Starlink rival'. Space News, 21 January 2026. https://spacenews.com/blue-origin-plans-bespoke-high-speed-starlink-rival/
'Everything you need to know about Project Kuiper, Amazon's satellite broadband network'. Amazon. https://www.aboutamazon.com/news/innovation-at-amazon/what-is-amazon-project-kuiper

95 Stephen Clark: 'China's Guowang megaconstellation is more than another version of Starlink'. Ars Technica, 20 August 2025. https://arstechnica.com/space/2025/08/china-may-have-taken-an-early-lead-in-the-race-for-a-military-megaconstellation/

96 Jeff Foust: 'SpaceX files plans for million-satellite orbital data center constellation'. Space News, 31 January 2026. https://spacenews.com/spacex-files-plans-for-million-satellite-orbital-data-center-constellation/

97 Jeff Foust:'Space sustainability comes down to Earth', op cit.

98 Erik J. L. Larson, Robert W. Portmann, Karen H. Rosenlof, David W. Fahey, John S. Daniel, & Martin N. Ross: 'Global atmospheric response to emissions from a proposed reusable space launch system', op cit.

10 per cent of sulphuric acid aerosol, the commonest type of particle in the stratosphere. They were able to match the ratio of rare elements they measured with alloys used in rockets and satellites, confirming beyond doubt their origin from vaporized space components reentering the Earth's atmosphere.[99]

Among the elements observed in the particles were niobium and hafnium – rare elements that are refined from mineral ores and used in semiconductors and superalloys. A significant number of particles also contained copper, lithium and aluminium at concentrations far above the level found in meteoric residues. These elements are characteristic of heat-resistant, high-performance alloys, pointing to the aerospace industry as their source. In total over 20 distinct elements originating from spacecraft were identified, including silver, iron, lead, magnesium, titanium, beryllium, chromium, nickel, zinc and lithium.

The influence of this level of metallic content on the properties of stratospheric aerosol is unknown, but there is a risk that that metals from spacecraft reentry could induce changes in the stratospheric aerosol layer. Although, at 10 per cent, the proportion of particles containing spacecraft metals is not large, the NOAA team warn that this could grow to 50 per cent or more based on the number of satellites scheduled for launch into low Earth orbit. "Over 5,000 satellites have been launched in the past five years. Most of them will come back in the next five, and we need to know how that might further affect stratospheric aerosols," says atmospheric scientist Martin Ross of the Aerospace Corporation.[100]

New research submitted in October 2025 to the pre-print directory ArXiv confirms these trends. A study led by researchers from Germany's Technische Universität Braunschweig found that the quantities of 'space waste' injected into the atmosphere by satellite burn-up is increasing dramatically. In 2020 366 tons of satellite derived material entered the atmosphere, rising to 887 tons in 2025 with around 1,400 tons expected in 2025. Although these quantities were lower than the mass injected naturally by meteors, the mass of metals derived from satellites in 2024 reached 14 per cent of the input than natural sources – a level that is now beginning to approach the quantity from natural sources. In 2024, inputs of 24 elements, commonly used in the aerospace sector, were greater from satellites than from natural sources, compared to 18 in 2015. Notable among these are aluminium, copper, titanium, and niobium, which are transition metals known for their catalytic activity, raising questions about potential long term effects on the atmosphere via both known and as yet unknown chemical pathways. The paper concludes by highlighting a "substantial risk" associated with space waste reentry and possible effects on Earth's atmosphere and the human habitat.[101]

It is possible that stratospheric loading – pollution resulting from the reentry of satellites and space debris – could eventually reach levels requiring international regulation to prevent harm to the atmosphere and to humans. This could impose limits on the rate of disposal of objects from low Earth orbit, which in turn would limit the rate at which new satellites could be launched, given constraints imposed by risks from space debris (see section 4 below).[102]

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99 Daniel M. Murphy et al.:'Metals from spacecraft reentry in stratospheric aerosol particles'. Proceedings of the National Academy of Sciences, Vol 120(43). 16 October 2023. https://www.pnas.org/doi/10.1073/pnas.2313374120|
Michael Gerding, Robin Wing, Wuhu Feng, John M. Plane, Gerd Baumgarten: 'New Li lidar observations and model simulations: A window to anthropogenic signatures'. Geophysical Research Letters, Vol 52, e2025GL118710. 12 November 2025. https://doi.org/10.1029/2025GL118710

100 'Vaporised spacecraft linked to metals in atmosphere'. University of Leeds, 17 October 2023. https://www.leeds.ac.uk/news-science/news/article/5435/vaporised-spacecraft-linked-to-metals-in-atmosphere

101 Leonard Schulz, Karl-Heinz Glassmeier, Moritz Herberhold, Adam Mitchell, Daniel M. Murphy, John M. C. Plane, Ferdinand Plaschke: 'Space waste: An update of the anthropogenic matter injection into Earth atmosphere'. ArXiv, 24 October 2025. https://arxiv.org/abs/2510.21328v1

102 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit.

3.5 Upper atmospheric impacts

Rockets have impacts at high altitudes, right up through the atmosphere and into space. In the higher levels of the atmosphere – the thermosphere and beyond – it is challenging to gather research data and we know very little about these parts of the atmosphere.

The upper atmosphere includes the ionosphere, an ionized region extending from about 50 km to 1000 km above the Earth's surface. Chemicals in the ionosphere are ionised by solar radiation into electrons and electrically charged atoms and molecules (ions), which influence the propagation of radio waves and can affect communications and GPS systems. Absorption of solar radiation by the ionosphere also protects life below from its harmful effects.

On 18 November 2023, SpaceX launched its Starship, the largest and most powerful rocket ever built. At an altitude of 90 km the boost engine exploded, followed shortly afterwards by an explosion of the main spacecraft at an altitude of 149 km. This event provided a rare opportunity allowing scientists to study the effects of such catastrophic phenomena on the ionosphere. Researchers from Russia and France analysed the explosion by collecting data from 2,500 ground stations located across North America and the Caribbean. They found that the rocket launch and explosion produced an unexpected response in the ionosphere, generating large-scale multi-oscillation supersonic conic waves and causing a depletion in total electron content – a 'hole' in the ionosphere which closed up after 30 to 40 minutes. The hole extended from Mexico's Yucatán peninsula to the south eastern part of the United States, although its exact size is unknown.[103]

An uncontrolled reentry involving a SpaceX Falcon 9 over Europe in February 2025 allowed further study of the impact of space debris on the upper atmosphere. The incident resulted in a ten-fold enhancement of lithium atoms in the mesosphere and lower thermosphere at an altitude of 96 km. The lithium plume was detected approximately 20 hours after reentry of the spacecraft's upper stage. This observation represents the first measurement of upper-atmospheric pollution resulting from space debris re-entry.[104]

There have been other recorded instances of rockets causing impacts on the ionosphere. In September 2023 a Firefly Aerospace Alpha rocket launched from Vandenberg Space Force Base in California created a huge exhaust plume visible from more than 1,500 km away. After the plume dissipated, a faint red glow remained in the sky.[105] Similar events were observed in June 2023, when a SpaceX Falcon 9 rocket launched from Vandenberg created a red fluorescent glow after passing overhead, which was visible for 20 minutes afterwards, and by other Falcon 9 rockets in August 2017 and June 2022 (see Image 7).[106] The June 2022 launch created a display of red light stretching from New York to the

103 Darren Orf: 'Whoopsie, SpaceX Blew Up Two Rockets and Punched a Massive Hole in One of Earth's Layers'. Popular Mechanics, 5 September 2024. **https://www.popularmechanics.com/space/rockets/a62047078/starship-explosion-ionosphere/**
Y. V. Yasyukevich, A. M. Vesnin, E. Astafyeva, B. M. Maletckii, V. P. Lebedev & A. M. Padokhin: 'Supersonic Waves Generated by the 18 November 2023 Starship Flight and Explosions: Unexpected Northward Propagation and a Man-Made Non-chemical Depletion'. Geophysical Research Letters, Vol 51(16). 28 August 2024. **https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL109284**

104 Wing, R., Gerding, M., Plane, J.M.C. et al: 'Measurement of a lithium plume from the uncontrolled re-entry of a Falcon 9 rocket. Communications Earth & Environment Vol 7, 161. 19 February 2026. **https://doi.org/10.1038/s43247-025-03154-8**

105 Harry Baker: 'Oops! US Space Force may have accidentally punched a hole in the upper atmosphere'. Live Science, 21 September 2023. **https://www.livescience.com/space/space-exploration/us-space-force-may-have-accidentally-punched-a-hole-in-the-upper-atmosphere**

106 'SpaceX Just Punched A Hole In The Ionosphere'. Spaceweather.Com, 21 July 2023. **https://www.spaceweather.com/archive.php?view=1&day=21&month=07&year=2023**

Carolinas that many observers mistook for the aurora borealis. These events were caused by ionospheric interactions with chemicals from rocket exhausts. Carbon dioxide and water vapour from the rocket's exhaust caused ionized oxygen atoms to recombine back into normal oxygen molecules. This process excites the molecules and causes them to emit light energy.

Image 7. Red fluorescence in the night sky caused by exhaust gases from a SpaceX Falcon 9 rocket in the ionosphere. Vandenberg Space Force Base, California, 19 July 2023. **Credit:** Jeremy Perez / SpaceWeather.Com

Ionospheric impacts are becoming increasingly common as numbers of rocket launches increase. They may have impacts on radio transmissions and cause sudden errors in GPS systems. However, the effects are short lived as solar radiation quickly causes reionisation to occur. Nevertheless, such interactions are poorly understood and further study is warranted, given increasing frequencies of launch and the importance of the ionosphere to everyday technologies and human health.

3.6 Conclusions

Rocket launches have been described as "small geoengineering experiments".[107] In some proposed geoengineering applications, particles or gases would be deliberately introduced into the stratosphere to alter radiative forcing, with the aim of tackling climate change by modifying the effects of solar radiation. Rocket exhausts have a similar effect, although they are not consciously intended to alter atmospheric composition. While there is caution about the consequences of geoengineering and the potential for unpredicted and undesirable impacts, such prudence does not yet extend to the space sector.

The long term impacts of chemicals and particles resulting from space operations are not yet understood, and their continuing injection into the atmosphere represents a form of uncontrolled geoengineering. While rocket launches used to be rare enough that pollution was not much of a concern, launch rates have increased rapidly over the past two decades and their impacts

107 Martin N. Ross and Patti M. Sheaffer: 'Radiative forcing caused by rocket engine emissions', op cit.

on the atmosphere are now beginning to reach a scale at which they can no longer be ignored. The injection of space waste metals that are only present in low levels in natural meteors may cause the chemistry of the mesosphere and stratosphere to change. New materials, especially those with catalytic properties, may support nucleation of polar mesospheric and stratospheric clouds and could cause ozone destruction and / or accelerate climate change by stimulating radiative forcing. This could result in long term changes to the atmosphere.[108]

Recent scientific research has provided some insights into the space sector's climate impacts, but there are still large uncertainties about the full impact of rocket launch and reentry heating emissions on atmospheric chemistry and the global climate. Scientific uncertainty and the rapid growth of the sector mean that space policies based on the assumption that environmental impacts are minimal are no longer appropriate. In the first instance, an urgent and vigorous programme of scientific research is needed in order to increase understanding of the global impacts of space flight. Secondly, management is necessary to mitigate against environmental harm, based around a comprehensive assessment of the likely impacts and risks. This will entail agreement on and regulation of launch and space activities to meet the imperative to protect and conserve the atmosphere.

Case study 3 Space tourism and the billionaire space race

Although private space flights were first marketed in the 1960s by Pan American World Airways,[109] space tourism first really began on 28 April 2001 when American businessman Dennis Tito took off in a Russian Soyuz spacecraft to spend seven days on the International Space Station (ISS). Tito was the first space tourist to fund his own trip, and over the next eight years a further six tourists made similar trips to the ISS on Soyuz rockets, reportedly paying up to $US50 million per person for the trip.[110] There was then a ten year hiatus in trips to the ISS, until in December 2021 Japanese billionaire Maezawa Yusaku and colleague Hirano Yozo spent twelve days on the space station on a trip arranged with the National Aeronautics and Space Administration (NASA), reportedly for a price of $US88 million.[111] In the meantime SpaceX had entered the orbital space tourism market, and in September 2021 a Falcon 9 rocket launched the Crew Dragon Resilience spacecraft into orbit for three days with a civilian crew of three. NASA and SpaceX continue to market orbital space tourism trips.[112]

Earlier in 2021 two billionaires took well-publicised flights into space as the first ventures of their space tourism companies. In July Richard Branson flew in Virgin Galactic's SpaceShipTwo craft and a few days later Jeff Bezos travelled in Blue Origin's New Shepard reusable launch vehicle.[113] Both companies offer sub-

108 Leonard Schulz, Karl-Heinz Glassmeier et al.: 'Space waste: An update of the anthropogenic matter injection into Earth atmosphere', op cit.

109 Karl Tate: 'Fantastic Flight: The Orion III Spaceplane from "2001: A Space Odyssey"', Space.com, 15 March 2016. https://www.space.com/32258-orion-space-plane-2001-space-odyssey-photo-essay.html

110 M. Wall: 'First Space Tourist: How a U.S. millionaire Bought a Ticket to Orbit'. Space.com, 27 April 2011. https://www.space.com/11492-space-tourism-pioneer-dennis-tito.html
Emile A. Margolis: 'Space Tourism: Then and Now'. Smithsonian National Air and Space Museum, 25 October 2021. https://airandspace.si.edu/stories/editorial/space-tourism-then-and-now

111 'Japanese billionaire blasts off to International Space Station'. BBC News, 8 December 2021. https://www.bbc.co.uk/news/world-asia-59544223

112 NASA Space Tourism: Exploring the Future of Off-World Travel'. Space Voyage Ventures, 7 September 2025 https://spacevoyageventures.com/nasa-space-tourism/

113 Dave Webb: 'The Environmental Effects of Space Tourism'. In 'Space Tourism: Legal and Policy Aspects, Ed. Sandeepa Bhat B. Routledge India, 2024. https://doi.org/10.4324/9781032617961

orbital space trips of a few minutes, in which the spacecraft reaches an altitude qualifying as 'space', but does not complete an orbital revolution.

Virgin Galactic's spacecraft is air-launched from a carrier aeroplane called White Knight Two. The company commenced undertaking commercial space flights in 2023, claiming to want to launch a "new age of clean and sustainable access to space".[114] The company has reportedly sold around 700 flight tickets, currently priced at around $US600,000 per seat, and aims eventually to launch up to 400 flights with six passengers per year.[115] Virgin Galactic paused commercial flights in 2024 and is currently developing its new Delta-class spacecraft, which the company hopes will enter into service in 2026 and is intended to fly more frequently and at lower costs than SpaceShipTwo craft.

Blue Origin is currently the leader in the sub-orbital space tourism sector, having launched commercial trips regularly since Bezos' flight in 2021. Ticket prices are reportedly between $US200,000 – 500,000 and the company currently has three New Shepard launchers available for flights.[116]

The global space tourism market size was estimated at $US888.3 million in 2023 and is growing, projected to reach over $US10 billion by 2030 and with more companies planning to enter it.[117] Proposals for future developments are even more ambitious. Some companies are developing plans for space transport systems, including SpaceX, which has considered using its Starship rocket to fly up to 100 people around the world in minutes.[118] SpaceX is also offering commercial trips to orbit the Earth and the Moon, and Axiom Space is hoping to construct its own space station in the near future and provide spaceflight services to individuals, as well as corporations and national space agencies.[119] The not-for-profit World Monuments Fund has highlighted the risks that space tourism may pose to the Moon, listing it as one of 25 endangered cultural heritage sites on the World Monuments Watch list for 2025. The Fund warns that more than 90 important locations on the Moon may be harmed as a result of future space tourism including Tranquillity Base, the Apollo 11 landing site where Neil Armstrong first stepped onto the Moon's surface.[120]

These proposals do not bode well for the environment, especially if space tourism becomes more affordable and more readily available. As the number of space tourism launches increases, impacts on the environment also increase. One of the most important of these impacts is on climate (see section 3.2). Rockets that use kerosene as fuel, such as SpaceX's Falcon 9 and Russia's Soyuz rockets, emit black carbon and alumina particles into the stratosphere. Blue Origin's liquid oxygen / liquid hydrogen propellant produces large quantities of water vapour. Virgin Galactic has not announced which fuel type will power

114 Jasper Jolly and Gwyn Topham: 'Richard Branson's quest: to boldly go where no billionaire has gone before'. Guardian, 10 July 2021. https://www.theguardian.com/science/2021/jul/10/richard-branson-virgin-galactic-flight-billionaire-space-tourism-race-jeff-bezos

115 Mike Wall: 'Blue Origin launches 'Perfect 10' space tourists on New Shepard rocket'. Space.Com, 25 February 2025. https://www.space.com/space-exploration/private-spaceflight/watch-jeff-bezos-blue-origin-launch-10th-space-tourism-flight-today

116 Mike Wall: 'Virgin Galactic on track to start launching customers again in 2026, but seat prices will rise'. Space.com, 22 March 2025. https://www.space.com/space-exploration/private-spaceflight/virgin-galactic-on-track-to-start-flying-customers-again-in-2026

117 'Space Tourism Market (2024 – 2030)'. Grand View Research. https://www.grandviewresearch.com/industry-analysis/space-tourism-market-report

118 Michael Sheetz: 'Super fast travel using outer space could be $20 billion market, disrupting airlines, UBS predicts'. CNBC, 18 March 2019. https://www.cnbc.com/2019/03/18/ubs-space-travel-and-space-tourism-a-23-billion-business-in-a-decade.html

119 Mike Wall: 'Axiom Space: Building the off-Earth economy'. Space.com, 17 January 2022. https://www.space.com/axiom-space

120 Zachary Small: 'World Monuments Fund Puts Moon on List of At-Risk Sites'. New York Times, 15 January 2025. https://www.nytimes.com/2025/01/15/arts/world-monuments-fund-moon-endangered.html

its new Delta spacecraft, but the SpaceShipTwo vehicles operated using solid HTPB fuel with nitrous oxide as oxidiser. Ross and Sheaffer have estimated that, taking into account the effect of black carbon emissions, the carbon footprint of a passenger in a typical sub-orbital space tourism flight is comparable to that of a passenger travelling thousands of times in aircraft between Los Angeles and London.[121]

Space tourism is a big impetus that is pushing the development of certain aspects of the space industry. However, its effects are environmentally harmful and contribute disproportionately to global climate change. It is not an industry which is driven by commerce to provide a service with widespread benefits, nor undertaken by governments to meet their national priorities. It is entirely the province of the super-rich, engaging in conspicuous consumption as customers and seeking to profit at the expense of the climate as entrepreneurs. Even the UK's Prince William – himself one of the super-rich elite – has suggested that entrepreneurs should focus on saving Earth rather than engaging in space tourism, saying that they should be "trying to repair this planet, not trying to find the next place to go and live" and warning that there is a "fundamental question" over the carbon cost of space flights.[122]

121 Martin N. Ross and Patti M. Sheaffer: 'Radiative forcing caused by rocket engine emissions', op cit.

122 George Bowden: 'Prince William: Saving Earth should come before space tourism'. BBC News, 14 October 2021. https://www.bbc.co.uk/news/uk-58903078

4 Space debris and orbital crowding

Over the course of nearly seventy years of human activity in space considerable quantities of material have been launched into orbit. The European Space Agency estimates that, as of January 2026, around 25,170 satellites have been placed into orbit, of which 14,200 are still functioning. In total, the mass of all space objects in Earth orbit is more than 15,800 tons. There are currently around 54,000 space objects greater than 10 cm in orbit and 140 million much smaller space debris objects between 1 mm and 1 cm in size.[123] These objects travel at orbital velocities of the order of 10 kilometres per second. At these very high speeds, even a one-centimetre piece of debris has the kinetic energy of an exploding grenade. Space debris therefore poses a catastrophic collision hazard to functional satellites (see Image 8).

Space debris consists of defunct satellites, spent upper stages of launch rockets, and other mission-related objects such as launch adapters (sections between rocket stages) and camera lens covers which are discarded into orbit. Much of the remaining larger debris has resulted from in-orbit fragmentation events, principally explosions caused by residual fuel remaining in tanks or fuel lines of satellites or rocket stages after they have reached the end of their life. More than 500 fragmentation events have been recorded since 1961 and the majority of these have been caused by explosions, with just a fraction of this number caused by collisions. The first accidental in-orbit collision between two satellites occurred in February 2009 in low Earth orbit when the American Iridium-33 communication satellite collided with a Russian military satellite, Kosmos 2251, at a speed of over 11 km/s. Both satellites were destroyed, generating more than 2,300 trackable fragments of debris and posing risks to other satellites in the Iridium constellation which were orbiting nearby. In addition to accidental collisions and fragmentation, the US, Russia, China and India have all conducted tests of kinetic anti-satellite weapons to destroy a satellite of their own using missiles launched from a ship at sea, aircraft, or the ground. These tests can generate large quantities of debris. One such test conducted by China in January 2007 increased the trackable space object population by 25 per cent.[124]

123 'Space debris by the numbers'. European Space Agency. Update 16 January 2026. https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers

124 'About Space Debris'. European Space Agency. https://www.esa.int/Space_Safety/Space_Debris/About_space_debris

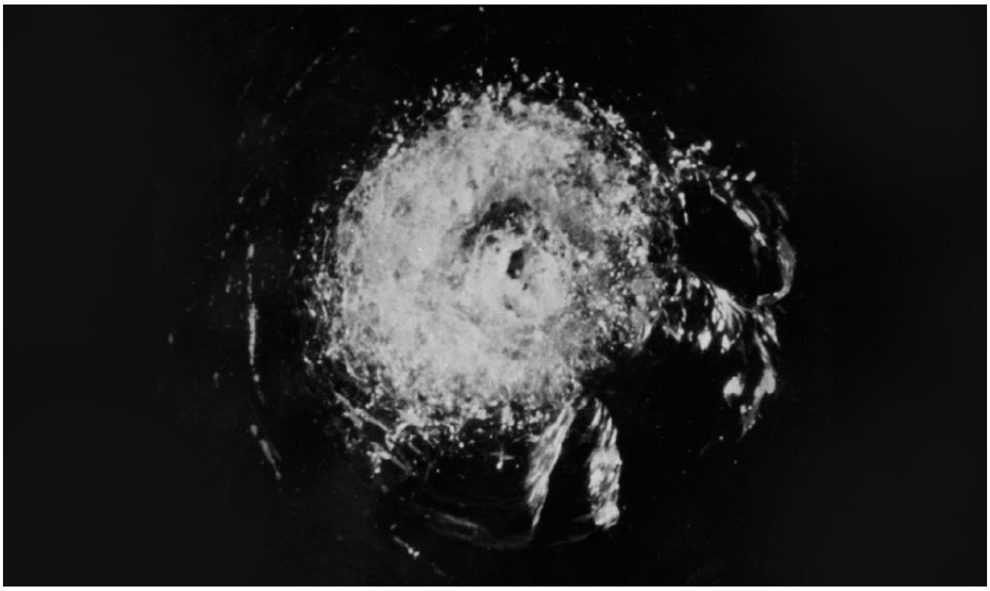


Image 8. A pit on the windshield of the Space Shuttle Challenger caused by impact with an orbiting paint chip. **Credit:** NASA.

Space debris has also resulted from the deliberate release of material from satellites, such as copper needles used to create an artificial ionosphere as part of US military communications experiments in the early 1960s, and the ejection of reactor cores from Soviet surveillance satellites in the 1980s which introduced droplets of sodium-potassium alloy coolant liquid into orbit. Solid rocket motor firings also release particulate alumina into orbit as micrometer-sized dust and larger slag particles. The harsh space environment and the impact of high levels of ultraviolet radiation will erode the surfaces of objects in space and cause the loss of surface coatings and the detachment of small flecks of paint.[125]

In order to avoid collisions, satellite operators undertake collision avoidance manoeuvres when passing close to other satellites or detectable debris. However, this consumes scarce fuel reserves, reducing the lifetime of the satellite. Smaller, undetected debris cannot be avoided and so there is a permanent risk of damage or potential mission failure from collision with such items. As the debris population grows more collisions can be expected to occur, with risks increasing geometrically: doubling the number of space objects will increase the collision risk by approximately four times. The European Space Agency warns that in a business-as-usual scenario for the space sector, collisions will overtake explosions as the main generator of space debris within a few decades. Eventually collision fragments will collide with collision fragments, reducing the entire debris population to subcritical sizes and possibly giving rise to a self-sustaining process known as the 'Kessler syndrome'.[126]

The Kessler syndrome, first postulated by NASA scientists Donald J. Kessler and Burton G. Cour-Palais in 1978, theoretically occurs when the density of objects in orbit becomes high enough for collisions between objects to cascade, in a similar manner to a radioactive chain reaction. Collisions produce orbiting fragments, each of which increases the probability of further collisions, leading to an exponential increase in the amount of space debris and the creation of a belt of debris around the planet which could make the space environment unusable for hundreds to thousands of years. Writing in 1978, Kessler and Cour-Palais predicted that "under certain conditions the belt could begin to form within this century and could be a significant problem during the next

125 'About Space Debris'. European Space Agency, op cit.

126 'About Space Debris'. European Space Agency, op cit.

century".[127] Kessler syndrome projections are based on modelling, and there are uncertainties in models used. However, the rate of increase for collision fragments will increase rapidly with increases in the number of satellites in orbit. Even without an increase in the number of launches, the number of objects in space is expected to continue to grow because of fragmentation events, and the risk of catastrophic collision is increasing.[128]

Space debris is particularly critical in the low Earth orbit region (300 – 2000 km above the earth's surface). Over 80 per cent of active satellites orbit in this zone, including Starlink and other megaconstellations, Earth observation satellites, and the International Space Station.[129] It also has the greatest density of space debris, holding over half of the catalogued population of debris.[130] Loss of low Earth orbit to debris would disable critical services upon which the global economy relies, such as GPS navigation services and communication and internet services. The European Space Agency points out that active satellites must perform an increasing number of collision avoidance manoeuvres to keep out of the way of other satellites and fragments of space debris, and that the amount of space debris in orbit continues to rise quickly. The Agency warns that "without further change, the collective behaviour of space-faring entities (private companies and national agencies) is unsustainable in the long term".[131]

The problem is being exacerbated by the effect of greenhouse gas emissions on the thermosphere, which extends into the low Earth orbit region. Recent research from scientists at the University of Birmingham has shown that greenhouse gases are cooling and contracting the thermosphere as global warming effects draw heat via conduction from the upper atmosphere. As the region cools down, it also contracts, leaving satellites orbiting in areas where the atmosphere is less dense and therefore exerting less atmospheric drag on them. The reduction in friction could slow down orbital decay, prolonging satellite lifetimes and increasing the risk of space debris accumulation. Modelling of carbon dioxide emission scenarios over the period 2000–2100 indicates a potential 50–66 per cent reduction in satellite carrying capacity between the altitudes of 200 and 1,000 km.[132]

127 Donald J. Kessler & Burton G. Cour-Palais: 'Collision frequency of artificial satellites: The creation of a debris belt'. Journal of Geophysical Research Space Physics, Vol 83(A6), p2637-2646. 1 June 1978. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/JA083iA06p02637

128 D.J. Kessler & P.D. Anz-Meador: 'Critical number of spacecraft in low Earth orbit: using satellite fragmentation data to evaluate the stability of the orbital debris environment'. Proceedings of the Third European Conference on Space Debris, 19 – 21 March 2001, Darmstadt, Germany. Ed. Huguette Sawaya-Lacoste. ESA SP-473, Vol. 1, Noordwijk, Netherlands: ESA Publications Division, 2001. P265-272 https://adsabs.harvard.edu/full/2001ESASP.473..265K,
Sarah Thiele, Skye R. Heiland, Aaron C. Boley, Samantha M. Lawler: 'An Orbital House of Cards: Frequent Megaconstellation Close Conjunctions'. ArXiv, 10 December 2025. https://arxiv.org/abs/2512.09643

129 'How Many Satellites Are Orbiting Earth in 2025? Latest Facts and Surprising Insights'. Orbital Exploration. https://orbitalxploration.com/how-many-satellites-are-orbiting-earth-in-2025-latest-facts-and-surprising-insights

130 'Space Environment Statistics'. European Space Agency. Update 21 October 2025. https://sdup.esoc.esa.int/discosweb/statistics/

131 'ESA Space Environment Report 2024'. European Space Agency, 19 July 2024. https://www.esa.int/Space_Safety/Space_Debris/ESA_Space_Environment_Report_2024

132 William E. Parker, Matthew K. Brown & Richard Linares: 'Greenhouse gases reduce the satellite carrying capacity of low Earth orbit'. Nature Sustainability Vol 8 p363–372. 10 March 2025. https://www.nature.com/articles/s41893-025-01512-0

4.1 Efforts to control space debris

Space debris is now accepted by the space industry as a critical problem which is beginning to affect its routine operations. Congestion in key orbital bands has resulted in an exponential increase in collision avoidance manoeuvres and space object flux (the rate at which objects, such as satellites and debris, pass through a specific area in space over time) in some low orbit regions is so high that the total number of objects in orbit is expected to increase even without further launches.[133] The United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) has developed international guidelines to mitigate the impacts of space debris (see Table 1).

Table 1. International space debris mitigation guidelines formulated by the Committee on the Peaceful Uses of Outer Space.[134]

Guideline 1	Limit debris released during normal operations.
Guideline 2	Minimize the potential for break-ups during operational phases.
Guideline 3	Limit the probability of accidental collision in orbit.
Guideline 4	Avoid intentional destruction and other harmful activities.
Guideline 5	Minimize potential for post-mission break-ups resulting from stored energy.
Guideline 6	Limit the long term presence of spacecraft and launch vehicle orbital stages in the low-Earth orbit region after the end of their mission.

These guidelines are, sensibly, centred around good practices for avoiding the creation of space debris. To this end partially reusable launch vehicles such as the Space Shuttle and SpaceX's Falcon 9 play a role in tackling the problem, and some launch companies claim to be developing reusable rockets designed to leave zero debris in orbit, such as the Orbex Prime small rocket launcher.[135] These measures can help avoid the creation of useless space 'junk' and fragmentation debris, but do not address the fundamental problem of what to do about satellites which have been intentionally placed into orbit when they reach the end of their life. The possibility of developing 'reusable satellites' with heat shields, thermal protection and new reentry technologies for certain types of mission may help to mitigate this problem, but at present such an approach shows no sign of replacing a 'limited lifetime' approach to satellite operations.[136] Research is also underway into the use of satellites based on wooden structures, but although such satellites can be expected to generate far less metal residues upon reentry, they still contain aluminium and steel components, and wooden sections also generate ash upon burn-up.[137]

133 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit.

134 'Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space'. United Nations Office for Outer Space Affairs. https://www.unoosa.org/documents/pdf/spacelaw/sd/COPUOS-GuidelinesE.pdf

135 'Orbex Secures Patent for Coaxial Rocket Fuel Tanks'. Orbex, 13 February 2024. https://orbex.space/news/orbex-secures-international-patent-for-coaxial-rocket-fuel-tanks

136 Jason Rainbow: 'Lux Aeterna nets US government partnerships for reusable satellite technology'. Space News, 13 November 2025. https://spacenews.com/lux-aeterna-nets-us-government-partnerships-for-reusable-satellite-technology/

137 Ben Turner: 'NASA and Japan launch world's 1st wooden satellite into orbit. Here's why it could help solve a huge problem for our planet'. Live Science, 9 January 2025. https://www.livescience.com/space/space-exploration/nasa-and-japan-to-launch-worlds-1st-wooden-satellite-as-soon-as-2024-why

The industry approach to limiting the presence of spacecraft in orbit after the end of their mission has traditionally been to use the last of their propellant to move them out of active orbit and either deorbit them, so they burn up in the atmosphere or fall to Earth, or move them into a higher 'graveyard' orbit where they will be out of the way of functional satellites. Moving debris to higher graveyard orbits further away from the atmosphere, where it may remain for hundreds of years, does not deal with the problem but merely puts off the moment when it will have to be tackled. Ultimately it is an unsustainable practice as it leads to further debris congestion and pollution of space.[138]

4.2 Sea dumping of space debris

As we have seen in section 3.5 above, allowing redundant satellites to burn up in orbit creates new problems related to the atmospheric impacts of disintegration products. This approach to managing space debris raises other issues, too. Items of space debris which are too large to burn up in the atmosphere must be brought to Earth in a controlled descent so that they land in an area where they will cause little harm. The 'spacecraft cemetery' where such items are brought down is a large ocean area known as the South Pacific Ocean Uninhabited Area (SPOUA), located around 'Point Nemo' – the furthest point from any land on planet Earth. Point Nemo is approximately 3,000 miles east of New Zealand and 2,000 miles north of Antarctica (see Image 9) and has a depth of 2.5 miles. There are no islands in SPOUA and very little human activity such as fishing or shipping. SPOUA is beyond the national jurisdiction of any state and over the period 1971-2019 over 260 pieces of space debris have been sunk in this area, including the remains of the Skylab space station, the Mir space station, and three Salyut Russian military space stations.[139] It is expected that the International Space Station will be deorbited into SPOUA and the number of space debris splashdowns into the area is likely to increase in future given that deorbiting is an established measure for eliminating space debris.[140]

While dumping space debris allows satellite operators to minimise their risks of liability and may currently be the least worst option for its disposal, there are concerns around this practice. Because of their remoteness, Point Nemo and the SPOUA are pristine areas largely unspoilt by human activity, and host unexplored and probably vulnerable ecosystems. We are not aware that any environmental impact assessments have been published for disposing of space debris in this manner, and the cumulative effects of hundreds of splashdowns may be significant. Debris does not land in the SPOUA as a single fragment, but rather as a shower of pieces, some possibly of a considerable size, which may be spread out over a trail of thousands of kilometers as a satellite breaks up during reentry. It is rarely clear what materials a redundant satellite consists of, and the main risk posed by the dumping of space debris at sea is the chemical risk posed by the eventual decomposition of surviving equipment, which is likely to contain hazardous and possibly radioactive substances. Although space debris dumped at sea may be out of sight and out of mind, splashdowns use the ocean commons without consideration for potentially harmful consequences that may result for

138 Kevin J Gaston, Karen Anderson, Jamie D Shutler, Robert JW Brewin, Xiaoyu Yan: 'Environmental impacts of increasing numbers of artificial space objects', op cit.

139 Vito De Lucia & Viviana Iavicoli: 'From outer space to ocean depths: The 'spacecraft cemetery' and the protection of the marine environment in areas beyond national jurisdiction'. California Western International Law Journal Vol 9(2) p345–390. 2019. https://scholarlycommons.law.cwsl.edu/cgi/viewcontent.cgi?article=1551&context=cwilj

140 Leonard David: 'Ocean experts raise concerns over deorbiting the International Space Station'. Space News, 9 October 2024. https://spacenews.com/ocean-experts-raise-concerns-over-deorbiting-the-international-space-station/

the marine environment. International lawyers Vito De Lucia and Viviana Iavicoli have concluded that whilst splashdowns are considered a lawful and legitimate way of disposing of debris under space law, "if approached through the rules and schemes of the law of the sea, splashdowns breach one or more substantive and/or procedural rules".[141]

Redundant satellites and space debris will not always deorbit in a controlled manner and come to ground in a specified zone. Large objects will reenter uncontrolled if abandoned in space, and may not fully disintegrate upon reentry. Typically about 30 per cent of the mass of a satellite which falls uncontrolled through the atmosphere fails to incinerate, particularly larger components such as thrusters, pressure vessels, batteries and reaction wheels. The risks of space debris causing damage or harm on reentry are low, but can only become statistically more likely in future as the number of objects in space increases. In 2024 parts of SpaceX Dragon spacecraft survived reentry to crash in North Carolina and Canada in 2024, and a 0.7 kg fragment surviving from a pack of batteries which had been discarded from the International Space Station in 2021 crashed through the roof of a Florida home. Impact from falling space debris could be catastrophic for an aircraft in flight, and was a concern during the Columbia space shuttle disaster when at least nine planes flew through the debris tail from the accident.[142]

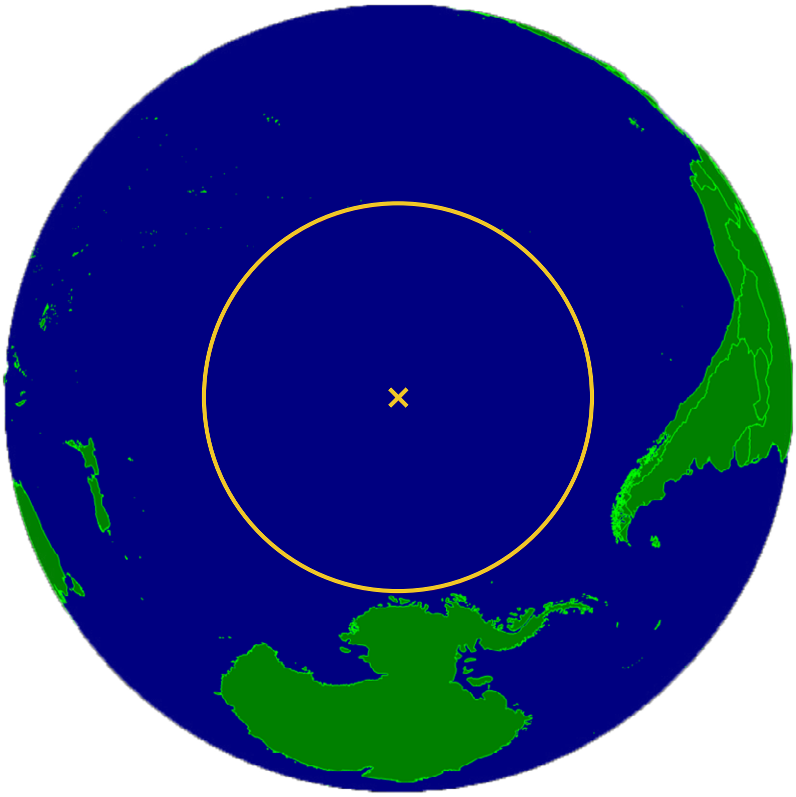


Image 9. Location of Point Nemo in the South Pacific Ocean Uninhabited Area (SPOUA).
Credit: Timwi / Wikimedia Commons

141 Vito De Lucia & Viviana Iavicoli: 'From outer space to ocean depths: The 'spacecraft cemetery' and the protection of the marine environment in areas beyond national jurisdiction', op cit.

142 Sarah Scoles: 'Plans to Trash the Space Station Preview a Bigger Problem'. Scientific American, 28 October 2024. https://www.scientificamerican.com/article/plans-to-destroy-the-international-space-station-preview-a-bigger-orbital/
Mike Wall: 'Object that slammed into Florida home was indeed space junk from ISS, NASA confirms' Space.Com, 15 April 2024. https://www.space.com/object-crash-florida-home-iss-space-junk-nasa-confirms

On a number of occasions in the past radioactive materials from satellites and spacecraft have been released or lost after reentry. The most serious case of this was the Soviet satellite Cosmos 954, which in January 1978 crashed in the Northwest Territories of Canada, scattering radioactivity over a 124,000 square kilometer area.[143] A Cosmos satellite had previously dropped its reactor into the Pacific Ocean north of Japan in 1973 when a launch failed, and subsequently in 1983 Cosmos 1402 fell with its reactor into the South Atlantic. The ill-fated Apollo 13 spacecraft also contained a cask of 3.9 kg of plutonium, intended to provide fuel for a number of experiments on the Moon's surface. The flask was lost in the Tonga Trench in the Pacific Ocean when the spacecraft returned to Earth.[144] In addition to incidents where radioactive materials carried on board spacecraft and satellites have contaminated the surface of the Earth, there have also been a number of incidents where radioactive materials have been released and dispersed into the atmosphere.[145]

4.3 In-orbit servicing and active debris removal

Clearly there are economic advantages as well as environmental benefits in moving away from the viewpoint that satellites are one-shot items with their lifespans coming to an end when they can no longer manoeuvre effectively. A new niche of in-orbit servicing is emerging within the space industry to exploit opportunities for managing the issue of space debris. In-orbit servicing aims to delay the creation of space debris by extending the lifetime of satellites by refuelling, repairing, or upgrading them while they are in orbit. This approach to managing space debris is favoured by, among others, the UK Space Agency, which provided funding to support research and development into satellite refuelling products and missions.[146] Space Logistics, a subsidiary of the Northrop Grumman arms company has developed two Mission Extension Vehicles which have docked with and provided station-keeping services for two Intelsat geostationary satellites that were running low on fuel, prolonging their operational lives.[147]

A related approach is to capture redundant satellites using a grappling device, robotic arm, net, or magnetic tether and then move them from a decaying orbit into a more stable location. China has developed the Shijian-21 satellite which in December 2021 docked with the defunct Beidou-2 G2 navigation satellite and towed it to a parking orbit high above the geostationary orbit band where it had been located.[148] The European Space Agency is funding the ClearSpace-1 mission, intended to demonstrate the removal of a satellite from orbit by a capture device. The ClearSpace mission, intended to take place in 2029, will

143 'Previous nuclear incidents and accidents: COSMOS 954'. Government of Canada, 3 September 2019. https://www.canada.ca/en/health-canada/services/health-risks-safety/radiation/radiological-nuclearemergencies/previous-incidents-accidents/cosmos-954.html

144 Matthew Van Dusen: 'Will Anyone Recover Apollo 13's Plutonium?' Space Safety Magazine, 2 June 2014. https://www.spacesafetymagazine.com/aerospace-engineering/nuclear-propulsion/will-anyone-recover-apollo-13s-plutonium/

145 'Nuclear Incidents in Space. From the Palm Beach Post, 15 March 2003'. The Global Network Against Weapons and Nuclear Power in Space. https://space4peace.org/nuclear-incidents-in-space/

146 'Satellites could become more sustainable, thanks to new UK Space Agency funding'. UK Space Agency, 9 February 2024. https://www.gov.uk/government/news/satellites-could-become-more-sustainable-thanks-to-new-uk-space-agency-funding

147 Sandra Erwin: 'Northrop Grumman to launch new satellite-servicing robot aimed at commercial and government market'. Space News, 23 September 2021. https://spacenews.com/northrop-grumman-to-launch-new-satellite-servicing-robot-aimed-at-commercial-and-government-market/
'MEV-2's Historic Rendezvous with IS-10-02 in Geostationary Orbit'. Northrop Grumman. Youtube, 23 September 2021. https://www.youtube.com/watch?v=JUnA88PQY3k

148 Andrew Jones: 'China's Shijian-21 towed dead satellite to a high graveyard orbit'. Space News, 27 January 2022. https://spacenews.com/chinas-shijian-21-spacecraft-docked-with-and-towed-a-dead-satellite/

see a capture device rendezvous with, capture, and bring down the PROBA-1 satellite launched in 2001. Both the PROBA satellite and the ClearSpace capture device will be destroyed during reentry.[149] Irradiation using space-based lasers has also been proposed as a means of eliminating small items of space debris.[150]

New satellites can be designed to make them easier to remove from orbit, for example by installing navigation aids for close proximity operations and a coupling interface such as a magnetic docking point to allow a capture device to grab hold of it easily. Modular design approaches could allow life-limited components to be replaced by mission extension packs. However, in-orbit servicing and active debris removal missions have limitations in addressing the impacts of space debris. Technology is still at a relatively early stage and refuelling and life extension missions would only be viable for servicing high-value space assets. Although several debris removal missions are planned over the next few years, these aim to target defunct satellites to prevent them from generating further additional debris, rather than removing meaningful quantities of existing debris. Their potential for remediation is therefore low. Recovery missions are not commercially viable, and it seems likely they would be focused on removing satellites from critical congested orbit zones such as geosynchronous equatorial orbit, or as a 'last resort' in moving a malfunctioning satellite which cannot be manoeuvred using its own systems. Destructive reentry during active debris removal missions such as the ClearSpace mission would add to the chemical loading on the atmosphere resulting from burn-up of satellites and capture devices. The recovery of items from orbit by bringing them safely back to Earth is not economic and is currently not possible in the absence of a Space Shuttle type capability.

Like all space technologies, debris removal and in-orbit servicing technology is dual use and can be used for offensive military purposes as well as civilian purposes. There are concerns that such systems will be used to disable or interfere with satellites in future in space warfare. The US Defense Advanced Research Projects Agency has developed a robotic payload for a second generation version of the Mission Extension Vehicles built by Space Logistics,[151] and space services provider Astroscale has been awarded a $US25.5 million contract to design and deliver to the US Space Force a satellite to refuel other satellites in space.[152] As a result, military space powers can be expected to develop evasion and protection capabilities for their satellites, raising the risk of a military space technology arms race. To quell concerns and reduce such risks, space debris removal and in-orbit servicing operations will need to be conducted with a maximum of transparency.

149 'ClearSpace-1'. European Space Agency. https://www.esa.int/Space_Safety/ClearSpace-1

150 Quan Wen, Liwei Yang, Shanghong Zhao, Yingwu Fang, Yi Wang, & Rui Hou: 'Impacts of orbital elements of space-based laser station on small scale space debris removal'. Optik, Vol 154 p83-92. February 2018. https://www.sciencedirect.com/science/article/abs/pii/S0030402617312068#!

151 Sandra Erwin: 'Northrop Grumman to launch new satellite-servicing robot aimed at commercial and government market', op cit.

152 'New contract will advance space mobility and logistics capabilities beyond the constraint of launching with a fixed lifetime supply of fuel'. Astroscale U.S., 17 January 2024. https://www.astroscale-us.com/en/news/new-details-on-the-revolutionary-astroscale-u-s-in-space-refueler-for-the-united-states-space-force

4.4 Conclusions

The space industry has become aware that it has created a problem for itself by taking a single use, 'throwaway' approach to its activities which has led to the accumulation of increasing quantities of space debris. Approaches currently taken to tackling this problem serve the industry's interests but do not serve the interests of the environment. They are based on a 'dilute and disperse' approach which spreads pollutants over a wide area but does not reduce the quantity of pollutant introduced into the environment. Pollution impacts are externalised to global commons such as the atmosphere and the ocean. Eventually it seems likely that these impacts will cease to be sustainable and will have consequences for ecosystems and humanity. Rachael Craufurd-Smith, a space and policy law expert at the University of Edinburgh, has pointed out that none of the international treaties governing the use of space consider environmental harm to the Earth's environment.[153] Likewise, existing international treaties protecting air quality and oceans do not address impacts from the space sector, which at the time they were drawn up was seen as having a minimal global impact.

In part, the problem results from the duplication of functions by satellites operated by different countries, companies, and scientific institutes. Increased co-operation and more open sharing of data could play a role in reducing the number of satellites placed into orbit. However, this is at odds with the current market-based approach to the space economy, and so 'technical fixes' have been proposed to address the problem of space debris rather than tackle its underlying causes.

It is not clear that mitigation and remedial measures for dealing with space debris will be adequate to tackle the problem. Lois Miraux has suggested that the sustainable carrying capacity of low Earth orbit – the maximum number of orbiting satellites that can be sustained in the long term – may already have been exceeded, because the space debris population is increasing even without additional launches.[154] The European Space Agency has concluded that "our current behaviour in space is unsustainable" and is working on the development of measures for orbital and space environment capacity.[155] In an academic paper published at the beginning of 2025 other researchers have proposed adding space sustainability to the UN's sustainable development goals to provide a co-operative framework for mitigating orbital debris. They advocate applying lessons learnt from addressing environmental concerns such as marine pollution to space debris, for example by implementing global treaties, fostering international cooperation, encouraging technological innovation, and adopting a waste hierarchy for space to promote reusability and recycling. "Key to achieving sustainability is treating Earth's orbit as a finite global commons, much like the ocean," they conclude.[156]

153 Tereza Pultarova: 'Could the next big environmental problem come from space?' Royal Aeronautical Society, 10 January 2025. https://www.aerosociety.com/news/could-the-next-big-environmental-problem-come-from-space/

154 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit.

155 'Space Environment Capacity'. European Space Policy Institute. ESPI Report 82, April 2022. https://www.espi.eu/wp-content/uploads/2022/06/ESPI-Report-82-Space-Environment-Capacity-Full-Report.pdf

156 Imogen Ellen Napper et al: 'A sustainable development goal for space: Applying lessons from marine debris to manage space debris'. One Earth, Vol 8(2), 21 February 2025. https://www.cell.com/one-earth/fulltext/S2590-3322(24)00598-0

5 Dark and quiet skies

The night skies have held significance for humans ever since the earliest days of prehistory. Archaeologists are now beginning to understand how ancient peoples carefully observed celestial phenomena as an intrinsic element of predicting the weather, seeking food, navigating, and tracking time. Celestial symbols decorate prehistoric pottery, jewellery, and art. One of the most famous archaeological finds linked to the night sky is the Nebra sky disc – a bronze disc estimated to be roughly 3,600 years old which was unearthed in Germany and shows symbols which many researchers identify as the sun, the crescent Moon, and stars – including a grouping that appears to be the Pleiades constellation (see Image 10).[157] The pristine night sky is part of a common heritage of humankind, with important cultural and religious roots and a close connection to people's sense of place. Indigenous cultures have deep cultural associations with the sky at night, which influences art, navigation, architecture, agricultural practices, and storytelling.[158] Light pollution of the night sky has the potential to erode and damage these cultural elements, and may also have adverse impacts on stargazing and scientific inquiry and unforeseen effects on wildlife and human health.

Satellites stand out like stars in the sky. Although it is difficult to differentiate their contribution from other anthropogenic sources and assess what their contribution to light pollution on the ground may be, large numbers of satellites will interfere with the appearance of constellations and star patterns. Artificial skyglow and the alteration of patterns of celestial bodies are likely to have a number of biological impacts, including providing false cues about time of day and season and changing the background illumination under which inter-species interactions, such as predator-prey relations, play out. They may also obscure or cause confusion over celestial reference points for local orientation and long-distance migration by species of insects, night-migrating birds and mammals. Such creatures have adapted navigational strategies based on a centre of celestial rotation, the Milky Way, or a lodestar. Many of these abilities are thought to have evolved by tracking moving objects, so the rapid movement of satellites across the night sky, rather than their brightness, may be a key factor disguising

157 Kata Karáth, Rachel Feltman, Madison Goldberg, Kelso Harper & Jeffery DelViscio: 'How Ancient Humans Interpreted the Cosmos'. Scientific American Science Quickly podcast, 1 August 2024. https://www.scientificamerican.com/podcast/episode/what-did-ancient-humans-think-when-they-looked-up-at-the-night-sky/

158 Jimena Pereira Paz, Kit Archibald, & Hannah Dalgleish: 'Access to an unpolluted night sky'. EASST Review, Volume 42(2) December 2023. https://easst.net/easst-review/42-2/access-to-an-unpolluted-night-sky/

Image 10. The Nebra Sky Disc – one of the most famous archaeological finds linked to the night sky
Credit: Frank Vincentz / Wikimedia

the influence of background stars.[159] The weight that large numbers of low Earth orbit satellites may have in disrupting these abilities is as yet unknown.

Looking to the future, American company Reflect Orbital has also proposed launching over 50,000 space-mirrors by 2035 to enable them to provide responsive lighting and 'sell sunlight' during the nigh time for solar energy generation. This is also likely to have serious effects for wildlife and astronomers.[160]

Large satellite constellations can reduce the visibility of the night sky by reflecting sunlight down to Earth and emitting radio signals which interfere with astronomical observations. Satellites in low Earth orbit, especially those with polished flat surfaces, can act as point sources reflecting and scattering sunlight when above the horizon and, because of their altitude, remain illuminated. The number of satellites which may be visible falls as the sun drops further below the horizon, and depends upon the time of night and time of the year. Modelling by Jonathan McDowell of the Harvard & Smithsonian Center for Astrophysics has shown that, for a megaconstellation of around 12,000 Starlink satellites, hundreds of satellites may be visible at once to naked-eye observers at dark sites at intermediate latitudes (45°–55°, covering much of Europe) at low elevations around twilight. At lower latitudes, where major observatories are mainly located, these satellites would not be illuminated for six hours in the middle of the night during winter.[161]

159 Kevin J Gaston, Karen Anderson, Jamie D Shutler, Robert JW Brewin, Xiaoyu Yan: 'Environmental impacts of increasing numbers of artificial space objects', op cit.

160 Drew Reagan: 'DarkSky International opposes Reflect Orbital's proposed orbital illumination system'. DarkSky International, 19 December 2025. https://darksky.org/news/organizational-statement-reflect-orbital/

161 Jonathan C. McDowell: 'The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation'. The Astrophysical Journal Letters, Vol 892(2). 6 April 2020. https://iopscience.iop.org/article/10.3847/2041-8213/ab8016

As satellites overfly a ground-based observatory they can interfere with observations and photography undertaken by astronomers. Following the launch of the first Starlink satellites astronomers reported satellite trails impairing the quality of images of the night sky, appearing as streaks across images which obscure information and block detail.[162] Light from satellites may also generate saturation effects which ruin the entire image, not just the portion behind the streak. A sudden flare of reflected sunlight from a satellite's flat surfaces can generate a brief but intense glint of light, causing a bright burst in an image. Even when a satellite does not reflect sunlight it may block the view of astronomical features behind it and confuse interpretation of the obscured space (see Image 11). There are concerns that up to 30 – 40 per cent of images from the new state-of-the-art Vera C. Rubin observatory in the remote Atacama Desert in northern Chile – a panoramic optical telescope which scans broad areas of the sky – may be unusable due to interference from overflying satellites.[163]

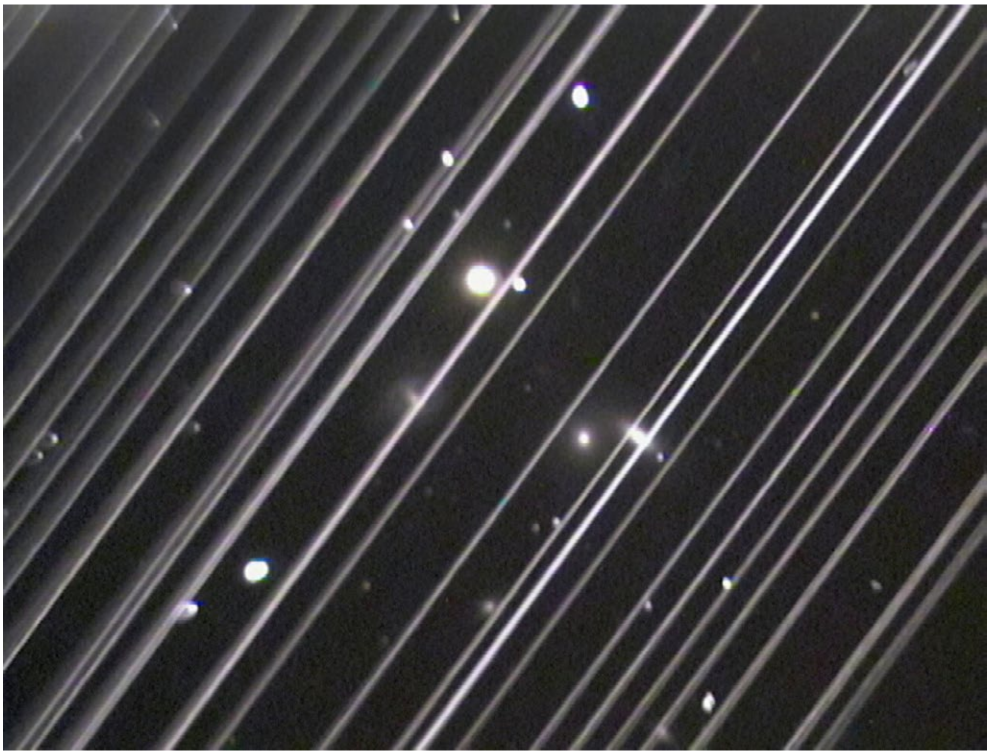


Image 11. An image of the NGC 5353/4 galaxy group made with a telescope at Lowell Observatory in Arizona, USA on the night of Saturday 25 May 2019. The diagonal lines running across the image are trails of reflected light left by more than 25 of the 60 recently launched Starlink satellites as they passed through the telescope's field of view. Although this image serves as an illustration of the impact of reflections from satellite constellations, please note that the density of these satellites is significantly higher in the days after launch (as seen here) and also that the satellites will diminish in brightness as they reach their final orbital altitude. **Credit:** Victoria Girgis/ Lowell Observatory

The proliferation of artificial objects in space is also contributing to a new general background brightness in the night sky which is cumulatively degrading the ability to detect faint, remote points of light. Kocifaj et al. (2021) have calculated that satellites and space debris are already responsible for a skyglow effect which increases the night sky brightness by approximately 10 per cent above natural levels. This is of concern to astronomers, as night sky brightness is already at a critical limit adopted the International Astronomical Union (IAU) for light pollution levels which should not be exceeded at observatories.[164]

162 Leonard David: 'Blinded by the light: How bad are satellite megaconstellations for astronomy?' Space.Com, 9 May 2024. https://www.space.com/satellite-megaconstellations-spacex-starlink-interference-astronomy

163 David A. Koplow: 'Blinded by the Light: Resolving the Conflict between Satellite Megaconstellations and Astronomy'. SSRN, 2 February 2023. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4346299

164 M Kocifaj, F Kundracik, J C Barentine, & S Bará: 'The proliferation of space objects is a rapidly increasing source of artificial night sky brightness'. Monthly Notices of the Royal Astronomical Society: Letters, Vol 504(1, p L40–L44. 29 March 2021. https://doi.org/10.1093/mnrasl/slab030

Satellites can be 'seen' across the electromagnetic spectrum, not just at visible light frequencies. At radio frequencies they appear particularly bright at the frequencies at which they actively transmit. When transmitting at maximum power they may effectively be more intense than the sun at their transmission frequencies. Satellites are also detectable outside assigned transmission frequency bands and generate a radio 'hum' detectable by radio telescopes. This 'leakage' of unintended electromagnetic radiation, caused by onboard electronic systems, can be detected at low frequencies at distances of up to 400 km away.[165] Impacts from satellites on radio telescopes are even more significant than on optical observatories. Radio telescopes receive signals over a wide range of frequencies to detect the "hidden universe" where the presence of dust and debris obscures optical light. They detect very faint signals from the most distant reaches of space and are highly vulnerable to anthropogenic noise. For this reason radio telescopes are often situated in remote areas and surrounded by radio quiet zones. However, they cannot be isolated from satellite overflight. Radio frequency uplinks, downlinks, and crosslinks between satellite networks and ground-based infrastructure pose major challenges to radio astronomy. Even unintended background leakage emissions can appear ten million times brighter than the dim astronomical sources radio astronomers are trying to detect.[166] A satellite downlink can generate major interference with data collection by a radio telescope and may saturate or blind the receiver. High powered synthetic aperture radar signals used by remote sensing satellites for Earth and climate observation can even burn out and damage or destroy the receiver. Astronomers from the IAU's working group on dark and quiet skies have concluded that this is "a time of unprecedented risk as the radio spectrum is exploited without adequate concern for the scientific enterprise".[167]

Some operators have made modest, voluntary efforts to mitigate the interference of their satellites with astronomical observations. SpaceX, for example, has made experimental modifications to some Starlink satellites to reduce their reflectivity and has undertaken not to downlink directly onto ground-based radio telescopes.[168] Impacts can be mitigated by altering satellite size, making satellites less reflective by giving surfaces a dark finish or sun shield, and / or modifying the satellite's orientation or orbit so it reflects less light. However, all of these approaches present difficulties for operators and so far solutions have not been widely implemented. Radio telescopes can be protected by rigid frequency allocation, requiring satellites to broadcast only on assigned wavelengths and preserving other channels for undisturbed sensitive astronomical collection. Other possible measures could include temporarily silencing a satellite or deflecting its transmitter when it is overflying an observatory's quiet zone during a sensitive observation period.[169] Astronomers recommend that their concerns are addressed early in the design of satellites, with engineers adopting a conscious goal of minimizing harm to optical and radio telescopes, if necessary using low-visibility military-standard stealth technology. However, most satellite constellations currently in development

165 M Peel, S Eggl, ML Rawls, H Qiu, & DL Clements: 'Understanding The Impact Of Satellites On Radio Astronomy Observations'. ArXiv.Org, 15 April 2025. https://arxiv.org/pdf/2504.11561

166 Daniel Clery: ''Worst nightmare': Elon Musk's Starlink satellites could blind radio telescopes'. Science, 18 September 2024. https://www.science.org/content/article/worst-nightmare-elon-musk-s-starlink-satellites-could-blind-radio-telescopes

167 David A. Koplow: 'Blinded by the Light: Resolving the Conflict between Satellite Megaconstellations and Astronomy', op cit.

168 Leonard David: 'Satellite megaconstellations are threatening astronomy. What can be done?' Space.Com, 4 May 2023. https://www.space.com/satellite-megaconstellations-astronomy-dark-skies

169 David A. Koplow: 'Blinded by the Light: Resolving the Conflict between Satellite Megaconstellations and Astronomy', op cit.

are brighter than recommended limits, and satellite designers have warned that they consider it very difficult, if not impossible, to meet the magnitude limit for brightness recommended by astronomers.[170]

With these concerns in mind, the IAU has reported to the United Nations Committee on the Peaceful Uses of Outer Space on the need to conserve "dark and quiet skies for science and society". Their study warned of the dangers posed by satellite constellations to ground-based astronomical observatories and stressed that the cumulative effects of satellite megaconstellations have not been adequately studied, providing a reminder that astronomical discoveries can only continue if the night sky remains clear and unpolluted. The IAU has petitioned UNCOPUOS for better protections for dark and radio-quiet skies.

The space industry has been operating on the basis that international laws allow it to do whatever it wants to in space, and that in the meantime astronomers will just have to adapt to the new circumstances. This means that the time and the cost of undertaking astronomical observations will rise considerably, and that opportunities to gather data will be lost, resulting in wider losses for science. However, astronomy is the oldest science known to humanity, and astronomers also have legal rights to the free use of space.[171] As a relatively new arrival, the space industry is disrupting long-standing customs and trespassing on the global commons of the night sky. The night sky is not solely the province of the space industry – it belongs to everyone and every species.

170 Jeff Foust: 'Satellite constellations fall short of meeting brightness goals'. Space News, 26 August 2025. https://spacenews.com/satellite-constellations-fall-short-of-meeting-brightness-goals/

171 Leonard David: 'Blinded by the light: How bad are satellite megaconstellations for astronomy?', op cit.

6 Space weather and the magnetosphere

Space weather is the state of the space environment between the Sun and the Earth. The Sun is continuously emitting a stream of charged particles known as the solar wind. It also has a strong magnetic field that extends to the outer regions of the solar system, which is known as the interplanetary magnetic field. The interplanetary magnetic field is carried towards the Earth by the solar wind where it interacts with the Earth's magnetic field, compressing it on the side facing the sun (the dayside), while drawing it out into a long wake on the opposite side (the nightside).

The region of the Earth's magnetic field is known as the magnetosphere and it acts as a 'magnetic shield', protecting the atmosphere and the Earth's surface from harmful radiation and maintaining conditions which allow life to continue on the surface. It begins several hundreds of kilometers above the Earth's surface and extends tens of thousands of kilometers into space. In contrast to Earth, Mars's magnetic field dissipated about 4.2 billion years ago, causing it to lose its magnetosphere. The solar wind is subsequently thought to have stripped away most of Mars' atmosphere, leaving it an uninhabitable world with a much thinner atmosphere than that of the Earth.[172]

Sometimes the solar wind blows extremely strongly as a result of increased solar activity. When the Sun ejects massive quantities of ionised gas (plasma) from extremely active regions, as in solar flares, the energetic particles and magnetic fields which are produced cause geomagnetic storms on Earth.

The Earth's magnetosphere is permeable and the solar wind will frequently connect with the magnetosphere, causing it to reconfigure and absorb incoming solar energy which results in explosive releases of energy during geomagnetic storms. These events can disrupt space systems, with potentially serious impacts on communications networks, GPS navigation, and electrical grids.[173]

The magnetosphere traps electrons and protons from the solar wind in two toroidal zones of energetic charged particles known as the inner and outer Van Allen radiation belts. Particles remain trapped in the radiation belts for an indefinite length of time, but electrons in the belts may be released into the Earth's atmosphere by the effects of solar storms and electromagnetic waves created by lightning strikes. generating an electromagnetic pulse which

172 'Earth's Magnetosphere'. NASA Science, 25 March 2018. https://science.nasa.gov/science-research/planetary-science/earths-magnetosphere/

173 Harry Baker: 'The next Carrington-level solar superstorm could wipe out 'all our satellites,' new simulations reveal'. Live Science, 30 October 2025. https://www.livescience.com/space/the-sun/the-next-carrington-level-solar-superstorm-could-wipe-out-all-our-satellites-new-simulations-reveal

propagates throughout the atmosphere. The electromagnetic waves travel from the atmosphere along the Earth's magnetic field to the inner radiation belt, where they free some of the trapped high energy electrons, generating a 'microburst' of high energy electrons. Electrons descend through the atmosphere, effectively creating an atmospheric electrical circuit between the ionosphere and the Earth's surface, a process that connects space weather, atmospheric physics and meteorology.

The high energy electron precipitation can also damage critical electronics on satellites in low earth orbit and also cause interference with communication transmissions. In addition, as they descend, electrons collide with nitrogen and oxygen molecules and ionise them. This results in the formation of nitrogen oxides, which act to destroy ozone in the stratosphere. Electron precipitation can lead to substantial short-term losses of ozone and also contributes to long term ozone depletion.[174]

Changes in the Earth's magnetic field caused by geomagnetic storms deliver larger than usual numbers of high-energy particles to the ionosphere, and may have biological impacts. Geomagnetic activity has been shown to be correlated with changes in the human cardio-vascular system and blood flow, blood biochemistry, clinical depression, suppression of synthesis of the hormone melatonin, and increases in morbidity and mortality rates.[175]

'Stratospheric loading' and the chemical impacts on the atmosphere resulting from the space industry are now beginning to be acknowledged, but there is also a possibility that deposition of metallic material originating from space hardware in the atmosphere may also be adding a 'magnetospheric loading' onto the planet. A theoretical analysis by Sierra Solter-Hunt of the University of Iceland raises the question of whether the accumulation of conductive, electrically charged material in the atmosphere could alter or weaken the magnetosphere.[176]

Solter-Hunt points out that the combined mass of all the charged particles in the Van Allen belts is estimated to be only 0.00018 kilograms. In contrast, the mass of a single Starlink satellite is around 1250 kilograms, which will eventually all become conductive particulate material during reentry and burn-up, and which will remain in the lower ionosphere for an indefinite time. In 2022 alone the space industry polluted the atmosphere with over 500 tons of particulate material from reentry and launches. This is approximately two billion times the mass of the Van Allen belts. Since the beginning of the space industry an estimated 20,000 tons of material has been deposited in the atmosphere: over 100 billion times greater than the quantity in the Van Allen belts. The space industry is adding enormous amounts of material to the magnetosphere in comparison to natural levels and because of the conductive nature of satellite residues and the massive disproportionality with natural levels of charged particles, Solter-Hunt postulates that this may perturb or change the magnetosphere. To date it has been assumed that the magnetosphere and Van Allen Belts are robust and durable, whereas in fact they may be more sensitive and delicate than suspected.

174 Kate Graham-Shaw: 'Lightning on Earth Knocks 'Killer Electrons' Loose in Orbit'. Scientific American, 2 December 2024. https://www.scientificamerican.com/article/lightning-on-earth-knocks-killer-electrons-loose-in-orbit/

175 James Close: 'Are stress responses to geomagnetic storms mediated by the cryptochrome compass system?' Proceedings of the Royal Society B, 279(1736) p2081–2090 . 14 March 2012. https://pmc.ncbi.nlm.nih.gov/articles/PMC3321722/
Ruslan M. Sarimov, Dmitry A. Serov, and Sergey V. Gudkov: 'Biological Effects of Magnetic Storms and ELF Magnetic Fields'. Biology 2023 12(12), p1506. 8 December 2023. https://www.mdpi.com/2079-7737/12/12/1506

176 S. Solter-Hunt: 'Potential Perturbation of the Ionosphere by Megaconstellations and Corresponding Artificial Re-entry Plasma Dust'. ArXiv, 6 December 2023. https://arxiv.org/abs/2312.09329

In support of her hypothesis Solter-Hunt cites a NASA model of the upper atmosphere which shows a sharp increase in the electron Debye length in the 'ablation zone' in the lower ionosphere, where satellites burn up on deorbiting. The Debye length indicates the distance over which the electrostatic effects of a charge persist before becoming neutralised by other charges in the environment. An increase in the Debye length means that the influence of a charged particle extends further, meaning that the electric field caused by charged particles in the ablation zone can be felt at a greater distance away. The potential consequences of this are as yet unknown, but there is a risk that the charged particles could interfere with the electronic systems of new satellites. More significantly, there is also a possibility that the much higher-density charged particles from satellite burn-up may disrupt the Van Allen belts. The Earth's magnetic field may be shielded by the conductive layer resulting from satellite debris, possibly compromising the magnetosphere and reducing the protection it provides from solar radiation.

Solter-Hunt's analysis is based on simplistic assumptions, and other analysts have pointed out that there are uncertainties around how charged particles from space debris will become distributed in the atmosphere, the quantities of particles deposited, and the degree of magnetic shielding that may result from their presence. Nevertheless, there seems to be a broad body of scientific opinion that the effects of metal pollution in the atmosphere cannot be ignored and that research is urgently needed to increase understanding of the phenomenon.[177]

177 Harry Baker: 'Controversial paper claims satellite 'megaconstellations' like SpaceX's could weaken Earth's magnetic field and cause 'atmospheric stripping.' Should we be worried?' Live Science, 13 March 2024. https://www.livescience.com/space/space-exploration/controversial-paper-claims-satellite-megaconstellations-like-spacexs-could-weaken-earths-magnetic-field-and-cause-atmospheric-stripping-should-we-be-worried

7 Reversing the trends

The previous sections of the report have shown that, although the environmental impacts of the space industry have traditionally been considered to be negligible, they are rapidly increasing as the sector expands. For some parameters, such as space debris, impacts are already unsustainable, and others may be approaching critical thresholds. Our knowledge of the impacts of the space sector on the atmosphere is uncertain and limited, and further research is urgently needed to establish how human activity may affect it.

This section of the report looks at ways in which the environmental impacts of the space sector can be better understood and controlled with the aim of ensuring that they do not erode the stability and resilience of the Earth's ecosystem. It identifies a number of approaches which industry, government, and citizens could take to address the growing environmental impacts of the space sector and makes recommendations for action by the UK government, its agencies, and others.

7.1 Planetary boundaries

The concept of planetary boundaries was first proposed in 2009 by a group of internationally renowned scientists led by Johan Rockström. Planetary boundaries set quantitive safe limits for human pressure on critical environmental processes which affect how global systems function.[178] Together, they serve as critical thresholds which define a 'safe operating space' for humanity. Crossing these environmental limits increases the risk of causing large-scale irreversible environmental changes. The boundaries are interconnected, meaning that changes to one process will affect other processes. Nine fundamental planetary boundaries have been identified, and according to assessments made in 2025 seven of these have now been breached.[179]

Of the nine planetary boundaries, three relate directly to the atmosphere and are subject to the impact of the space industry. As the previous sections of this report explain, climate change, stratospheric ozone depletion, and atmospheric aerosol loading are all influenced by pollution caused by rocket launches and the burn-up of satellites and space debris. The climate change planetary boundary

178 'Planetary boundaries'. Stockholm Resilience Centre, Stockholm University. https://www.stockholmresilience.org/research/planetary-boundaries.html

179 Boris Sakschewski & Levke Caesar:'Planetary Health Check 2025: A Scientific Assessment of the State of the Planet'. Potsdam Institute For Climate Impact Research, 2025. https://publications.pik-potsdam.de/rest/items/item_32589_5/component/file_33151/content

has been passed and carbon dioxide concentrations are increasing, resulting in rising global temperatures and altered climate patterns. Thinning of the ozone layers as a result of human-made chemicals is slowly recovering because of the phase out of ozone-depleting substances since the 1980s, and ozone depletion is currently within a safe operating space. Atmospheric aerosol loading, which can influence the climate by altering temperature and precipitation patterns, is currently just inside a safe operating space.[180]

Lois Miraux has suggested that the concept of planetary boundaries could be extended to cover the proliferation of objects in orbit and night sky brightness to encourage action to keep these measures within sustainable limits.[181] The limits are intertwined: for example, satellite debris is likely to contribute more to night sky brightness than an intact satellite because it has a greater total reflective surface area. As well as compromising the global commons of Earth's orbit, space debris could also aggravate night sky pollution. Inter-relations between environmental limits may also complicate efforts to tackle problems: for example, efforts to reduce the impact of space debris by allowing it to reenter the atmosphere and burn up will increase pollution impacts on atmospheric chemistry.

At present it is not possible to set quantitative planetary boundaries for space debris and night sky brightness because of gaps in scientific knowledge about the environmental effects of these factors and the pathways through which they cause impacts. For example, different pollutants have different impacts at different altitudes in the atmosphere and have different effects in the troposphere and the stratosphere. As well as being necessary to undertake sustainability assessments, this kind of knowledge is necessary to guide the future design of launch systems and space hardware.

The European Space Agency has adopted a similar method to the planetary boundaries approach by establishing an annual health index for the space environment. The index is based on the impacts of space debris and will be reported each year in the Agency's Space Environment Report. It combines a number of variables into a single score assessing the impact of space debris on orbital sustainability, like an energy efficiency rating for household electrical appliances. The ESA intend the index to be used to help assess the risk that a future mission will create space debris, and to guide policy. It can be used as a design target and applied by industry during space mission design to minimise environmental impacts, and also by licensing authorities and insurance companies to allow them to ensure new missions comply with sustainability thresholds.[182]

The ESA's Space Environment Health Index was published for the first time in 2025. A value of 1 represents the proposed threshold for long term orbital sustainability. According to the ESA "the alarm is sounding": the current score is health index level 4, which the ESA describes as "far beyond the sustainability threshold".[183]

180 Boris Sakschewski & Levke Caesar:'Planetary Health Check 2025: A Scientific Assessment of the State of the Planet', op cit.

181 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit

182 'Sounding the alarm: ESA introduces space environment 'health index''. European Space Agency, 22 October 2025. https://www.esa.int/Space_Safety/Space_Debris/Sounding_the_alarm_ESA_introduces_space_environment_health_index

183 'Sounding the alarm: ESA introduces space environment 'health index''. European Space Agency, op cit.

Miraux points out that, whereas up until now it has generally been assumed that the development of the space sector will be constrained by only technological or economic factors, in future environmental sustainability will be a limiting factor in the development of space activities. The conventional vision that the sector will continue to expand, and even that humanity will inevitably conquer space and become a multi-planetary species, is challenged by the physical realities of planetary and orbital boundaries.[184]

Recommendations

The Department of Science, Innovation, and Technology and the UK Space Agency, working through the European Space Agency, should continue to fund research into the broader environmental impacts of the space sector, and particularly the atmospheric and climate impacts of metal residues from satellite burn up and combustion products from rocket launch.

The Department of Science, Innovation, and Technology and the UK Space Agency, working through the European Space Agency and other international institutions, should rapidly develop planetary boundaries for the proliferation of objects in orbit and night sky brightness, and press for the global use of planetary boundaries as a tool for regulating the impacts of the space industry.

The Civil Aviation Authority should require compliance with ESA Space Environment Health Index standards as a condition of licensing for orbital operators.

7.2 Regulation of the space sector

The Committee on the Peaceful Uses of Outer Space (COPUOS) was set up by the UN General Assembly in 1959 to govern the exploration and use of space for the benefit of all humanity: for peace, security and development. The Committee led negotiations over the five outer space treaties that govern the international space regime (Image 12) and meets regularly to consider civil and commercial space issues.

Image 12. Principal treaties governing the international space regime

The Outer Space Treaty (1967)

The Agreement on the Rescue of Astronauts (1968)

The Liability Convention (1972)

The Registration Convention (1975)

The Moon Agreement (1979)[185]

184 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit
Loïs Miraux, Andrew Ross Wilson, & Guillermo J. Dominguez Calabuig: "Environmental sustainability of future proposed space activities". Acta Astronautica Vol 200 p329-346. November 2022. https://pureportal.strath.ac.uk/en/publications/environmental-sustainability-of-future-proposed-space-activities/

185 "Space Law Treaties and Principles". United Nations Office for Outer Space Affairs. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties.html

These treaties were all formulated between 1967 and 1979 and reflect the ethos and Cold War political balance of the time. The most important of these, the Outer Space Treaty, was negotiated nearly 60 years ago at a time when only the USSR, the USA, and France had launched satellites into space. Since the 1990s the number and type of nations and organisations with space programmes has become increasingly broad and complex. The private sector has become a key player in space, and competition between both nations and private enterprises is now a major element in the political geography of space. While the Outer Space Treaty's principles – particularly the principle that all activities in outer space by States must comply with international law – remain relevant and of great importance, the treaty lacks concrete rules and standards and does not address critical issues relating to the current political landscape relating to space. Since the end of the Cold War few new international rules or guidelines have been established to regulate conduct in space. Those that have been introduced are voluntary in nature, resulting in inconsistent compliance and no enforcement. There is currently less of a consensus than there once was about the rules and norms governing space, and wealthy countries and corporations are now seeking to rewrite international law to their advantage, undermining the neutrality of space and privatising its resources.[186]

The Outer Space Treaty recognises outer space as a global commons to be used for peaceful purposes, stating that: "the exploration and use of outer space shall be carried out for the benefit and in the interests of all countries and shall be the province of all [hu]mankind." This element of the treaty was an attempt to prevent colonial-style acquisition and exploitation of space, establishing outer space as a neutral and demilitarised zone belonging to no one and everyone and providing space with protections under international law. As we have seen, commercial and military competition, self-interest, and a lack of regulation are rapidly leading to a 'tragedy of the commons' as low Earth orbits, atmospheric stability, and night sky brightness become degraded as a result of the rapid expansion of the space sector. At present there is a serious governance and collective action problem, and existing treaties need to be supported and new measures need to be developed to address this if space is to remain a global commons.

There is international recognition of the need for greater regulation of space. Achieving consensus on the way forward, however, will be a considerable challenge. International politics and the poor current state of international relations between the major global powers are reflected in discussions at the United Nations over space issues. Whereas the US and its allies advocate the development of codes of conduct to control behaviour in space, China and Russia support an approach based around formal treaties. As Parliamentary researcher Claire Mills observes, "there is a perceived preference, on all sides, for regulation that promotes freedom of their own action, while curtailing the activities and aspirations of others".[187]

The US, China, and Russia have all announced intentions to establish permanent lunar bases and nuclear reactors on the Moon by 2030, while various private corporations hope to settle on Mars, and build orbital data centres, manufacturing facilities, and space settlements. Protections under the Outer Space Treaty and related agreements are being increasingly eroded by

186 Dave Webb and Peter Burt: "For Heaven's Sake – Examining the UK's Militarisation of Space". Drone Wars UK and Campaign for Nuclear Disarmament. 9 June 2022. https://dronewars.net/wp-content/uploads/2022/06/For-Heavens-Sake-long.pdf

187 Claire Mills: 'The militarisation of space'. House of Commons Library, 14 June 2021. P12-13. https://researchbriefings.files.parliament.uk/documents/CBP-9261/CBP-9261.pdf

corporate interests and powerful nations, who wish to dismantle one of the last remaining commons of humanity and apply the structures of private ownership and capitalism that currently exist on Earth to outer space. These interests are attempting to reinterpret sections of the Outer Space Treaty that prevent appropriation of space resources and land.

Durham University's Carla Ibled has analysed and documented the space industry's attack on international space legislation, which she describes as a "co-ordinated effort to reinterpret international space law in favour of the private sector".[188] As an example she describes how the space industry, and notably corporate interests in the US, "targeted" the Moon Agreement because of its "progressive (and revolutionary) stance". The Moon Agreement defines the Moon as the "heritage of all (hu)mankind" and calls for the exploration of the Moon to "be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development". It mandates an international regime to manage and redistribute the Moon's resources among all countries and effectively places all activities on the Moon under the jurisdiction of international law, including the United Nations Charter. Lobbyists in favour of space colonisation successfully campaigned to prevent the US from signing the treaty, and other space-faring nations have followed this lead. Only 17 states are currently parties to the treaty, giving it little practical relevancy to international law.

Right-wing think tanks which have been active on space issues, such as the Reason Foundation, the Competitive Enterprise Institute, and the Cato Institute, are strongly in favour of private property rights and hostile to the principles of common ownership and redistribution of resources. They are therefore ideologically opposed to the principles which underpin the Outer Space Treaty and support the granting of exclusive property rights to space entrepreneurs. In the UK both the Westminster and Scottish Governments are keen to develop the space sector and attract investment in space-related projects. Elected representatives in both the UK and Scottish Parliaments often seem to be more interested in advocating for the sector rather than scrutinising its activities. The UK 2024 Space Regulatory Review was drafted after consultation with the space industry and suggests adapting licencing regulations to the needs of the industry via the use of innovative regulatory tools. Libertarian think tanks such as the Adam Smith Institute, the Institute of Economic Affairs, Policy Exchange, and the Centre for Policy Studies have all supported policies to promote the privatisation and commercialisation of space.[189]

The US government has led the drive to transfer space resources into private hands and is seeking to impose its interpretation of the Outer Space Treaty and property rights on international customary law. This interpretation is central to the Artemis Accords, a set of agreements between the United States government and other governments that set out norms for conduct in outer space and for the exploration and use of the Moon and Mars. The Accords were drafted by the US Department of State and NASA and are related to the US-led Artemis programme, which aims to reestablish a human presence on the Moon and set up a permanent base on the Moon. The Artemis Accords were first signed in 2020 by a group of eight states, led by the US and including the UK. At the time of writing 60 nations have signed the Accords.

188 Carla Ibled: "Star Wars: Why the Left Should Protect the Status of Space as Humanity's Commons". Common Wealth, 24 April 2025. https://www.common-wealth.org/publications/star-wars-why-the-left-should-protect-the-status-of-space-as-humanitys-commons

189 Carla Ibled: "Star Wars: Why the Left Should Protect the Status of Space as Humanity's Commons", op cit.

Participation with NASA and involvement in US space programmes is conditional upon collaborating states signing up to the principles set forth in the Artemis Accords.

The Artemis Accords are controversial because they guarantee a right to extract resources such as minerals and water, which the US maintains does not inherently constitute "national appropriation" – forbidden under the terms of the Outer Space Treaty. The US argues that resources, which can be extracted and appropriated, are not the same as territory. The Artemis Accords also sanction the creation of zones of non-interference and exclusion around operational areas where, for example, mining or military activities may be taking place. Critics argue that they are intended to protect the interests of the United States in pursuing the appropriation of the Moon's natural resources, and say that if the US wishes to negotiate on space mining, it should do this through the United Nations treaty process. If adopted by enough nations the interpretation of the Outer Space Treaty which is presented in the Artemis Accords would prevail. This would effectively result in the historical, treaty-based approach to the regulation of activities in space being supplanted by an informal and looser, non-prescriptive approach to space governance.[190]

If efforts to rewrite international law succeed, space resources will be attributed on a first come, first served basis. This will favour wealthy nations like the US and billionaires who already operate advanced space programmes. Resources currently held in common will be transferred into the hands of just a few individuals, with predictable consequences: the expansion of corporate power, deepening inequality among citizens on Earth, and export of the ransacking of the environment into space.

Potential regulation of atmospheric pollution also faces hurdles. Lois Miraux points out that space technologies are characterised by long life cycles from the design to exploitation phase. Decisions critical for the environmental performance of a system are made at the early stages of product development and may be impossible to change at a later stage. To maximise returns on investment, technologies remain in service for as long as possible. The Ariane 5 launcher remained in service for 27 years and if this trend is maintained, launchers under development today are likely to still be operating in the 2050s. This means that, should regulation of pollution of the stratosphere with black carbon be introduced before then, launch systems could become obsolete much earlier than their planned end of service date. This could result in significant losses for operators, who could be expected to strongly resist such regulation.[191]

While technological solutions like in-orbit servicing and green propellants offer the prospect of some improvement, stronger international regulations are needed to prevent irreversible atmospheric damage. Existing treaties need to be supported and new instruments need to be developed to prevent the further deterioration of space commons and protect them from encroachment. However, powerful interests are opposed to such measures and are actively working to dismantle existing protections. Urgent and forceful action is needed from civil society and progressive governments if this trend is to be reversed.

190 Rossana Deplano: 'The Artemis Accords: Evolution or Revolution in International Space Law?' International & Comparative Law Quarterly, Vol 70(3) p799-819. 15 June 2021. https://doi.org/10.1017/S0020589321000142

191 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit

Recommendations

The UK government should restate its commitment to the position that space is a global commons to be used for peaceful purposes. It should develop policy opposing the extension of private property rights into space and clearly articulate this policy during discussions on space issues at the United Nations.

The UK government should continue to find ways to further discussions and agreement on the creation of treaties and agreements that set international norms and principles for responsible behaviour in outer space through participation in UNCOPUOS and other international bodies.

International non-government civil society organisations with an interest in peace, disarmament, and the environment should, where possible, seek representation as observer organisations at the UN Committee on the Peaceful Uses of Outer Space and should advocate in favour of regulatory instruments to protect the global commons of space.

International non-government civil society organisations with an interest in peace, disarmament, and the environment should open a wider public debate on whether, and if so, how space can be explored in ways that guarantee shared prosperity and conserve the space environment.

7.3 An ethical approach to space policy

Weaknesses in the international legal framework governing space and the blockages which are preventing space law from being updated to meet modern needs suggest that a fresh approach is needed to deal with shortfalls in space governance. Efforts to build a consensus among scientists and policymakers on a responsible, ethical approach to space issues may have a role to play in moving things forward.[192]

As yet there has been little international discussion and limited agreement on what constitutes responsible behaviour with regards to humanity's presence in space, and the field of space ethics is in its infancy. Further work is needed in these fields to set out 'ground rules' before the commercial exploitation of space results in significant environmental harm.[193] Such ground rules might, for example, limit launches to those which:

- Minimise adverse effects on health and the environment.
- Solve problems and satisfy needs in a sustainable way.
- Strengthen cooperation rather than duplicate for competition.
- Avoid the possibility of catastrophic effects.

An important principle in this respect is the 'precautionary principle', adopted by the 1992 Rio Declaration on Environment and Development and incorporated into several treaties and international agreements. The precautionary principle encourages pro-active action to protect the environment in the face of uncertainty, and states that where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

192 Dave Webb and Peter Burt: "For Heaven's Sake – Examining the UK's Militarisation of Space". Drone Wars UK and Campaign for Nuclear Disarmament, op cit.

193 Institutes working on the application of space ethics include: Northeastern University Ethics Institute: https://cssh.northeastern.edu/ethics/space-ethics-and-diplomacy/
Open University Space Ethics Research Group: https://fass.open.ac.uk/research/groups/space-ethics
Palestine Space Institute: https://www.palestinespace.org/

Until we know more about the environmental effects of space programmes, it would appear prudent to adopt a precautionary approach.

Key questions underlying decisions to invest in space programmes have important ethical implications. Problems on Earth which pose existential threats to human society, such as poverty and the division of wealth, climate change, and loss of biodiversity, require urgent solutions and major changes in political and economic systems. Commercial space projects are in many ways the antithesis of measures which might help tackle such problems. Rather than bring benefits across society and provide solutions to intractable problems, commercial space projects generate profits for wealthy elites and result in unknown harms to the environment. The significant environmental and economic impacts of some proposed space projects, particularly space colonisation and rocket-based point-to-point travel on Earth, could not only be prohibitively high but could also become increasingly ethically questionable and socially unacceptable (see case study 3 above).[194]

For reasons outlined in the previous section, direct appeals to governments and corporations pursuing space programmes and international measures to regulate the space sector are unlikely to bear fruit in the short term. An increased focus on space ethics from civil society, media, and citizens may help to create a climate where negotiation on space governance can take place, and act as a pragmatic first step in an incremental process to create new legal instruments to protect the space environment. An ethical approach to technology development and the responsible use of space can act as a 'moral compass' in the absence of regulation and serve as a foundation for developing new law and policy.

An ethical path to considering space issues will require activities such as the following:

- Education and public awareness-raising initiatives, with a particular focus on policy makers and STEM students who will form the next generation of space practitioners.
- Adoption of ethical guardrails and codes of practice for the responsible use of space and development of technology by institutions working in the sector.
- Public-facing campaigns for action on critical issues.

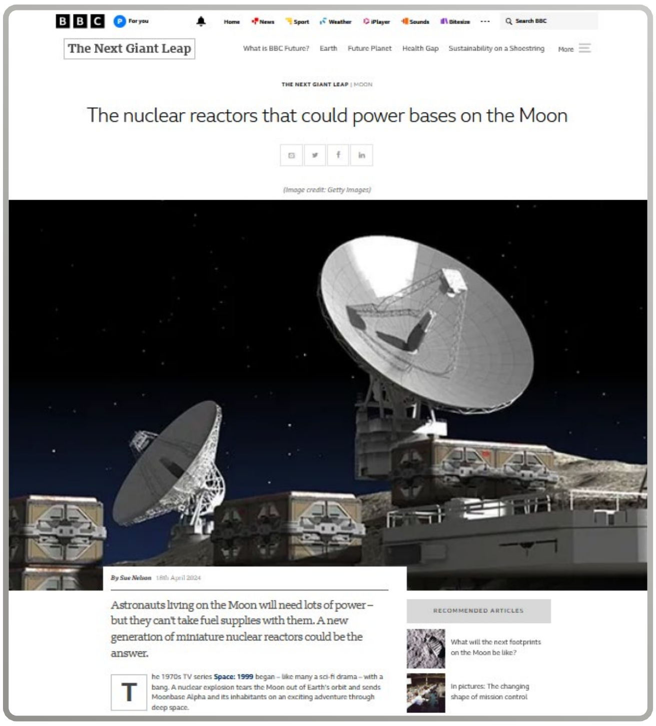
Diplomacy through dialogue over science is a recognised means of achieving diplomatic and political objectives.[195] Science diplomacy has a role to play in the development of ethical principles for the use of space, and also in identifying areas for international co-operation – for example, over the International Space Station programme – which may act as foundations for discussion of more significant matters. Scientists have advocated publicly for improved environmental review and regulation of satellite megaconstellations (see section 7.7 below) and have been key movers in the development of codes of conduct for responsible behaviour in space.[196]

194 Loïs Miraux: 'Environmental limits to the space sector's growth', op cit.

195 Royal Society: 'Science diplomacy in an era of disruption'. https://royalsociety.org/about-us/what-we-do/international/science-diplomacy/

196 Lucas Gutterman and Stephanie Markowitz: '120 top astronomy researchers call on FCC to study satellite mega-constellations'. Public Interest Research Group, 23 October 2024. https://pirg.org/articles/120-top-astronomy-researchers-call-on-fcc-to-study-satellite-mega-constellations-spacexs-starlink/

Ethical scrutiny and challenge requires an educated public that recognises our dependence on the natural world and is willing to support measures to conserve natural resources and global commons. Raising the profile of space ethics among citizens will require greater investment in scientific literacy among the public. STEM education currently very much serves national economic and military interests, with a focus on technical content and little or no discussion of broader political and ethical contexts in which science and technology is applied. This actively serves the space sector, not only by producing personnel with skills required in the sector but by promoting 'desirable conduct' and neoliberal mindsets, helping to manage resistance to space developments regardless of harms they may cause.[197]



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THE NEXT GIANT LEAP | MOON

The nuclear reactors that could power bases on the Moon

(Image credit: Getty Images)

By Sue Nelson 18th April 2024

Astronauts living on the Moon will need lots of power – but they can't take fuel supplies with them. A new generation of miniature nuclear reactors could be the answer.

The 1970s TV series Space: 1999 began – like many a sci-fi drama – with a bang. A nuclear explosion tears the Moon out of Earth's orbit and sends Moonbase Alpha and its inhabitants on an exciting adventure through deep space.

RECOMMENDED ARTICLES

What will the next footprints on the Moon be like?

In pictures: The changing shape of mission control

Image 13. Mainstream reporting of space issues can sometimes be based around industry publicity rather than an objective approach which considers ethical issues.

At the present time the public is largely unaware of our dependence on space. After conducting a global survey on public attitudes to space in 2022, satellite telecommunications company Inmarsat concluded: "It's clear that people have a low understanding of the breadth and richness of the work being done in space today. Perhaps because the technology deployed is essentially invisible, people do not appear to understand the role space is already playing in their everyday lives, nor its potential to deliver a brighter future for our planet." Science education is not currently positioned to address this deficit. One way forward could be to emphasise 'space literacy' in STEM education, addressing questions such as 'how does human activity in space threaten this limited natural resource?' and 'how does society make informed decisions about our use of space resources?'[198]

Likewise, science and technology journalists have an important role to play in awareness-raising on space issues. Regrettably, science reporting in the mainstream media seldom looks beyond technological and policy angles when covering a space news story. At best reports tend to be based on an underlying narrative that space is an infinite resource waiting to be exploited by humans, and there is rarely meaningful coverage of ethical or environmental issues relating to space. At its worst, space writing can be little more than the regurgitation of corporate or government propaganda (see Image 13).[199] A more critical approach to space reporting by science journalists would help encourage public debate over space policy and could help raise awareness about the environmental impacts of space programmes – and add to pressure to control such impacts.

197 Peter Howson: 'STEM Wars: Winning hearts and minds for private sector 'NewSpace' industries'. Space Policy, V74 November 2025, 101703. https://www.sciencedirect.com/science/article/pii/S026596462500027X

198 Beverly B. Bachelder and Robert S. Bachelder: 'Space literacy: Environmental education for a spacefaring civilization'. Space Review, 24 February 2025. https://www.thespacereview.com/article/4942/1

199 Peter Burt: 'BBC News: Supposed factual reporting on space colonisation is regurgitation of corporate propaganda'. Space Watch UK. https://spacewatch.uk/bbc-science-fiction-supposedly-factual-reporting-on-space-colonisation-is-merely-the-regurgitation-of-corporate-propaganda/

Recommendations

The UK government should continue to support diplomatic initiatives to develop international codes of practice for the responsible use of space and the responsible development of space technology, as a step on the way to developing new international space laws. A number of draft and regional codes have already been proposed.[200]

The Department of Science, Innovation, and Technology, UK Space Agency, and the Ministry of Defence should develop and implement an ethical code of conduct to govern UK space policy and the activities of UK actors in the space sector. There should be wide consultation with the public and interested stakeholders, including civil society, in developing such a code. Funding support should only be provided to activities which are sustainable and comply with ethical guardrails.

Space operators should undertake a formal ethical assessment at an early stage as part of the development of space projects, with external scrutiny and input from affected communities and outside experts.

University and school educators and civil society should emphasise the importance of broader ethical factors in science and engineering and move away from an approach which stresses technology development and business enterprise at the expense of ethics.

Journalists and science writers should play their part in opening a wider public debate on space ethics. This should include helping the public to look critically at policy decisions, and critiquing whether and how space can be developed in sustainable ways to bring about shared prosperity and scientific knowledge.

Policy makers and politicians should scrutinise space policy in greater detail and examine the ethical and environmental aspects of policy, rather than focus on economic and technical factors.

Case study 4 The ethics of space colonisation[201]

The colonisation of space is usually presented as the inevitable next stage in humanity's 'journey' as part of a romantic technological narrative about humankind's urge to explore and innovate. Journalists and commentators writing on space rarely present colonisation as anything other than beneficial for humankind and a goal which will eventually be within our technological grasp. This optimistic mindset exists throughout the space sector, and one of NASA's official goals is the eventual establishment of a human settlement on Mars.[202]

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200 For example:
'Draft International Code of Conduct for Outer Space Activities'. European Union, 31 March 2014. https://www.eeas.europa.eu/sites/default/files/space_code_conduct_draft_vers_31-march-2014_en.pdf
'Responsible use of outer space. Conference room paper by the Space Generation Advisory Council'. Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee. Document A/AC.105/C.1/2025/CRP.15, 3 February 2025. https://www.unoosa.org/res/oosadoc/data/documents/2025/aac_105c_12025crp/aac_105c_12025crp_15_0_html/AC105_C1_2025_CRP15E.pdf

201 This case study draws on material and ideas from the following articles:
Nakul Malik: 'Space Colonization and Why Humanity is Better Off Not Pursuing It'. Viterbi Conversations in Ethics, 11 November 2024. https://vce.usc.edu/volume-7-issue-3/space-colonization-and-why-humanity-is-better-off-not-pursuing-it/
Victoria Michael: 'The Ethics of Escape: Should Humanists Support Space Colonization?' The Humanist, 2 June 2025. https://thehumanist.com/news/science/the-ethics-of-escape-should-humanists-support-space-colonization
Julia Sullivan: 'Ethics of Space Colonization'. Blue Marble Space Institute of Science, October 12, 2016. https://bmsis.org/ethics-of-space-colonization/

202 'Mars'. NASA. https://www.nasa.gov/humans-in-space/humans-to-mars/

Reflection on fundamental questions about the need for and benefits of space colonisation is seldom found in government policy on space or in mainstream media coverage of space issues. Yet such a project would significantly affect humanity as a whole, meaning that space colonisation is not merely a technical or scientific challenge but also a complex ethical project demanding caution, responsibility, and wisdom.

The first central question about space colonisation is why we would wish to undertake such an immense project in the first place. To be viable in terms of utilitarian philosophy and conventional economics, the benefits of space colonisation would need to outweigh its massive costs. This could result from the export of valuable materials or information back to Earth, or increases in standards of living from employment in space projects. Alternatively, the need to ensure the survival of humanity in the face of looming catastrophic environmental crises might be considered by some to be adequate justification for establishing colonies on other planets.

Further difficult questions are already emerging. Who will front the vast costs of bringing materials back to Earth from space, and how will the benefits from this activity be distributed? Would investment in projects on Earth surely not bring greater returns than risky space projects? Who would make decisions on these matters? The time frame necessary for tackling runaway climate change is likely to be far less than the time it will take to develop a viable settlement on another planet. A utilitarian approach would therefore suggest that resources should be used to tackle problems on Earth rather than pursue the goal of settling on another planet.

A second important question is who would get to colonise space? Would they have to carry the costs of the mission? How would they be selected, and by whom? What will happen to those who remain on Earth? Apart from the obvious risks of trying to settle in a remote and inhospitable world there are major uncertainties about the potential health impacts of permanent settlement in space. Should people be allowed to face such risks, and what mutual obligations should those who remain on Earth and those who venture into space have to each other?

Advocates for space colonisation generally assume that settlements would be established on a lifeless planet which would be developed to support human life, with the Moon and then Mars being the first destinations for colonisation. Although there is currently no life in these locations there is the potential that life may eventually develop there. There is a strong ethical case that barren lands should be left as they are, and that humans should not change anything beyond our immediate environment. This would not be the case if the purpose of space colonisation is to extract resources, for example by mining, for return to Earth. The proposed use of nuclear power, generating long-life hazardous wastes, to provide energy for space travel and space settlements poses further risks for the environment on host planets. There are also biological risks associated with dealing with unknown habitats, with unknown consequences if new life-forms are introduced into a new environment. Microorganisms from Earth could potentially grow at a rapid rate in a new habitat if inadvertently introduced by humans, with potential to irreversibly change the local environment.

Many of these questions are easily answered – although not resolved in practical terms – if space resources are treated as private property and the first come, first served approach is applied to their ownership. This is precisely what billionaire advocates of space colonisation and their supporters in the US government envisage, despite the concept of the 'common heritage of humankind' which is enshrined in space law. Space colonisation projects will in principle be no different to any other venture capital project, with speculators funding the costs and reaping the rewards by claiming ownership of the sites they control. Key decisions would be made by project funders alone – most likely on the basis of economics rather than ethics. Vast resources would end up in the hands of just a few of the wealthiest individuals and companies supported by their respective governments, with no interest in a fair international order or distribution of wealth.

Problems could be expected to arise if private corporations or nations were eventually to colonize the Moon or Mars and lay claim to its resources. In the absence of an accepted legal framework it is hard to imagine a future without political, and possibly even armed conflict over who owns what. State authority in space would weaken further, and settlements themselves would be beyond laws as we understand them, most likely governed by codes and regulations imposed by corporate employers rather than rights and legal protections for citizens under constitutional law. This should be a concern for all who value human dignity and democratic principles.

The space economy, and the push to colonise the Moon and Mars, is dominated by corporate and national powers competing for wealth, prestige, and control over space resources. These powers are motivated entirely by their own interests, and are not acting in the broader interests of humanity. Terms often used when discussing space colonisation, such as 'conquest', 'pioneering', 'claiming the wilderness', and 'progress' disguise programmes for extraction and exploitation. Such language also sidelines human values such as collectivity, pluralism, and cultural continuity. The history of colonialisation on Earth should set alarm bells ringing about ethical hazards and should warn us of the dangers of exploitation, injustice, and expropriation.

Humankind's behaviour and treatment of the environment on Earth suggests that, generally, humans cannot be trusted to colonise other planets without harming them. Before seeking to move into space, humanity should first focus on stewarding Earth's natural resources responsibly and sustainably. Without such an approach, space colonisation is exposed as no more than the goal of exploiting other worlds while abandoning the planet humanity has already wrecked. Unleashed to travel through space, humanity could become the celestial equivalent of a virus that jumps from planet to planet, destroying habitats one at a time.

During the 1950s fears of competing Cold War territorial claims on Antarctica caused major powers to refrain from making their own claims on the continent, and eventually led to negotiation of the Antarctic Treaty and other related treaties. These treaties provide a framework which regulates behaviour and international relations on Antarctica, protecting the continent's environment and designating it as a scientific preserve. Such arrangements, alongside existing space law and treaties, could act as a model to regulate any future settlement on the Moon or Mars.

However, there is a long, long, way to go before humans are ready to start thinking about settling beyond the Earth. In his book 'Brief Answers To The Big Questions' physicist Steven Hawking wrote: "The exploration of space is a fundamental aspect of human nature, and it has the potential to inspire and educate people around the world, but we need to be careful and responsible in our actions".[203] To date humanity's approach to space has been conspicuously lacking in care and responsibility.

203 Stephen Hawking: 'Brief Answers To The Big Questions'. Hodder and Stoughton, 2018.

7.4 Decoupling space from the military

Space technologies were originally developed not for the collective benefit of humankind but for military purposes during World War 2 and its immediate aftermath as the Cold War commenced. As Bleddyn Bowen, Associate Professor of Astrophysics at Durham University has written: "Space technology was developed to enhance the killing power of the state. The Moon landings and the launch of the Space Shuttle were mere sideshows, drawing public attention away from the real goal: military and economic control of space as a source of power on Earth."[204]

The military use of space has become an increasingly important part of modern warfare, and today space is fundamental to military operations and underpins the ability to undertake the majority of military tasks. No major military power can do without space systems. Navigation, communications and remote sensing satellites play a vital role in civilian infrastructure and are equally important to the military. Although governments maintain their own secure satellites for military purposes, virtually everything space-related – technologies, systems, and assets – is dual use, with both civil and military applications. The military is a major driver for the space sector, with space and the arms industry closely linked as a result of the Cold War history of space development. The space sector is substantially funded by the military – in 2023 the amount of space funding worldwide declared as military expenditure exceeded civil space expenditure for the first time in decades[205] – and military uses of space tie closely in with all other uses.[206]

Space is not a remote theatre of operations where battles will be fought far from Earth. War-fighting in space will have serious implications for society below. Space systems play an essential role in critical civilian infrastructure, especially in the energy and communications sectors, and are indispensable to the provision of essential services on which civilians depend. Acts of war which disrupt or destroy space systems that carry out such functions would have far-reaching consequences for the civilian populations. As the role of space systems in military operations during armed conflict increases, the likelihood of dual use systems being targeted also increases.

Space systems also provide communications, intelligence, and positioning information needed to enable war to proceed on the ground. The humanitarian impacts of war are well documented and are grave. Well over 100,000 civilians were killed during armed conflict around the world in each of the two years 2024 and 2025. Gaza's total population fell by about 254,000 people, a 10.6 per cent decline compared with pre-conflict estimates, as a result of Israeli military action following Hamas's October 2023 assault, and in total 18,592 children and about 12,400 women are known have been killed by the end of 2025. More civilians were killed in Ukraine in 2025 than in the two previous years – a recorded total of 2,514 – and millions of homes have lost electricity and other utilities as a result of Russian attacks.[207]

204 Bleddyn E. Bowen: 'Original Sin: Power, Technology and War in Outer Space'. Oxford Academic Books, 1 February 2023.

205 'Government Space Program: A Comprehensive Overview of Government Space Strategies, Activities, and Budgets'. Novaspace Market Intelligence (fomerly Euroconsult). 2023. Cited in: Sebastian Fehrler, Lars Hornuf & Daniel Vrankar: 'What do citizens expect from space?' Acta Astronautica, V235 p660-669. 16 June 2025. https://www.sciencedirect.com/science/article/pii/S0094576525003388#tbl1

206 "There's no distinction between missile and rocket". Interview with Sahba El-Shawa. 18.00 onwards. https://itsspaceplus.substack.com/p/theres-no-distinction-between-missile

207 Geneva Academy of International Humanitarian Law and Human Rights: 'War Watch: IHL in Focus Report. 1 July 2024 to 31 December 2025'. 2 February 2026. https://geneva-academy.ch/wp-content/uploads/2026/01/WarWATCH-IHL-in-Focus-Report-2024-25.pdf

Image 14. Military recruitment posters for the Royal Air Force, London **Credit:** Pete Howson

As well as humanitarian consequences, war also has major adverse impacts on the environment. The following environmental consequences have resulted from the ongoing war in Ukraine:

- Warfare has become the largest source of carbon emissions in the country. Emissions reportedly reached 230 metric tons of carbon dioxide equivalent at the end of the third year of conflict, which is the equivalent of the annual emissions of Austria, Hungary, Czech Republic and Slovakia combined, or the annual emissions of 120 million fossil fuel-powered cars.[208]
- Air quality has also deteriorated, with air monitoring in Kyiv after the first two weeks of hostilities showing pollutant concentrations 27 times higher than normal.[209]
- Damage to Ukrainian nature and wildlife has been severe. Fires sparked by attacks have already damaged over 100,000 hectares of natural ecosystems, according to satellite data from the European Forest Fire Information System. According to the Ukrainian Ministry of Environment and Natural Resources, at least 900 protected areas together covering 1.2 million hectares or 30 per cent of all protected areas in Ukraine have been affected by military action.[210]

208 Martina Igini: 'Warfare Now Largest Source of Ukraine's Annual Carbon Emissions, Report Warns on Third Anniversary of Russia's Invasion'. Earth.Org, 24 February 2025. https://earth.org/warfare-now-largest-source-of-ukraines-annual-carbon-emissions-report-warns-on-third-anniversary-of-russias-invasion/

209 Shereena Qazi: ''An Ecocide': How the conflict in Ukraine is bombarding the environment'. TRT World, 28 April 2022. https://www.trtworld.com/article/12788819

210 Bohdan Vykhor and Andreas Beckmann: 'Assessing the Environmental Impacts of the war in Ukraine'. WWF Central and Eastern Europe. https://wwfcee.org/our-offices/ukraine/assessing-the-environmental-impacts-of-the-war-in-ukraine

- The State Environmental Inspectorate of Ukraine had reported at least seven confirmed incidents of release of toxic industrial chemicals caused by military activities up to June 2022.[211]
- Millions worldwide also continue to face a food and fertiliser crisis as a result of reduced exports from Ukraine which are a ripple effect of the war.[212]

For these reasons it is in everyone's interests to move towards the demilitarisation of space. Space is becoming a competitive and increasingly dangerous domain, with a risky three-way space arms race developing between China, Russia, and the US.[213] As well as facilitating ground warfare the militarisation of space presents a threat to gains and benefits from co-operation over the peaceful use and exploration of space. Security concerns are the major underlying cause of the deadlock on negotiations on conduct in space and international space law. In the UK, spending on space science research is facing major cuts at the time of writing while billions of pounds have been allocated to military space programmes (see case study 5).

Demilitarising space will be a complex, long term project which will be bitterly opposed by governments and the military aerospace industry. The Palestine Space Institute (PSI), a think tank working on space ethics and the responsible use of outer space advocates for the peaceful and ethical exploration of space.[214] PSI advocates the following approaches to reducing and managing risks associated with space militarisation.

Space Technology Control: Technology development is a major underlying cause of arms races and the demilitarisation of space will require steps to encourage responsible technology development and use in space, discourage the development of weaponry and military applications of technology, and ensure that new technologies are used for the benefit of all. Ethical codes and guidelines for the responsible use and control of space technology can play a role in this, as advocated in section 7.3 above.

Arms control and negotiation: Demilitarisation of space will require a new approach to resolving conflict between governments, based on a 'human security' approach rather than the use of armed force.[215] This approach prioritises dialogue and diplomatic solutions to conflict, confidence-building measures to encourage trust and co-operation, and international agreements and treaties to prohibit offensive weaponry.

Separating military and civil interests in space: Dual use systems and technologies are common in the space sector. This has a number of consequences. Civil space projects may be unduly influenced by military requirements and dependent on partnerships with the military. Investment in the sector is dominated by arms corporations, resulting in financial dependencies that can hinder the growth and independence of civil and commercial space initiatives. Civilian applications of dual use systems are at increased risk during times of hostility. To tackle these limitations, there is a need to reduce reliance on dual-use systems. This will require

211 'The Environmental Impact of the Conflict In Ukraine. A Preliminary Review'. United Nations Environment Programme and GRID Arendal, October 2022. https://wedocs.unep.org/rest/api/core/bitstreams/f7ab9710-344b-4899-beb6-ca5c333a556e/content

212 'The Environmental Impact of the Conflict In Ukraine. A Preliminary Review'. United Nations Environment Programme and GRID Arendal, op cit.

213 Samuel Oyewole and Ezenwa E. Olumba: 'Space arms race may be underway – it comes with enormous risks'. The Conversation, 17 June 2024. https://theconversation.com/space-arms-race-may-be-underway-it-comes-with-enormous-risks-231545

214 Palestine Space Institute. https://www.palestinespace.org/home

215 'Rethinking Security: A Discussion Paper'. The Ammerdown Group. May 2016. https://rethinkingsecurity.org.uk/wp-content/uploads/2016/10/rethinking-security-a-discussion-paper.pdf

moving towards creating distinct, specialised capabilities for defence purposes rather than relying on shared commercial infrastructure. Likewise, other systems should be reserved for purely civil use. Alternative pathways of independent funding for space activities that are not entrenched in the military industrial complex are also necessary, alongside guidelines and agreements that promote the peaceful use of space for scientific and humanitarian purposes.[216]

Important among any agreement to promote the peaceful use of space would be an international treaty on the Prevention of an Arms Race in Outer Space (PAROS) to prevent any nation from placing objects carrying any type of weapon into orbit. A PAROS resolution is adopted each year in the United Nations General Assembly by an overwhelming majority of UN member states. The only country which consistently votes against a PAROS treaty is the US, arguing that the existing multilateral arms control regime is sufficient to address concerns over an arms race in space. The US did, however, vote in favour of a UN General Assembly Resolution in 2020, introduced by the UK, which called for action to reduce space threats through norms, rules and principles of responsible behaviours. Both Russia and China voted against the resolution on establishing norms of behaviour but voted in favour of a binding PAROS treaty. More positively, in November 2021, the UN General Assembly's First Committee approved a compromise resolution that sets up a new open-ended working group to develop rules of the road for military activities in space. This will hopefully act as a first step towards controlling the militarisation of space.[217]

Recommendations

The UK government should continue work to reduce space threats and should extend this work to enabling the demilitarisation of space, though the United Nations and other channels. The government should support the early negotiation of a PAROS Treaty and lobby the US administration to support such a move. The government should give an unambiguous commitment to reaffirm that space must be a global commons and reserved for peaceful and sustainable uses, and must not become a war fighting domain.

The UK government should support a domestic civil space sector which is independent of the military. Special incentives should be granted for developments which have civilian uses only, and which are not dual use.

Civil society organisations with an interest in peace and disarmament should highlight the risks that the militarisation of space poses to civilian infrastructure and services.

216 'Decoupling Defense and Space'. Palestine Space Institute. https://www.instagram.com/p/C4D1Q6wNokX/

217 Claire Mills: 'The militarisation of space'. House of Commons Library, op cit.
Dave Webb and Peter Burt: "For Heaven's Sake – Examining the UK's Militarisation of Space", op cit. P24-25.

Case study 5 UK space research funding down; military spending up

In January 2026 the UK government's Science and Technology Facilities Council announced that its funding for astronomy, particle and nuclear physics research would be cut by 30 per cent. This followed announcements a few weeks previously that the UK would be cutting its budget contribution to the European Space Agency – the only member nation to do so[218] – and withdrawing its funding from the ESA's UK-led TRUTHS climate monitoring mission, following which the programme has been suspended.[219]

Scientists are concerned that the spending cuts will affect an entire generation of space research scientists. "Cuts of this scale are a devastating blow for the foundations of UK physics, which is already battling a critical funding gap in universities, a decades-long shortage in teachers and a widespread skills shortage," Professor Paul Howarth of the Institute of Physics said in a statement. A lack of future astronomers and space scientists means that the UK will find it difficult to reap benefits from its collaboration in large international astronomy projects such as the European Southern Observatory.

The funding cuts were made as a result of directions from the government to funders to focus and do fewer things better, and align research with government priorities. One of the top priorities for government is currently national security, and this has been cited as a factor in the decision to cut astronomy and space research spending.[220] UK military and security spending is currently increasing to reach a target of 5 per cent of GDP, and the government is keen to instil a "whole-of-society" approach to defence.[221] This includes refocusing research and innovation to meet military requirements.

While space scientific research spending is falling, the UK government has allocated £6.4 billion for delivery of its defence space strategy over the period 2022-32.[222] According to the Director of the UK Space Agency, Rebecca Evernden, national security will be a focus for the Agency in future, and that the Agency will be prioritising funding for four areas – satellite communications, in-orbit servicing and manufacturing, and space domain awareness – which are important for defence and national security.[223]

218 Tereza Pultarova: 'UK government proposes 30% budget cut to astronomy and physics research: 'It's pretty disastrous''. Space.com, 6 February 2026. https://www.space.com/astronomy/uk-government-proposes-30-percent-budget-cut-to-astronomy-and-physics-research-its-pretty-disastrous

219 Robert Wall: 'ESA Drops Truths Mission from Funding Plan'. Aviation Week, 23 October 2025. https://aviationweek.com/space/space-exploration/esa-drops-truths-mission-funding-plan

220 Tereza Pultarova: 'UK government proposes 30% budget cut to astronomy and physics research: 'It's pretty disastrous'', op cit.

221 'The Strategic Defence Review 2025 – Making Britain Safer: secure at home, strong abroad'. Ministry of Defence, 8 July 2025. https://www.gov.uk/government/publications/the-strategic-defence-review-2025-making-britain-safer-secure-at-home-strong-abroad/the-strategic-defence-review-2025-making-britain-safer-secure-at-home-strong-abroad

222 Dave Webb and Peter Burt: "For Heaven's Sake – Examining the UK's Militarisation of Space", op cit. P10.

223 Emma Gatti: 'Q&A: Rebecca Evernden on UK space strategy'. Space News, 13 March 2026. https://spacenews.com/qa-rebecca-evernden-on-uk-space-strategy/

7.5 Citizen action

Public opinion can influence government and corporate policies, particularly over the long term. In the space sector, public opinion plays an important role in shaping priorities – in particular through the allocation of government funding for space projects. Research shows that most citizens consider space to be important, interesting, and exciting, although their overall awareness about space issues is low when compared to other topics.[224]

Opinion polling gives insights into the priorities and concerns of members of the public. Recent research led by the University of Bremen has surveyed citizens from nine nations with significant space budgets about their views about space-related topics.[225] The study showed that the top space priorities for most citizens are related to activities that have benefits on Earth, such as climate monitoring, detection of threats from asteroids, and research to increase understanding of space. The growing amount of space debris was one of the top two concerns across all nations, with citizens from France, Italy, and the UK stating that the environmental impact of space was their biggest concern.[226]

Despite the fact that the share of military expenditure in space budgets is increasing, and that the importance of space in defence is being highlighted by governments, citizens do not support steps to militarise space. Militarisation was the most frequently mentioned concern in the survey, and increasing military capabilities in space was consistently scored as the lowest priority by survey respondents. Most stakeholders in all countries wanted their own nations to comply with international space law.

These findings suggest that political and social acceptability could play an increasingly important role in the development of space projects, especially if these projects have high costs and environmental footprints and do not bring identifiable benefits to ordinary citizens. These projects may encounter difficulties and face growing opposition from the general public as the global environmental crisis unfolds.[227]

Public engagement and citizen action can have deep impacts on government space programmes. Hannah Harris and Pedro Russo have reported on three grassroots 'citizen science' campaigns based around advocacy, crowdfunding, and even the direct take-over of a space mission.[228] Space enthusiasts and citizen scientists mobilised to challenge government decisions when the Hubble Space Telescope and James Webb Space Telescope (JWST) projects faced cancellation. Spectacular photographic images taken by the Hubble Space Telescope helped to awaken public interest in astronomy and in the telescope itself, and when its future was at risk a movement of 'Hubble Huggers' lobbied online to save "the people's telescope". NASA opened a stakeholder dialogue with the public to explore options for keeping the telescope operational, and the American Astronomical Society worked with senators to secure funding for the repair and maintenance work needed to keep it in service. Likewise, when the

224 Sebastian Fehrler, Lars Hornuf & Daniel Vrankar: 'What do citizens expect from space?' Acta Astronautica, V235 p660-669. 16 June 2025. https://www.sciencedirect.com/science/article/pii/S0094576525003388#tbl1

225 The nine nations surveyed were China, France, Germany, India, Italy, Japan, Russia, the UK, and the US.

226 Sebastian Fehrler, Lars Hornuf & Daniel Vrankar: 'What do citizens expect from space?',op cit.

227 Loïs Miraux, Andrew Ross Wilson, & Guillermo J. Dominguez Calabuig: "Environmental sustainability of future proposed space activities", op cit.

228 Hannah E. Harris & Pedro Russo: 'The influence of social movements on space astronomy policy: The cases of "Hubble Huggers", JWST's "Science Warriors" and the ISEE-3 "Reboot Team"'. Space Policy, V31 p1-4, February 2015. https://www.sciencedirect.com/science/article/abs/pii/S0265964614000770

JWST project was at risk from defunding, a new movement of 'Science Warriors' responded to statements in support of the telescope from the American Astronomical Society and the Planetary Society with a wave of social media campaigning and letter-writing targeted on government representatives which resulted in the restoration of funding.

When NASA retired the International Sun/Earth Explorer 3 (ISEE-3) space probe a team of astronomers, engineers, and programmers expressed an interest in 'rebooting' the spacecraft to continue its original mission. An ISEE-3 Reboot Team was set up to work with a private space company, Skycorp, to completely take over the mission from NASA. The group raised nearly $US160,000 through crowdfunding to regain communication with the spacecraft, with the aim of sharing all data sent back. Professional astronomers, observatories, propulsion engineers, and aerospace companies offered their expertise to support the project. Again, social media and internet campaigning played a key role in building support for the project and raising public awareness about space science.

These three cases show that public interest in space science can be marshalled through social movements to successfully influence government funding and decisions on space policy. Experience from the examples suggests that campaigns work well when they are instigated by a specific need flagged up by professional scientists; engage enthusiast groups who can help disseminate the message to the broader public; and have support from lawmakers who can help bring about the changes in policy which are needed. Partnerships with institutions and companies who are able to provide specialist support can also play an invaluable role. It often appears to be the case that a previous movement helps to inspire the next.

Professional scientists are uniquely placed to alert the public to environmental problems, and their warnings play an essential role in mobilising citizens to take action. In October 2024, for example, 120 astronomy, astrophysics, and space researchers sounded the alarm on the as-yet-unknown effects of satellite megaconstellations on the atmosphere by writing a public letter calling on the US Federal Communications Commission to conduct environmental reviews for large constellations of satellites. The scientists highlighted a number of shortfalls in the environmental review process, including the categorical exclusion of megaconstellations from the review process and failure to investigate the aggregate effects of constellations.[229]

More radical campaigns have taken explicitly political action to oppose harms caused by the space industry. The Global Network Against Weapons and Nuclear Power in Space, for instance, was formed in 1992 to build a global consciousness and active constituency to protect space from militarization and weaponization, the extension of nuclear power into the heavens and concerns about environmental effects of launches. The Global Network supports action and campaigning on space issues around the world, and co-ordinates 'Keep Space For Peace Week' every October to coincide with the United Nations' World Space Week.[230] At a local level community campaigns around the world are opposing the development of spaceports in environmentally and culturally sensitive locations. An example is the Friends of Scolpaig, a community group on the Scottish island of North Uist which is challenging the technical case for the 'Spaceport 1' development on the island and campaigning for the permanent

229 Lucas Gutterman & Stephanie Markowitz: '120 top astronomy researchers call on FCC to study satellite mega-constellations'. Public Interest Research Groups, op cit.

230 Global Network Against Weapons and Nuclear Power in Space. **https://space4peace.org**

withdrawal of the proposal.[231] The group has mobilised hundreds of local people who have objected to planning permission for the spaceport.

At a time when governments and corporates are incapable of addressing the social and environmental crises the planet is facing – and in many cases are actually exacerbating them – citizen action may be the best hope of achieving change. Rather than waiting hopelessly for nation states to reach agreement on space issues at the United Nations, or for billionaire-owned space companies to cease ethically dubious practices of their own accord, ordinary people who will suffer from the environmental and military consequences of space programmes can apply concerted pressure on them to force a change. Citizen push-back can force corporates and governments who are following their own agenda with no regard to wider public interests or the environment to adopt a sustainable approach to space.

Recommendations

Professional scientific institutions and civil society should continue to highlight critical environmental and social risks arising from the misuse of space and technology, and mount education and advocacy campaigns to warn the public and politicians of the consequences of these risks.

Investors, including pension funds, should insist on ethical and sustainable practices by space and technology companies in which they hold stakes, and divest from companies who refuse to cease harmful behaviour.

All citizens everywhere should question and remain critical of governments, corporates, and emerging technologies and educate themselves and be willing to take political action to oppose abuse of human rights and the environment.

All stakeholders with an interest in space should open a wider debate on how space can be developed in ways that guarantee shared prosperity and the success of all people and future generations.

231 Friends of Scolpaig: https://www.friendsofscolpaig.org/ and https://www.instagram.com/friends_of_scolpaig/

8 Conclusion

Satellite constellations and space technologies have the potential to offer great benefits to society, but their unchecked proliferation and the militarisation of space is now threatening humanity's broader interests. We are beginning to see the dangers from multiple harmful impacts arising from space operations. These impacts have been relatively low until now but are growing as the space sector expands and commercial players enter. The space sector is beginning to degrade and damage several important global commons – the atmosphere, certain Earth orbits, the night sky, and the oceans. Powerful satellite companies and governments have basically been assuming that they can do whatever they want in space while everyone else has to put up with the consequences of their action. The global commons which the space industry is exploiting and polluting are now beginning to show signs of stress which may soon become critical.

Space and other global commons are not systems with unlimited capabilities to self-cleanse. There are limits to how much pressure we can place upon them without harming the planet. At the moment there is a great deal of uncertainty about how the atmosphere and the global environment are responding to pollution from human activities in space, and more research and modelling of the impacts is urgently needed. However, environmental changes often tend not to occur in gradual, linear ways but through sudden steps, meaning that changes with significant consequences for human wellbeing may happen rapidly and be difficult to predict, with unforeseen cumulative effects. If worst case scenarios are correct, the space industry may already be having a significant impact on atmospheric chemistry, with implications for global climate change and the health of the ozone layer. We also seem to be facing some intractable dilemmas as the problems mount. Should a responsible satellite operator, for instance, leave a satellite in orbit at the end of its life, and add to orbital clutter and space debris problems, or deorbit it to burn up and add to atmospheric pollution?

Many of the environmental threats to the space environment result from the fact that humans often fail to plan for the end of the lives of things we produce. Industry's throwaway approach has resulted in the absurdity of allowing an expensive space satellite consisting of valuable and rare materials to be burnt to cinders at the end of its life.

"We are changing the system faster than we can understand those changes," says Aaron Boley, an astronomer at the University of British Columbia and co-director of the Outer Space Institute. "We never really appreciate our ability to affect the environment. And we do this time and time again."[232] What all this

232 Shannon Hall: 'The New Space Race Is Causing New Pollution Problems', op cit.

is saying to us is that we must slow down the race for space and if necessary pause certain activities in space, at least until we have a greater understanding of how our presence in space is affecting the atmosphere and other commons. Environmental change is often irreversible, and it really is in humanity's interests to follow the precautionary principle.

We have found out the hard way that ecosystems need to be protected by legislation and regulation if they are not to be damaged irreparably, and the same approach must be applied to the 'space ecosystem'. Humanity has to find a way to overcome business and state rivalries and co-operate over the management of space, turning self-interest into mutual aid. If we do not, no one will come to our rescue and we will not be able to escape to another world.

List of acronyms used in this publication

AEE	Assessment of Environmental Effects
CAA	Civil Aviation Authority
COPUOS	Committee on the Peaceful Uses of Outer Space
DNA	Deoxyribonucleic Acid
EIA	Environmental Impact Assessment
ESA	European Space Agency
FAA	Federal Aviation Administration
GDP	Gross Domestic Product
GPS	Global Positioning System
HMX	'High Melting Explosive', 'High-velocity Military Explosive', 'High-Molecular-weight RDX' or octogen.
HTPB	Hydroxyl-terminated Polybutadiene
IAU	International Astronomical Union
ICBM	Inter-continental Ballistic Missile
ISEE-3	International Sun/Earth Explorer 3 spacecraft
ISS	International Space Station
JWST	James Webb Space Telescope
NASA	National Aeronautics And Space Administration
NOAA	National Oceanic and Atmospheric Administration
PAROS	Prevention of an Arms Race in Outer Space
PFAS	Per- and Polyfluoroalkyl Substances
PROBA	Project for On-Board Autonomy
PSI	Palestine Space Institute
RDX	'Research Department Explosive', 'Royal Demolition Explosive' or hexogen.
SPOUA	South Pacific Ocean Uninhabited Area
STEM	Science, Technology, Engineering and Mathematics
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio-Studies
UDMH	Unsymmetrical Dimethylhydrazine
UK	United Kingdom
UN	United Nations
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
US	United States

SPACE WATCH UK

SPACE FOR PEACE