Space: 2075

PERSPECTIVE

THE ROYAL SOCIETY

Emerging technologies
As science expands our understanding of the world it can lead to the emergence of new technologies. These can bring huge benefits, but also challenges, as they change society's relationship with the world. Scientists, developers and relevant decision-makers must ensure that society maximises the benefits from new technologies while minimising these challenges. The Royal Society has established an Emerging Technologies Working Party to examine such developments. This is the second in a series of perspectives initiated by the working party, the first having focused on the emerging field of neural interfaces.

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A perspective on Space
Preparing for 2075

The purpose of this report is to stimulate early discussion on the potential implications of the future possible outcomes in space activities that might be envisaged by 2075. It does not attempt to predict the future, nor advocate for a particular outcome, but rather to indicate the direction of travel so that society may be better prepared.

The implications of space exploration in the coming decades are as consequential to today's industry, society and culture as were the 18th century Industrial Revolution and the 20th century digital revolution in their times. Space can offer enormous real-world, practical impacts for citizens, the public sector and industry. We need to be better prepared for the opportunities, and the risks, that these present.

Governments, regulators and society in general should be aware of these implications so that the potential long-term consequences of successive near-term decisions and policies may be better understood and considered. Policy recommendations are presented, which emerged during the course of this study, to bring a focus to immediate priorities.

Over millennia, humans have progressively expanded their zones of endeavour – first on land, then by sea, then in the atmosphere – at an accelerating rate. Outer space is the next zone of expansion of human endeavour.

A human presence has been established in near Earth orbit, but the coming decades will see further exploration into interplanetary space, perhaps leading to long-term bases.

Advances already underway resulting in lower cost and higher mass transportation from Earth to orbit, combined with parallel developments in robotics, computing, AI and biological engineering (including synthetic biology), are driving fundamental transformations of human life and society.

Routine and relatively low-cost access to orbit, without the present limitations on launch mass and volume, through the latest generation of re-useable rockets, and future development of single stage to orbit (SSTO) spaceplanes combined with novel space-based power systems, could enable the construction of large-scale manufacturing facilities in orbit to build spacecraft less limited by launch constraints. Smaller re-usable rockets and SSTO spaceplanes, using 'green' propellants could provide rapid point-to-point sub-orbital logistical transport on Earth, greatly reducing current travel times and enabling governments to deploy resources rapidly for disaster recovery or security activities on a global scale.

Space traffic management and minimising the creation of debris in both the orbital and lunar environments will need international agreement for the benefit of all players, similar to the Astra Carta of King Charles III that sets environmental guidelines for space activities. It will be critical to agree on principles from this and similar initiatives such as the Earth & Space Sustainability Initiative's (ESSI) Memorandum of Principles and British Standards Institution standards. Enabled by more frequent launch and concomitant reduction in costs, space could also offer opportunities to address some of the environmental impacts of certain Earth-based industries. Such industries could gradually be relocated into orbit, taking advantage of plentiful solar energy or nuclear power generation and thermal dissipation to deep space, to support orbital factories, power-hungry applications (such as data server farms), and provide the potential for space-based, clean, reliable energy for Earth. Recycling technologies developed for the essential reuse of limited resources on space stations may have matching benefits on Earth. Utilising resources from the Moon or asteroids for space-based industry and re-cycling defunct satellites (creating a circular economy in space) could reduce the demand for materials and help reduce some of the negative environmental impacts of human activity on the Earth's surface.

Left
Hubble Space Telescope image of the Pillars of Creation, one of the largest seen star-birth regions in the galaxy.
© NASA, ESA, and the Hubble Heritage Team (STScI/AURA).

The exploration of space will continue to be led by increasingly capable robotic and autonomous systems, extending a reach beyond human frailty and preparing protective environments where human activity in space is essential (though the need for human presence should be reviewed regularly). Research laboratories in orbit (potentially run as autonomous, serviced platforms) may expand scientific capabilities and take advantage of microgravity and other space environmental conditions, to develop new or improved materials, pharmaceuticals and biological products not possible on Earth. 'Made in Space' goods, produced on an industrial scale in microgravity, may become commonplace on Earth. The increasing number of research platforms and laboratories will enable an expanded scale of space experiments, including essential trial repeats and replications, thus improving the quality of science in space and the number of Earth-based research groups that can send experiments into the Solar System.

A mining and construction industry, employing an advanced autonomous robotic workforce powered by solar or nuclear energy, could use in-situ or asteroid resources to construct infrastructure to support longer human endurance on the Moon, Mars and locations further afield. The Moon could host facilities and bases forming an international focus for scientific research, hubs for commercial activity, and a gateway for exploration further into the Solar System and beyond. These bases may be constructed beneath the lunar surface to provide protection from extreme surface temperatures and shielding from damaging solar radiation.

Using energy and materials mined and processed entirely on the Moon, robots could construct radio telescopes on the lunar far-side, free from Earth's radio interference, to look deeper in space and time and search for evidence of extra-terrestrial life. Inevitably, increasing human and robotic lunar activity will degrade the Moon's pristine environment for potential science use cases and care will be needed to retain high-value niche opportunities. It is likely that the Moon will host a number of nations each with their own facilities, not unlike the present-day Antarctic, alongside private sector commercial entities. The possible emergence of a lunar economy with a human workforce will prompt the need for new ethical, health, safety and risk management regimes appropriate to this particular environment.

The rapid increase in the number of players, state and non-state, large and small, having politically or commercially competitive interests in space will raise the potential for conflict over valuable, finite natural resources such as access to orbital positions and the radio-frequency spectrum. Near-Earth space is already an arena for geopolitical competition and, as a consequence, is being actively prepared for military confrontation with increased launches of military satellites and anti-satellite weapons. Humans have gone to war on land, sea and in the air; conflict in space is unlikely to be excluded, especially as space capabilities are now essential to enable military action on Earth. Intentional or accidental physical or electromagnetic intrusions in Earth orbit or on the Moon could be the trigger for conflict, not only in space but back on Earth. Robust and binding agreements on protocols will be essential to govern the interaction between national and private sector communities to ensure the equitable access to locations and resources, reliable channels of communications between competitors, protocols for emergency responses and the avoidance of misunderstanding that might escalate to conflict – whilst at the same time creating the environment for stable collaborative research and commercial development. Such protocols may first emerge as guidelines, such as the Astra Carta, building trust and confidence resulting in the development of best practice and forming the basis for new licensing frameworks.

International engagement and collaboration on space, wherever possible and however politically challenging, is critical if the UK is to play a significant role in space partnerships and influence behaviours. The long-term benefits of such collaborations are not necessarily obvious at the outset. For example, the Cospas-Sarsat satellite emergency beacon system was conceived and initiated by the US, Canada, France, and the Soviet Union in 1979 and has since enabled the rescue of over 60,000 people worldwide and the US-Soviet collaboration on Apollo-Soyuz, led to agreements on common interfaces that 35 years later enabled the US to maintain access to the International Space Station during a period of a lack of US crewed launch capability post-Shuttle.

The technologies and infrastructure networks initially developed for and tested on the Moon could provide the basis for the formation of facilities on Mars. Human activity on the Martian surface would face even greater challenges at a greater distance from Earth, with limited access to Earth's resources. While the Moon is almost a 'daytrip' from Earth, allowing for the relatively rapid provision of emergency supplies or evacuation, Mars involves a 750-1000 day round trip with existing propulsion technology, necessitating a high degree of reliance on independence of operation.

The need to produce biological systems and ecosystems for sustained human endurance, that can operate under diverse space environments could drive innovation in engineering biology and biotechnology: advances that could find applications on Earth in areas such as waste recycling, healthcare and food production.

The industrialisation of space and the technologies and infrastructure resulting from bases on the Moon and Mars could accelerate scientific exploration further into the Solar System and deep interstellar space. Robotic and autonomous technology could be used to construct interplanetary space stations, equipping them with the tools necessary for exploring various destinations such as Venus and Europa, redeploying them across the Solar System as needed. A system of communication satellites utilising quantum and laser technology could provide high-bandwidth, reliable and secure connections between distant locations and enable the collection and dissemination of scientific information from probes across the Solar System.

In the years to 2075, planetary sciences and astrobiology could bring us more concrete answers to the question of whether there are instances of life beyond Earth. The discovery of life that is related to life on Earth (transferred naturally to other planetary bodies in the past) would radically alter our ideas about the distribution of life and its ability to migrate. A discovery of an independent origin of life could open entirely new areas of microbiology, biochemistry and eventually applied biology, similar to the revolution that occurred after Antonie van Leeuwenhoek's discovery of microorganisms in the 17th century.

Alternatively, an apparent lack of life in all explored regions would raise questions about the uniqueness and specialness of life on Earth and the unusual conditions for its origin on this planet and our responsibility to protect its diversity. In other words, whatever the outcome in the search for life, important scientific and philosophical insights await us before 2075.

Of course, this vision will unfold in detail gradually through the coming decades. Individual, relatively short-lived, national government administrations and regulators as well as private sector commercial interests will have near-term challenges and priorities that will modulate their scale of commitment and rate of progress. There will be continual opportunities to shape and adjust the specific direction of future space activities and behaviours, but it will be important to place these considerations in the context of the general long-term direction of travel, weighing the potential benefits and accompanying risks at every stage.

Early awareness of what the future might hold should allow society to be better prepared for the unexpected – that history teaches us to expect – and make wiser choices; choices that allow us to benefit sustainably from both our Earthly and space environments into the future.

The UK Space sector

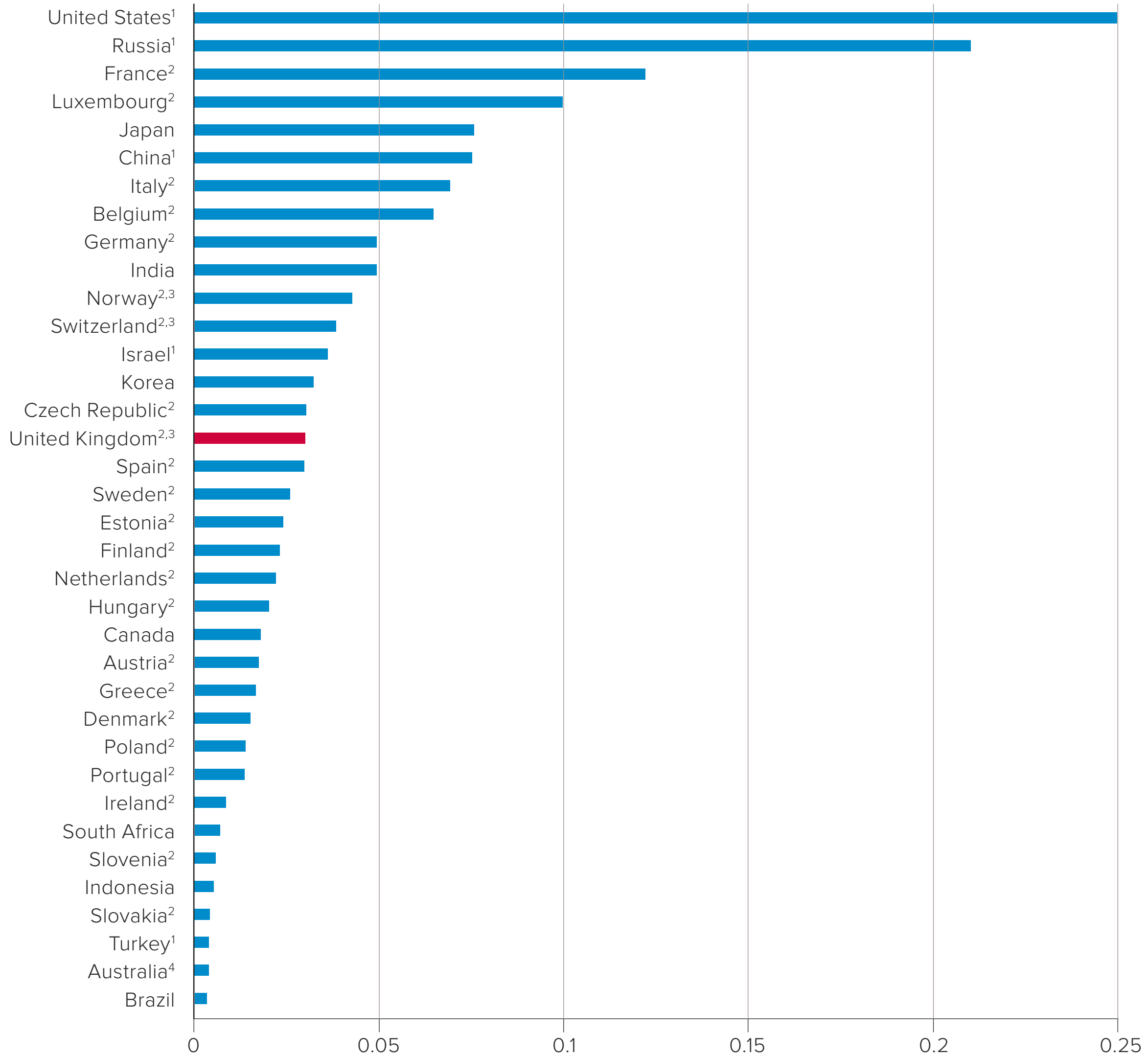
The UK has strengths in fundamental and applied research in space, which it should continue to draw on. Space technology is deeply rooted in the traditions of curiosity driven science, originating in the very earliest forms of the scientific method thousands of years ago – inference from pure observation. Conclusions have evolved in their sophistication and match to reality as old hypotheses have evaporated under the scientific glare of improved observational and experimental techniques. The resulting state of science and laws of physics underpin the satellite technologies that have become deeply integrated into every aspect of 21st Century life, from travel to communication, high finance, Earth observation, weather and climate prediction, and the continued exploration of the wider solar system and space. As such space science is perhaps one of the best examples of the enormous benefits to humanity that can accrue from long-sustained scientific research endeavours, where discovery research from long ago is continually drawn upon to drive repeated waves of innovation.

Space is already important to the UK economy with approximately 18% of UK GDP underpinned by satellites providing services to a wide range of private and public sector activity. Growth in the space sector has outpaced the rest of the UK economy by 3.5x, increasing in value by 6.4% on average each year since the year 2000. The UK also gets a favourable 9.8:1 return on investment in funds contributed to the European Space Agency[1]. All of this despite investment in space being significantly lower overall when compared to major space powers and countries with similar sized economies in Europe (Figure 1).

For the UK there is a need to take stock of our space activities and make choices about future strategic direction that build on our strong history in space science and recognise the increasingly complex integration of space technologies into services widely used in daily life. We need to examine our appetite and level of ambition for leadership in the fields of opportunity rapidly opening up, but also our responsibilty to lead in getting ahead of the risks inherent in rapidly innovating fields, in order that the potential benefits to humanity can be fully realised in both the practical domain, and in the fields of scientific discovery that always lay the path for future innovation.

FIGURE 1

The UK's spend as a percentage of GDP relative to other space faring nations



1. Conservative estimates, including defence programmes.
2. Includes contributions to the European Space Agency and Eumetsat.
3. Includes contributions to one or several EU space programmes (e.g. Copernicus, Galileo/EGNOS).
4. Includes only civil R&D.

Notes: GDP is a measurement of the market value of all final goods and services produced in the economy and it does not include the value of intermediate inputs. Budgets include data for civil and defence programmes, when available.
Sources: Government budget sources and OECD databases.

Conclusions

Now is a key moment for considering our future in space in 2075. International space activity in the public and private sectors is experiencing a rapid acceleration with far-reaching opportunities and consequences. Space technologies will become ever more integral and fundamental to the functioning of society and modern economies. The UK has been a leading nation in space science and technology and could play a critical leadership role in the international governance questions brought into sharp relief by the current pace of space innovation. The increased pace of space activity globally should prompt the UK to consider its level of ambition.

The geopolitical balance of power is already shifting with the expansion of the number of nations becoming active in space and with the rapid growth and leadership of the private sector supported by significant private finance. Transparent international communication and cooperation, recognising different national ambitions, societal constructs, social values, and commercial interests will be essential to avoid conflicts in Earth orbit and on the Moon and beyond.

Robust international agreements, ideally binding, on the governance of these space activities must be achieved at a pace hitherto not realised incorporating regulation and licensing regimes that must cover the use of scarce natural resources, including radio-frequency spectrum.

Industry on Earth as we know it may fundamentally change, with low-cost high-capacity launch to orbit being a key enabler. Combined with the capabilities of robotics, AI, and biotechnology, this will bring opportunities to create new products, expand science and reduce environmental damage on Earth alongside other efforts to mitigate environmental harms. Industrial paradigms may change as space applications become more integral to every-day life. Industrial policy and social planning needs to anticipate this change; as will international legal and regulatory frameworks and national policies.

Challenging ethical questions may arise regarding the use of engineering biology, agreements on sustainability of natural resources in space and in anticipation of definitive answers to the question of the discovery of extra-terrestrial life.

The UK Government, the international community, and society at large need to comprehend, anticipate and be prepared for these changes. Space is at an inflection point. Action now will empower the UK for the emerging future and avoid the risk of missing out

Recommendations

RECOMMENDATION 1

Examine approaches taken by other international space powers

that benefit from a single point of leadership in government, to consider how the UK might be better organised to deliver a coherent approach for space, resilient capability, and take full advantage of emerging opportunities.

RECOMMENDATION 2

Protect and maximise the use of space assets and data

to mitigate risks to the UK's Critical National Infrastructure, recognising UK reliance on space assets for obligations on the economy, security and climate change.

RECOMMENDATION 3

Make commitment to a long-term science vision

by implementing a minimum of 10-year priorities and funding horizons for space science to end the damaging cycle of short-termism and stop-start investment. This should include regular review cycles to ensure funding keeps pace with inflation.

RECOMMENDATION 4

Initiate and maintain a 10-year rolling programme of regular in-orbit/in-space technology and service demonstration missions

using small satellites to respond to emerging technologies, economic opportunities, and supporting national strategic and defence goals.

RECOMMENDATION 5

Reduce the risk of the UK space industry being left behind

by incentivising the finance sector to stimulate scale-up of space SMEs through access to capital markets at an order of magnitude greater than today to position the UK as a global supplier, innovative service provider, and a leader in satellite insurance and space reinsurance services.

RECOMMENDATION 6

Seek to broaden and grow international partnerships

(including existing and new programmes in Europe) to access a wider range of space opportunities, achieve best value for money through collaborative approach, and send clear signals to attract foreign direct R&D investment.

RECOMMENDATION 7

Recognising that the space environment is at risk

Show leadership in driving policy and regulation in sustainable space technologies to provide long-term confidence to encourage investment. Influence international agreements focussing on orbital congestion, debris management, fair resource sharing, and responsible planetary resource extraction with respect for sites of scientific importance.

A message from the co-chairs

We present our vision of what space could look like by 2075. We hope you will agree that there is cause for optimism in terms of the opportunities that space offers both in terms of our understanding of the Universe and the ways in which space exploration could provide the technological advances required to address the myriad challenges that humanity will face over the coming decades. But how do we get there? What are the building blocks to get towards this vision?

What can the UK do in the immediate and near-term future to advance its own capabilities and contribute to this longer-term interplanetary ambition in a safe and sustainable way?

Four thematic chapters consider different locations in space and how current science and technological developments in those locations might point towards the future we have set out:

1. Exploring the Universe: origins, current trends and likely developments
2. The leap from Earth
3. The evolution of orbit
4. Exploring the Moon, Mars and beyond

Throughout the report, the reader will come across some highly speculative scenarios that are yet to be shown to be empirically plausible. Examples include space-based solar power, and the widespread use of synthetic biology to engineer organisms that can be used in the space environment. These scenarios should not be taken as assertive scientific predictions of what is to happen, since for a world 50 years hence, this is difficult, some might say impossible, for any area of human activity (but especially technological). We use these examples partly because they have been suggested as potential directions for space development and it would be remiss not to discuss them, but more importantly, we use them as devices to illustrate that there are potentially remarkable developments in the next 50 years. These could be as extraordinary as the technological realities of today, from the viewpoint of life in 1974 such as the launch of private astronauts into space and the appearance of megaconstellations of satellites providing internet access to remote regions.

We have used these speculative scenarios to fashion our policy recommendations about how humanity, and the UK specifically, can ready itself for the future whatever those eventual realities are. Therefore, our speculations in the report are for the purposes of framing a state of mind that can anticipate future (and potentially unknowable) developments without the need to be predictive of what eventually transpires.

As a consequence of this, the report does not attempt to be exhaustive. There are many areas of space development that are already the focus of considerable effort, (such as overcoming the problem of orbital debris) and we don't replicate these efforts in the same level of detail here. Rather, we attempt to consider broad areas of development which will potentially shape the trajectory of space development in the next 50 years up to 2075, pointing out opportunities relevant to the UK's current capabilities and the capacities that it might develop in the light of this emerging vision. We have tried to make it clear where proposed futures are more, or less, speculative based on existing developments in science and technology.

Of course, our optimism is necessarily tempered with caution as effective governance will be essential to ensure the benefits are realised for all and not a select few. As such, governance challenges are highlighted at appropriate junctures to set out where decision makers across the world might need to pay careful attention.

Much of what is covered in the following chapters will not be new to those working in the space sector. However, we hope that it will be a particularly valuable resource for policy makers who find themselves working on space for the first time and indeed members of the public who would like to learn more about the opportunities and risks of space exploration out to 2075. Two companion pieces have been published separately: a Public Dialogue and a science fiction piece. These pieces are complementary to the contents of this report and the purpose and content of each is described in further detail on pages 180 – 181.

This report has been assembled with expert guidance from our working group and reviewers whose knowledge of space science, technology and legal process made this report possible. You can see the full cast list in the Acknowledgements section at the back of this report.

Sir Martin Sweeting FRS,
Professor Charles Cockell and
Professor Suzie Imber

A summary of key space legislation

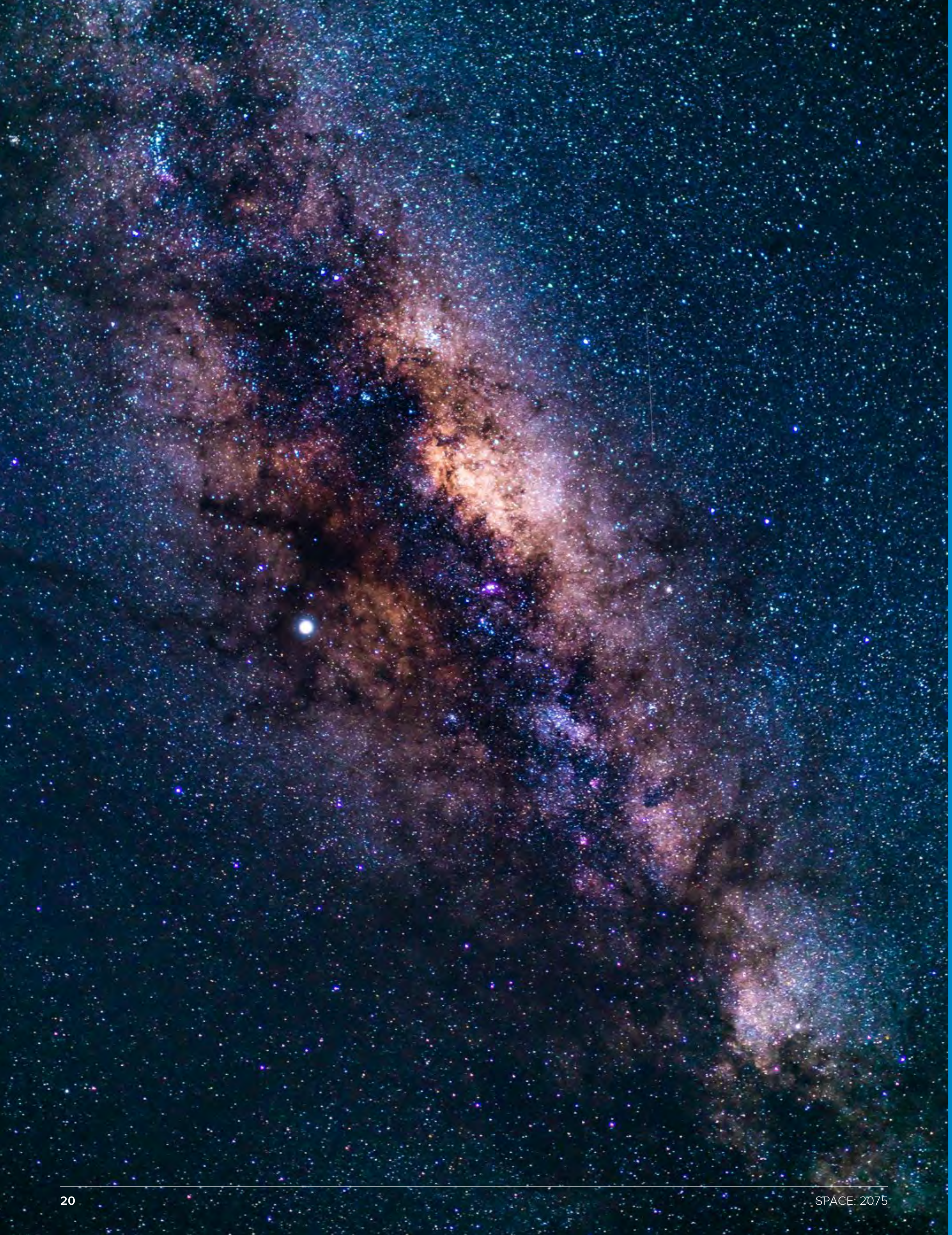
Useful context for discussion in the chapters of this report is the legislation and guidance which sets the customs and behavioural norms in space. The United Nations (UN) is responsible for the administration of some key international treaties, but many countries, including the UK have their own legislation to govern specific activities for their national space agencies and commercial companies, that sits beneath this.

Existing legislation, especially at international level is potentially insufficient to govern activity in space, especially in light of the pace of change in recent years. Legislation should be reviewed regularly to anticipate and avoid unintended consequences of this accelerated development.

Image
Signing of the *Outer Space Treaty*, 1967.

INTERNATIONAL SPACE LEGISLATION	
Outer Space Treaty (1967)	Establishes the basic framework for international space law. Prohibits the placement of nuclear weapons in space. Ensures space is free for exploration and use by all nations. Prevents any country from claiming sovereignty over outer space or celestial bodies.
Rescue Agreement (1968)	Requires states to assist astronauts in distress and return them safely. Obliges states to assist in the recovery of space objects that return to Earth outside the territory of the launching state.
Liability Convention (1972)	Establishes absolute liability for damage caused by space objects on the surface of the Earth or to aircraft. Provides for fault-based liability for damage caused in space. Outlines procedures for the settlement of claims for damages.
Registration Convention (1976)	Requires states to register space objects with the United Nations. Enhances transparency and accountability in space activities by maintaining a public registry of space objects.
Moon Treaty (1979)	Reaffirms that the Moon and other celestial bodies should be used exclusively for peaceful purposes. Declares the Moon and its resources as the common heritage of mankind. Calls for the establishment of an international regime to govern the exploitation of lunar resources. Largely considered a failure as only 17 nations (excluding the UK) are party to the treaty and major space nations with launch capabilities, did not become parties or signatories

UK SPACE LEGISLATION	
Outer Space Act 1986	Governs space activities in the UK or by UK entities overseas. Requires licensing for launching and operating satellites. Ensures compliance with international obligations. Establishes a UK Registry of Outer Space Objects.
Space Industry Act 2018	Regulates spaceflight and associated activities within the UK. Covers licensing for spaceports, launch operators, and range control services. Requires safety and environmental assessments. Specifies liability and insurance requirements.
Space Industry Regulations 2021	Provides detailed regulations under the Space Industry Act 2018. Defines eligibility criteria and prescribed roles for licensees. Includes requirements for risk assessments and safety cases. Establishes safety zones and public safety measures for spaceports.



CHAPTER 1

Exploring the universe: origins, current trends and likely developments

Humanity has always looked up and been curious to understand the Universe and its place within it. Science has uncovered much of the enormity of the universe, revealing that the Earth is not the centre of the Universe as was once thought, but instead one planet orbiting the Sun, as part of the wider Solar System. The Solar System itself is associated with one of the spiral arms of the Milky Way galaxy, which is one of more than 100 billion other galaxies like it in the observable universe. Objects such as black holes and exoplanets surrounding other stars and phenomena such as gravitational waves have been observed. Exploration of the Solar System and beyond has always been dominated by scientific endeavours rather than commercial interests and so it will largely continue over the next 50 years. By 2075, humans will have looked out further than ever before due to the expanding range of tools available in the quest to unravel the many mysteries of the universe.

Timeline of space science

Here a small selection of activity in space science is presented to provide context for future activity discussed in this chapter.

750 BCE
Mayan astronomers describe movements of the sun, moon and planets, predicting the waxing and waning of the moon within half a minute accuracy.

384 – 322 BCE
Aristotle proposes theory that Earth is at the centre of the universe.

1543
Copernicus proposes Heliocentric model of the universe.

1665/6
Sir Isaac Newton FRS develops theory of gravity which he uses to explain the movements of celestial bodies.

1609
Galileo uses spyglasses to make observations of the night sky and provides support for Copernicus's theory by observing moons in orbit around Jupiter.

1781
William Herschel FRS discovers Uranus orbiting the Sun beyond Saturn.

1860s
Sir William Huggins FRS uses spectroscopy to determine the chemical composition of stars based on the frequencies of light that their atmospheres absorb and emit.

1907 – 1915
Albert Einstein develops his Theory of General Relativity, refining Newton's law of Universal Gravitation and describing gravity in terms of matter warping spacetime. It also predicts the existence of gravitational waves, gravitational lensing and gravitational time dilation.

1912
Henrietta Swan Leavitt develops the 'standard candle' enabling astronomers to measure distances between stars more accurately. This was based on her discovery of the direct relationship between the brightness and pulsation period of Cepheid variable stars (Leavitt's Law).

1923
Edwin Hubble proves the existence of galaxies outside the Milky Way based on observations of 'standard candle' Cepheid variable stars in the galaxy NGC6822.

1931
Georges Lemaitre theorised that the universe's expansion must have started at a fixed point in time, growing from a concentrated mass-energy region, the 'primeval atom'. This was the founding principle of what later became the Big Bang theory.

1962
Giaconi's sounding rockets discover the first cosmic sources of X-rays, opening the field of X-ray astronomy.

1967
The Soviet Union's Venera 4 craft lands on Venus becoming the first probe to successfully perform in-situ analysis on another planet.

1970s
Vera Rubin publishes research on galaxy rotation rates. Her observations showed that galaxies rotate at speeds that cannot be explained by visible matter alone, suggesting the presence of unseen 'dark' matter, first proposed in 1933 by Fritz Zwicky.

1969 – 1973
NASA and the US Department of Defence's Vela satellites, whose primary role was to monitor for nuclear tests, (to support the Nuclear Test Ban Treaty), inadvertently discover cosmic gamma ray bursts.

1970
Uhuru (NASA), the first x-ray observatory is launched, providing the first observational evidence for black holes and recording the behaviour of neutron stars in binary systems.

1977
Voyager 1 and 2 probes launched to complete grand tour of the outer planets, sending valuable observational data of the Solar System before heading into interstellar space.

1978
First real-time controlled ultra-violet observatory; International Ultraviolet Explorer (IUE – joint US/NASA, UK, and ESA. In operation for nearly 20 years.

1983
IRAS, first infra-red observatory. Joint US, UK and NI project.

1989
NASA's Cosmic Background Explorer (COBE) launched to enhance understanding of the cosmic microwave background first discovered in 1964. COBE provided detailed measurements of this radiation by creating a detailed map of the sky.

1989
First astrometric satellite Hipparcos – ESA only. Pathfinder for 2013 Gaia, ESA only.

1990
Hubble Space Telescope is launched – a space-based observatory in low-Earth orbit, providing unprecedented images and data across the universe, from planetary systems to distant galaxies.

1992
Poltergeist and Phoebetor become the first confirmed exoplanets, found approximately 2,300 light years away in the constellation of Virgo. Now more than 5,800 exoplanets have been discovered as of 2025.

1998
Scientists discover that the Universe is expanding at an accelerating rate, which can only be accounted for with a mysterious additional component 'dark energy'.

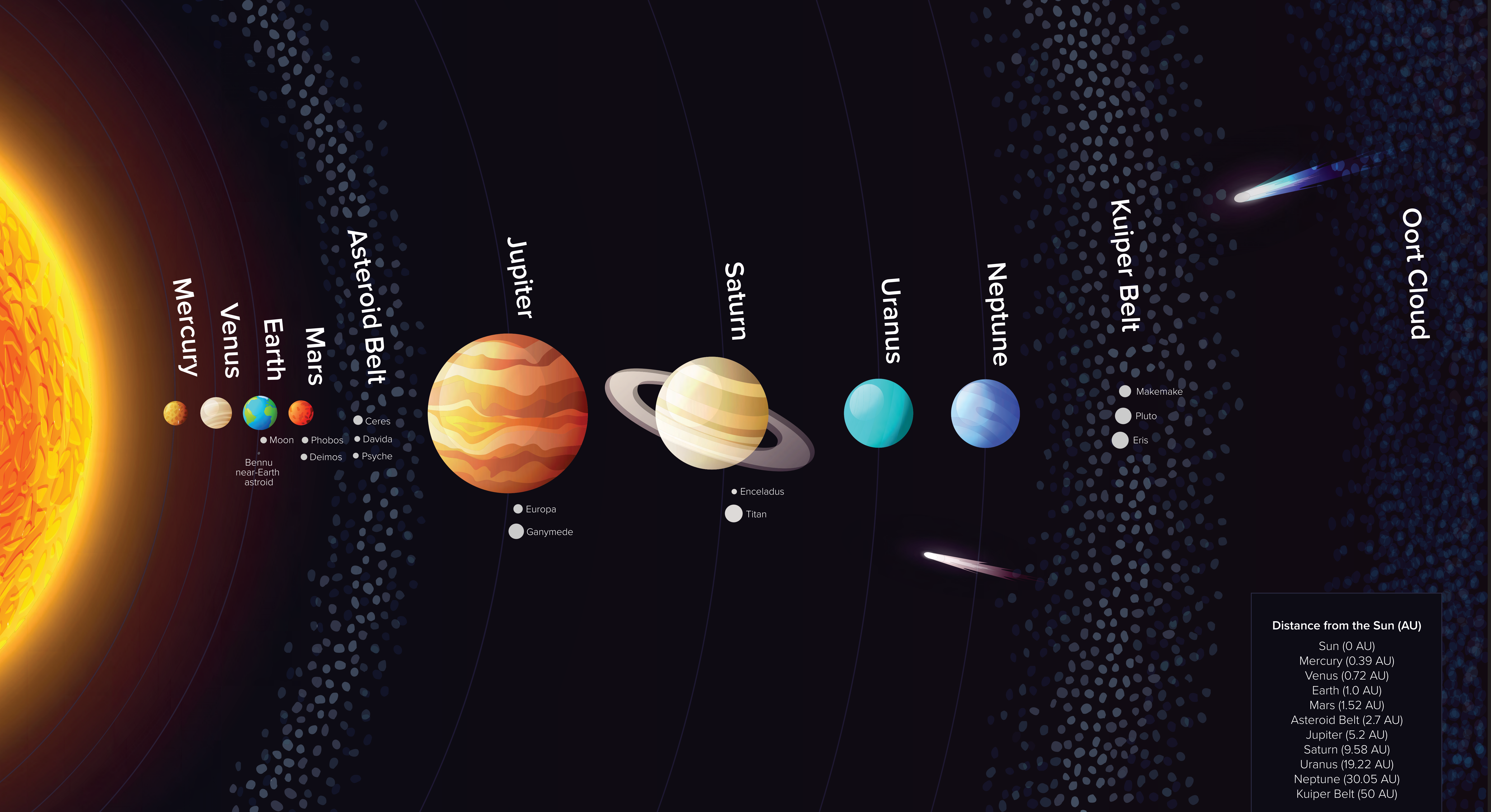
2005
NASA's Cassini mission identifies a subsurface ocean on Saturn's Moon Enceladus after observing plumes of water on the surface. Enceladus is now considered a promising location in the search for life beyond Earth.

2015
LIGO and Virgo collaborations detect gravitational waves from the merger of two black holes.

2019
The Event Horizon Telescope, a global network of radio telescopes collaboratively produced the first-ever image of the shadow of a black hole, specifically the supermassive black hole at the centre of the Messier 87 galaxy.

2021
James Webb Space Telescope (JWST) is launched, an orbiting infrared observatory designed to study the universe's earliest stages, and the atmospheres of exoplanets.

2023
Launched in 2018, the Parker Solar Probe (PSP) breaks the record for the fastest human-made object, hitting a speed of 635,266km/h after using gravity from a Venus flyby to generate an additional push. PSP continues to measure patterns of change on the Sun's surface.



Current position

When considering the Solar System and beyond, most science has focused on understanding the fundamental physical nature of the Universe and the objects and natural phenomena that emerge within it, including the search for life. In these endeavours, scientists make use of a range of tools to test their theories

Tools for exploring space

Over centuries, understanding of the Solar System and the Universe has advanced incrementally through observations, theory and modelling. Given the enormous distances between objects in space and the risks and huge costs involved in human spaceflight, most observations of the Solar System and beyond have been conducted remotely using telescopes and spacecraft (commonly referred to as probes) Recently a more limited number of sample return missions have also been conducted to bring materials back to Earth for more detailed study.

The world's major space agencies have set out a vision of science-rich space exploration through the International Space Exploration Coordination Group (ISECG) and the Committee on Space Research (COSPAR). Here, a small selection of space agency-led missions are presented, which are ongoing or proposed, to give a flavour of how space science might develop. That being said, the plans of space agencies can change. For instance a US government proposal to halve NASA's science budget was put forward in April 2025. This could mean that some proposed missions such as the Nancy Grace Roman telescope will be cut though they may be revived later. Whilst most planned missions currently are coordinated by different national space agencies, in the coming 50 years a continued expansion in private research endeavours to complement this is likely.

Left
Jodrell Bank Observatory. © Mike Peel.

FIGURE 3

Telescopes

Telescopes were one of the first instruments that humans used to explore space. They rely on electromagnetic radiation such as visible light (but also other frequencies invisible to human eyesight) which is reflected off, absorbed by or produced by, distant objects. There are two main categories, ground-based and space-based. Ground-based telescopes are much cheaper to build and easier to repair as they are readily accessible on Earth. Very large lenses/sensors can be deployed without the need to launch heavy components into space. However, certain parts of the spectrum, namely gamma rays, x-rays, short-wavelength ultraviolet, long radio waves, and infra-red are blocked by the Earth's atmosphere, which limits what these telescopes can see. Space-based telescopes open these areas of the electromagnetic spectrum, allowing observations of regions of space which would otherwise be blocked by the Earth's atmosphere or by objects which absorb frequencies seen by ground-based telescopes. The low gravity of many locations in space, enables the deployment of large and delicate telescopic structures.

Ground-based telescopes

For example the Jodrell Bank Observatory (the UK's largest radio telescope) has played an important part in the study of meteors and the moon, the discovery of quasars, quantum optics, and the tracking of spacecraft.

The largest ground-based telescope in the world is the Five-hundred-metre Aperture Spherical radio Telescope (FAST) which also detects cosmic radio waves, based in Guizhou, China. It has been used to observe pulsars and detect interstellar molecules.

FIGURE 3 (CONTINUED)

Space-based telescopes

2026: Planetary Transits and Oscillations of stars (PLATO)
To characterise Earth-like planets in the habitable zones of their stars.

2027: Nancy Grace Roman Space Telescope
To explore dark energy, exoplanets and infrared astrophysics.

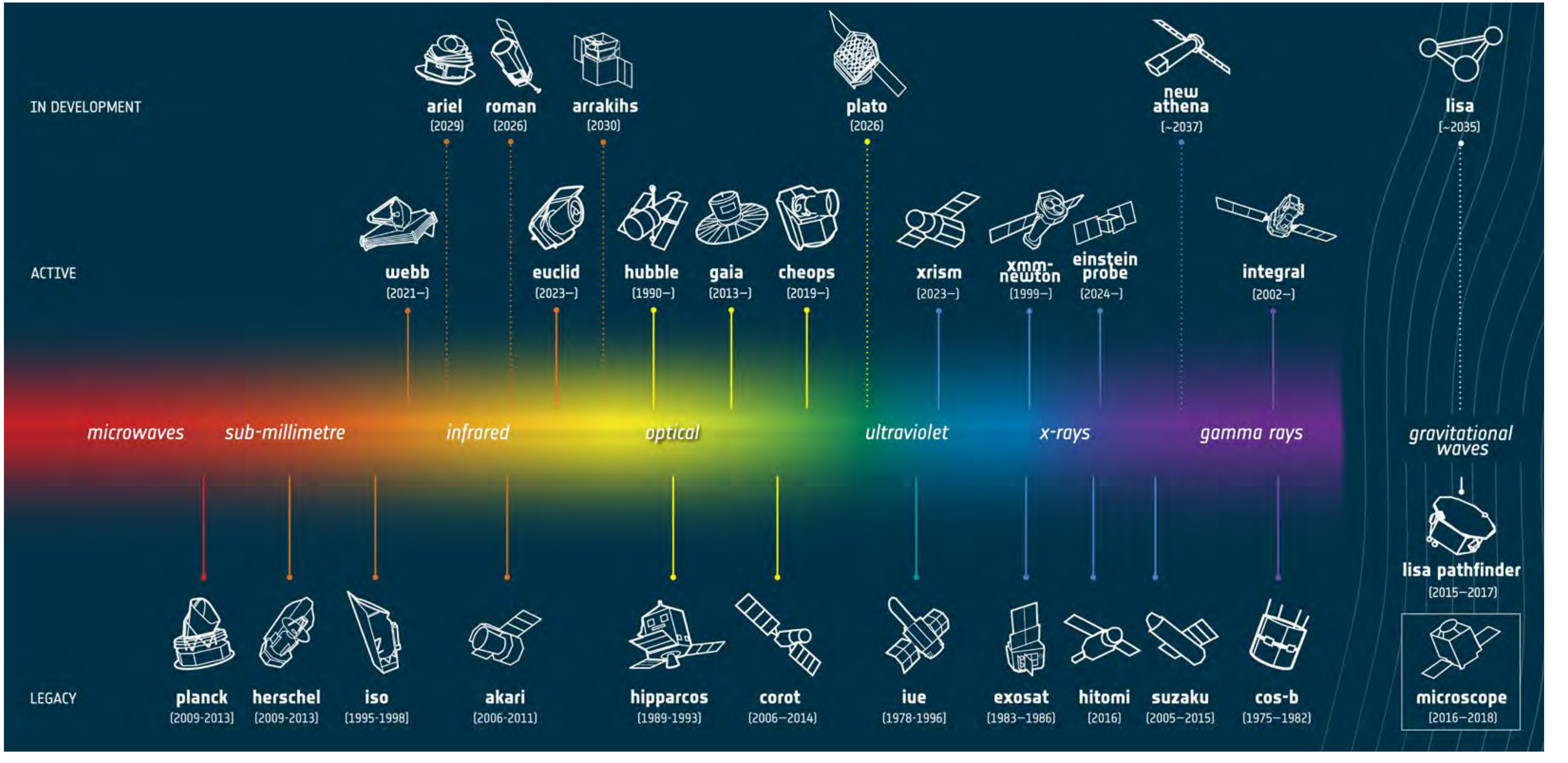
2027: Extremely Large Telescope
Part of the European Southern Observatory, it will have a light gathering area 250x that of Hubble enabling images that are 16x sharper to study a range of objects including exoplanets and phenomena such as dark matter.

2030: Spektr UV
Equipped with spectrographs to observe phenomena in the UV range.

2037: NewAthena
ESA mission that will be the largest X-ray observatory ever built. It will investigate some of the hottest and most energetic phenomena in the Universe with unprecedented accuracy and depth.

2041: Habitable Worlds Observatory
Will be used to search for and image, Earth-size exoplanets in the habitable zone of their Solar System, ie the region where liquid water can exist.

2051: Far-Infrared Great Observatory
Will serve a variety of purposes including studying black hole evolution, as well as looking for signs of water from molecular clouds to proto-planetary disks.



Above
Illustrations showing the current state of ESA's astronomy missions, including collaborative missions with partner agencies (e.g. the NASA/ESA Hubble Space Telescope and the NASA/ESA/CSA James Webb Space Telescope), upcoming missions of opportunity (e.g. the JAXA/NASA Xrism and the Chinese-led Einstein Probe). © ESA.

FIGURE 3 (CONTINUED)

Above
NASA's Perserverance rover in a clean room at NASA's Jet Propulsion Laboratory in Pasadena, USA. © NASA/JPL-Caltec.

Uncrewed spacecraft (probes)

Uncrewed spacecraft explore objects in the Solar System and in the case of Voyager 1 and Voyager 2, travelled beyond the Solar System into interstellar space.Uncrewed spacecraft can be equipped with a range of scientific instruments for the mission they are on, to gather data on a wide range of variables such as radiation levels, magnetic fields and atmospheric composition. They must be designed with materials which can withstand the harsh conditions of outer space using radiation hardened components and adequate thermal protection. Advances in materials science, robotics and computing have led to more sophisticated and robustspacecraft. Miniaturisation of sensors which are higher quality with improved sensitivity for data collection means that more instruments can be installed on the same craft making newer craft capable of doing more than their predecessors, increasing their scientific value. The ability to accurately and reliably transmit data back to Earth has also improved and artificial intelligence (AI) has been deployed to enable more precise control of craft in real time[2].

There are several broad categories of uncrewed spacecraft:

Orbiters
For sustained observations of planetary bodies.

2026 – JUICE (Jupiter Icy Moons Explorer)
A European Space Agency mission designed to explore Jupiter's moons Ganymede, Callisto, and Europa, focusing on their potential as habitable worlds.

2028 – EnVision
An ESA mission, with NASA participation, aimed at studying Venus' atmosphere, geology, and surface, to understand its evolution and compare it with Earth.

2029 – Psyche
A NASA mission set to explore the metal asteroid Psyche, which is thought to be the exposed iron core of a protoplanet, providing insights into planetary cores.

Flybys
Craft that fly past planetary bodies but do not orbit them.

2030 – Comet Interceptor (Flyby)
A European Space Agency mission designed to study a pristine comet or an interstellar object just as it is entering the inner Solar System.

Landers
Surface exploration

2027 – Dragonfly (Lander – rotorcraft)
NASA's mission to Titan, Saturn's largest moon, aims to explore its surface and atmosphere, studying prebiotic chemistry and extraterrestrial habitability. Will also have the ability to change position using vertical flight capability.

FIGURE 3 (CONTINUED)

Rovers

Rovers on Mars, such as Curiosity, Rosalind Franklin and Perseverance, explore the Red Planet's geology and search for signs of habitable environments and past life.

Penetrators

The Exobiology Extant Life Surveyor (EELS) is a snake robot designed to descend down narrow vents in the icy crust of Saturn's moon Enceladus to explore the ocean hidden below in search of life

They must be designed using appropriate materials to ensure they are fit for purpose for the mission they are on.

Sample return missions

Sample return missions involve sending robotic spacecraft to collect samples from extraterrestrial bodies, e.g., planets, moons, asteroids, and comets and returning them to Earth for comprehensive analysis. Returning samples from space to laboratories provides some notable advantages over in-situ analysis. Despite spacecraft instrumentation for in-situ analysis becoming increasingly sophisticated, laboratory-based instrumentation remains superior. Since 1969, cosmic material has been returned to Earth, from the Moon, two asteroids, comet Wild 2 and from the Solar wind – either by robotic spacecraft or by astronauts. Material has also been returned from low Earth orbit, comprising a mixture of interplanetary particles and space debris.

NASA-ESA Mars Sample Return

A collaboration between NASA and the European Space Agency (ESA), to return samples from Mars to Earth collected by the Perseverance rover, launched in 2020. The return date is now under review due to increases in mission costs and reductions in the NASA science budget. This mission seeks to answer critical questions about Mars' geology, climate, and potential for past life.

NASA OSIRIS-Rex

Launched by NASA, the OSIRIS-REx spacecraft returned from the asteroid Bennu. The mission has identified the building blocks of life providing insight for how life might have arisen on Earth

Chang'e 6: Lunar sample return

China collected the first sample from the far side of the Moon, revealing insights into how Earth's nearest neighbour was formed

JAXA Martian Moons eXploration

Probe with a scheduled launch in the late 2020s which aims to collect the first samples from the Martian moon, Phobos, as well as taking measurements of the Martian climate and conducting a flyby of Mars' other moon, Deimos.

Right
Astromaterials processors use tools to collect asteroid particles from the base of the OSIRIS-REx science canister. © NASA.

Funding space science

Financial constraints in recent years, exacerbated by inflation and other economic shocks have put governments around the world under pressure. This has resulted in cuts to various programmes which have hit space agencies and other funding bodies responsible for critical space science missions.

Examples include delays to the Mars Sample Return (MSR) mission which is due to bring back samples collected by NASA's Perseverance Rover. This has been deemed one of the highest priority missions for planetary scientists. Delays to missions often result in increased costs and sacrifices that must be made against budgets for other missions, resulting in a smaller amount of science per budget spent. It can also jeopardise collaborations with other space agencies who may be involved in other phases of the same mission but are nonetheless dependent on early stages being funded, such as the European Space Agency's role in creating the Earth Return Orbiter to support the MSR mission.

Similarly budget cuts to the Chandra X-Ray observatory will essentially result in its early decommissioning. Chandra provides valuable data to research groups around the world and whilst it is complemented by the European Space Agency's XMM-Newton, Chandra's decommissioning would represent a great loss to x-ray astronomy.

With the European Space Agency's NewAthena planned for 2037 and NASA's X-ray Great Observatory planned as a replacement planned for Chandra in 2047, it will potentially leave astrophysicists without access to an important imaging tool for decades. Funding cuts can therefore set the pace of science back and risk the cascading benefits of new discoveries.

The position for UK space science

The Space Academic Network (SPAN) in the UK is a consortium of UK-based space scientists and academics working in other disciplines who focus on space. SPAN have outlined some of the challenges that are unique to UK researchers[3]. The lead time for developing space science missions is substantial with more moving parts compared to many other types of discovery science. Depending on the nature of the mission, funding must be secured to design an instrument, launch it into space, monitor and calibrate data collection during its mission and employ scientists to analyse the data. It tends to be the case in the UK, that funding for different components of these missions must be secured from different funding pots. This creates a vulnerability if research teams manage to secure grants for one component but then fail to receive money for another, either because the grant is unsuccessful technically or because the funding would not be timely with fixed launch schedules. A recent example was the UK research group that designed the Lunar Thermal Mapper instrument for water detection on the surface of the Moon, making use of innovative freeform optics for improved performance. The instrument had received successful peer review several times in its development but was at high risk of being cancelled due to funding timelines not coinciding with the launch schedule set by NASA. The instrument did eventually fly with the mission (and unfortunately was lost when the craft failed to reach Lunar orbit) after a special case was made on the reputational damage that would be caused with international partners had they group had to withdraw its participation. However, it demonstrates the potential for wasteful inefficiencies that can occur in a system which does not secure the funding route for the entirety of a scientific mission.

SPAN supports the idea of provision of funding ideally over a 10-year planning cycle (with regular review periods and some inherent in-built flexibility to enable funding to be refocused where required). However, a more practical solution given Parliamentary terms might be a 3+2 scenario as used by the European Space Agency to set a 10 or more year outlook. This would provide stability for academia and make the UK a more trusted partner in bilateral and multilateral missions, enhancing the UK's soft power in space and science leadership,

Space research in the UK sits in the wider context of (possible) flat funding and cuts to research funding settlements across the board for different funding bodies. However, delays in funding provision due to government spending review timelines as well as the issue of spending within the constraints of the projections made for financial year boundaries can also impact space science research particularly acutely due to unavoidable changes in development and launch schedules which can dictate when spending lands. SPAN has indicated that greater flexibility or bridging funds would be particularly valuable to the UK's space science and technology development position.

This flexibility would also ensure that members of staff could be kept on contracts without having to be put at risk as is standard practice in UK universities when contracts are within three-six months of their end dates. This would help to avoid the loss of expertise on particular areas of space research with staff lost to other sectors and the real and potential loss of capability in academic space groups which help underpin the sector as a whole through R&D, training and interactions with industry and via clusters. SPAN has indicated potential benefits if long term projects could be funded across financial boundaries to avoid inefficiencies of a 'start and stop' approach. These projects would still need to be subject to review to ensure value for money. A long-term outlook/planning cycle could help ensure value for money by setting an agreed strategy.

Solar system wide science

What could science look like in the Solar System in future? Spacecraft hardware (instrumentation, power systems etc.) will become more sophisticated but advances in what can be done in ground-based laboratories will continue over the next 50 years as well, making sample return missions the best way to study some subjects in detail. Sample return missions might not always bringing objects back to Earth. In some cases, it may be more efficient and practical to transport samples to more convenient locations, such as the moon with its weaker gravity, to land samples more easily and analyse them in fully equipped laboratories[4]. However, analysis involving larger infrastructure such as giant particle accelerators, will still involve sample return to Earth for the foreseeable future as establishing such facilities on other planetary bodies would be prohibitively expensive.

By 2075, with sufficiently supportive policies, regulations, laws and international collaboration and cooperation, it is possible that laboratories in different conditions and locations across the Solar System will be built, forming a new network of space research centres. This could include orbital facilities in locations where robots and humans work in tandem. The Moon, Mars and other bodies of high scientific interest could host laboratories and telescopes of various kinds, making use of the unique properties in each location. In the longer-term, these laboratories may be precursors to robot-operated laboratories further afield, such as within the high radiation environment of the surface of the Jovian Moon Europa or on the surface of objects in the Kuiper Belt (a donut-shaped region of icy bodies beyond the orbit of Neptune).

Results could be shared and integrated across the Solar System at pace, relayed by laser communication between various satellites and other craft positioned in strategic locations via a Solar System-wide internet connection.

This new research capability will enable research that has never been done before. It will expand the datasets available and allow for more robust conclusions in a range of scientific fields.

An important benefit is that by making it possible to do more experiments (potentially resulting from cheaper access to space as well as the growing number of facilities) it will be possible to achieve greater replication in experiments. Robust science relies on the ability to replicate results to confirm findings. Given the costly nature of launching experiments into space currently, it is often the case that experiments involve a small number of replicates (microbiology experiments, for example, may involve three replicate samples). Thus, making it cheaper and easier to have studies with large sample sizes could improve the statistical and experimental quality of experiments and allow researchers not only to achieve greater replication in their own experiments, but to test and verify existing experimental data. Opening new locations would also enable experiments to be carried out in a range of different combinations of partial gravities and ionising radiation levels found across the Solar System, which could lead to myriad discoveries and benefits, demonstrating how life, including human life and associated organisms, responds to space conditions in different locations in the Solar System. A vastly expanded laboratory capacity in Earth orbit and across the Solar System could also widen access to space research to many more researchers.around the world.

Skills for space

With an increased range of research facilities and commercial activity anticipated in the space sector over the next 50 years, there will be a greater need for a workforce that can fill space sector roles. The 2023 UK Space Skills Survey[5], revealed existing challenges required for space careers in the UK with over half of organisations which responded reporting skills gaps in their current workforce. Notably, the survey shows that of those respondents, 72% reported gaps in software and data skills, driven by an increased need for the skills involved in using AI and machine learning as well as data analysis and modelling. The Royal Society believes that mathematical and data education needs to change in order to prepare all young people for future jobs, as well as their future lives as citizens. As such, in 2024 the Royal Society report *A new approach to mathematical and data education*[6] recommended that, among other reforms, the UK Department for Education should ensure computational tools and technologies form a substantive and embedded part of mathematical education.

In order to produce the widest possible pool to recruit from for the space sector, it is important to ensure that:

- As many young people as possible are taking a broad mix of subjects, including STEM subjects, for as long as possible;
- Barriers to participation in STEM education are reduced and removed as much as is possible.

The Royal Society advocates for long term education system reform, which, among other things, should prioritise ensuring that young people have the broadest possible education up to the age of 18. Allowing a broader range of study would help to address the low numbers of young people currently taking subjects such as physics and computing post-16.

Teacher recruitment and retention presents a broader challenge for STEM education and as a result, a challenge for space education and skills. STEM education has suffered hugely in recent years from missed targets in recruitment of new teachers, particularly in mathematics, physics and computer science. A 2025 National Foundation for Education Research (NFER) report shows that the government met just 31% of its target for teacher recruits in physics in 2024/25, and just 37% of its target for computing teacher recruits. In addition, the impact of teacher shortages tend to hit those in more disadvantaged areas harder. For example, the proportion of maths teaching hours taught by maths specialists is 12 percentage points lower in the most deprived schools than in the least deprived schools. As the Space Skills Alliance identifies, the space sector should support the work of the scientific learned societies to address these challenges.

Skills gaps are a problem in many hi-tech sectors and limit the ability of businesses to grow and innovate.

But what purposes can this new scientific infrastructure serve?

Here, two areas of science are considered which could be greatly enhanced as scientific instrumentation evolves over the next 50 years.

The future of biological sciences in space

The search for life

"Are we alone?" is a fundamental scientific question which is also of enormous interest to the public, and one which the space age has moved from the realm of intellectual conjecture to that of practical scientific investigation.

BOX 1

What is life?

People often think they intuitively know what is meant by 'life' but defining it in a simple and comprehensive way is difficult. Typical formulations of a definition may include the following features[7]:

- Ordered structures
- Energy Processing (use of food to provide energy for activity)
- Growth and development
- Responsiveness to the environment
- Reproduction (ability to reproduce their own kind)
- Regulation (ability to adjust their system to adapt eg temperature, sugar levels)
- Evolutionary adaptation

Infectious agents such as viruses and prions (infectious proteins like the causative agent of Bovine Spongiform Encephalopathy, BSE) exhibit some of these criteria but are sometimes not considered alive because they are unable to reproduce independently of a host.

Ultimately, the gradation in chemical complexity that leads from the simplest chemical compounds to life may obviate an all-encompassing and simple definition of life. Nevertheless, we can circumscribe a set of characteristics of matter that we are looking for elsewhere in the Universe that would be of interest to biologists. In this sense, an operational definition of life can be used to establish what it is that we seek. For example, chemical systems capable of reproduction and evolution would include many of the living things of interest to scientists on Earth and potentially elsewhere. With respect to its fundamental chemical structure, life on Earth is largely constructed from a number of common elements including the six key chemical elements Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus and Sulphur (often referred to as the CHNOPS elements). Our definitions of life may have to remain open-minded to the possibility of different chemical and biochemical architectures of life elsewhere, if we ever find it[8]. Astrobiology is the scientific study of life in the universe. It explores the origins, evolution, distribution, and future of life on Earth and beyond. This interdisciplinary field combines aspects of biology, chemistry, physics, astronomy, and geology to understand the potential for life on other planets and moons.

A significant asymmetry exists with respect to the depth of knowledge in space science across different fields. Physics and chemistry, through technologies such as space telescopes, have emerged as universal sciences, giving insights into the physics and chemistry of the Universe right back to shortly after the Big Bang and across the observable spatial scales of the universe. Yet, at the time of writing, biological sciences (the study of the matter known as life), appears to be confined to a single planet in the observable universe. Is it the case that life really is confined to a single planet or can instances of life be found beyond Earth?

As new missions are planned beyond 2030, their focus is likely to include the search for extant and extinct life beyond Earth – and the evidence they provide will take humanity closer to answering that question.

Spacecraft have already visited Mars and Saturn's largest moon, Titan, and flown past Jupiter's moons, Europa and Ganymede, as well as Saturn's moon, Enceladus. All these bodies are believed to possess large bodies of subsurface water and to be possible locations to test the hypothesis that instances of life exist, or have existed, on other planetary bodies[9].

Attention is now also turning to the myriad of exoplanets (planets beyond Earth's Solar System), of which more than 5,500 have now been found[10] (though there are likely trillions), with particular focus on biosignature gases, such as oxygen, their potential false positives and ways to establish with high confidence the presence of life. Meanwhile radio communications continue to search the Universe for intelligent life – through the so-called Search for Extra-terrestrial Intelligence (SETI).

BOX 2

Citizen science

Citizen science projects in space allow the public to contribute to scientific research and discoveries. SETI@home was a project launched by the Berkeley SETI Research Center. It aimed to use the idle processing power of volunteers' computers to analyse radio signals from space, searching for signs of extraterrestrial intelligence. Participants would run a program that downloaded and analysed data from radio telescopes. As of March 2020, SETI@home stopped distributing new tasks to volunteers. The project is currently in hibernation while the team focuses on analysing the vast amount of data collected over the years. They have left open the possibility of resuming volunteer computing in the future. With the huge datasets generated by scientific experiments only increasing, distributed computing projects like this may continue to be used into the future.

Other examples of citizen science in space:

Active Asteroids
Inspect images to find comet-like objects hiding in the asteroid belt[11]

Astroplant
Grow plants and collect data on potential crops to grow in space[12]

Backyard Worlds Planet 9
Search beyond Neptune for new planets and nearby stars[13].

Cloudspotting on Mars
Help map cloud formations in images of the Martian atmosphere[14]

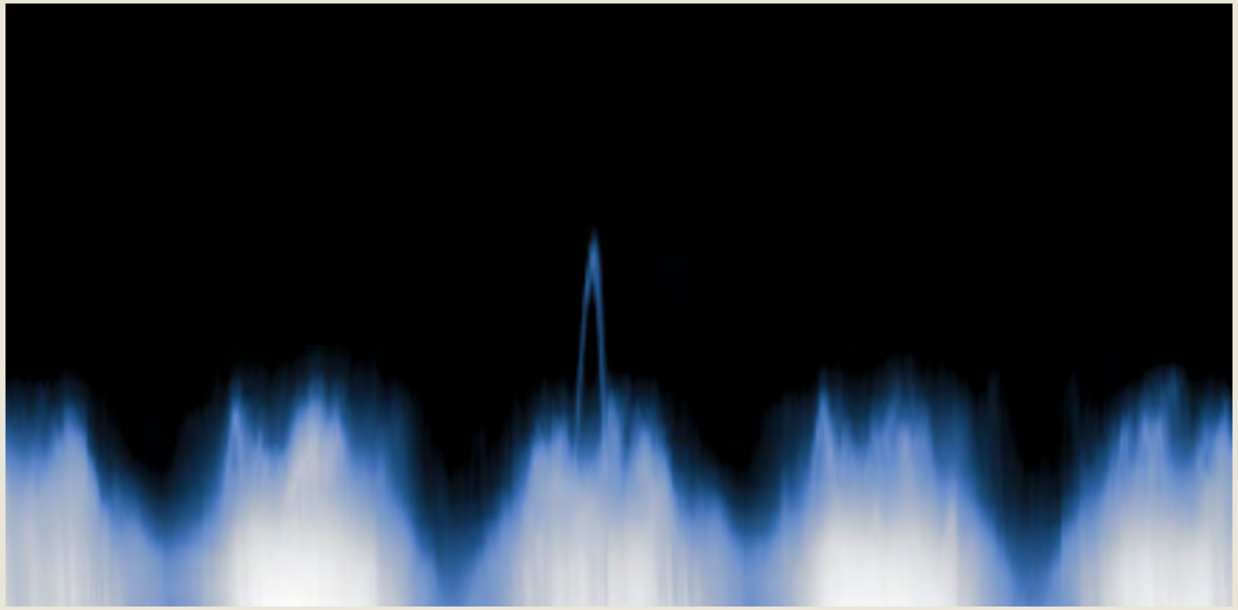
Eclipsing Binary Patrol
Examine space telescope data to find rare pairs of stars[15]

Exoasteroids
Search space telescope images for white dwarfs that flash as they devour asteroids[16]

Exoplanet Watch
Observe transiting exoplanets with small telescopes[17]

Zooniverse (Space Warps)
Search for the incredibly rare phenomenon of strong gravitational lensing in data from the Euclid telescope[18]

These projects are open to anyone with a smartphone or laptop, making it easy to participate from anywhere in the world. Citizen science projects offer a useful way to contribute to space exploration and learn more about the universe. In this way citizen science can be used to engage public audiences in space topics and serve as a useful educational tool.

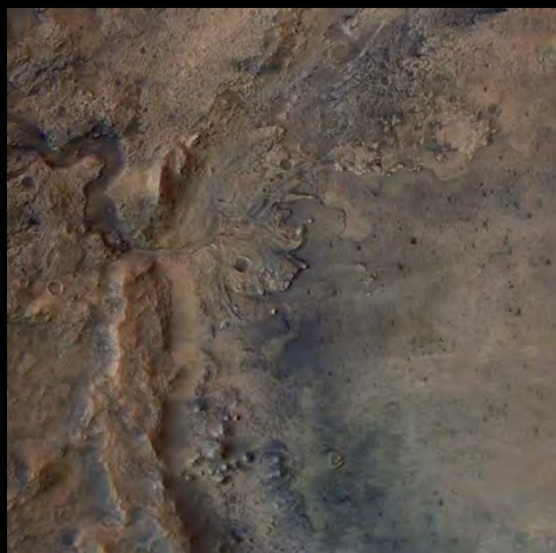


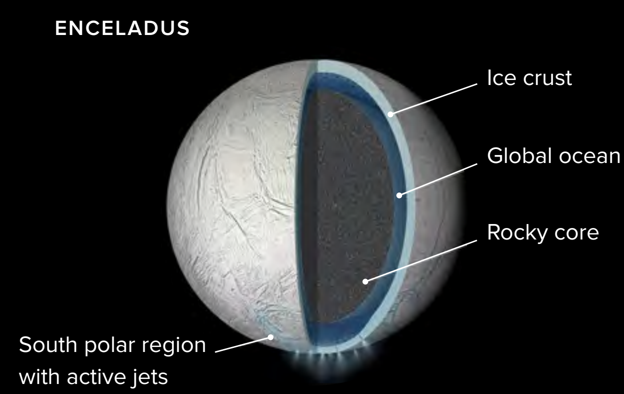
Left
Cloudspotting on Mars asks members of the public to look for arches in data such as this one collected by NASA's Mars Reconnaissance Orbiter. © NASA.

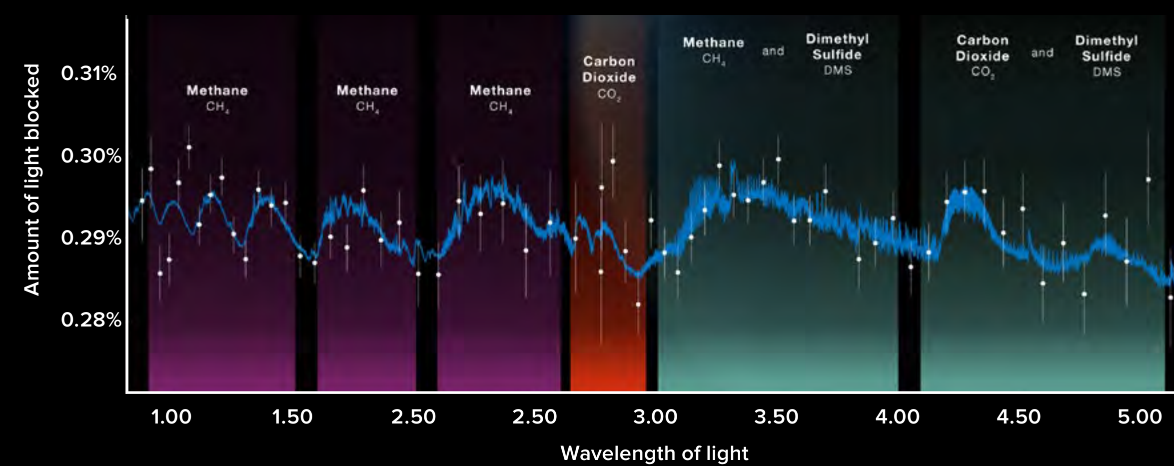
By 2075, further missions to Mars, the icy moons of the outer Solar System and telescopes capable of searching for biosignature gases in the atmospheres of exoplanets will have provided an array of substantial data. In the next 50 years, it is likely that there will be an answer to the question of whether there is unambiguous evidence of life on a wide diversity of planetary bodies in Earth's near neighbourhood. This will be significant because it will move the search for life beyond Earth past speculation to a much more empirical basis, with important scientific implications.

FIGURE 4

Examples of moons and exoplanets







MARS

Earth's nearest neighbour, Mars was known to have had liquid water more than 3 billion years ago. There is evidence of former rivers and lakes. It may be that life still exists underground, away from the harsher conditions on the surface, or that evidence exists for extinct life that has been fossilised over time.

Distance from Earth

55 – 400 million km (0.000042- 0.000057 light years, 4.3 – 20 light minutes)

MOONS WITH SUBSURFACE OCEANS

it is known that life on Earth requires liquid water to exist. It is present in the Moons of Jupiter (Europa and Ganymede) and Saturn (Enceladus) underneath thick crusts of ice. Could life exist in these subsurface oceans?

Europa and Ganymede

Distance from Earth: 628.3 million km (0.000066 light years, 35 light minutes)

Enceladus

Distance from Earth: 1.272 billion km (0.00013 light years, 71 light minutes)

DETECTING BIOSIGNATURES ON DISTANT EXOPLANETS

There are planets outside the Solar System that orbit other stars eg Proxima Centauri B, K-12 18b. By analysing the wavelengths of light reflected from exoplanets, it is possible to determine the type of chemistry in their atmospheres. If chemicals only known to be produced by living organisms on Earth are observed, it may imply the existence of similar living organisms. It is important to be cautious in how signals are interpreted because there could be other unknown chemical pathways that naturally generate the same chemicals without involvement of a living organism.

Proxima Centauri B

Distance from Earth: 40.11 trillion km (4.2 light years)

K-12 18b

Distance from Earth: 1.17 quadrillion kilometers (124 light years)

Images

(Left to right) The remains of an ancient delta in Mars' Jezero Crater. © NASA/ESA/DLR/FU-Berlin; Enceladus (thickness of layers is not to scale). © NASA/JPL-Caltech; and JWSTexoplanet. Illustration by NASA, ESA, CSA, Ralf Crawford (STScI), Joseph Olmsted (STScI) based on the science of Nikku Madhusudhan (IoA).

If life is found

The implications of the discovery of life will very much depend on the nature of the life. If it is microbial, then the next question – is it related to life on Earth (for example transferred between Earth and another planetary body by material ejected into space in asteroid and comet impact events) or did it originate and evolve independently? In the former case, much would be learnt about the biogeography of life on interplanetary scales, and even if the life was related to life on Earth, long-term evolutionary divergence could still make this life of considerable biochemical interest. Sample returns from the asteroid, Bennu were found to contain amino acids as well as RNA and DNA nucleotides – the building blocks of life[19]. This could imply that asteroids seed life like that found on Earth as they impact other planetary bodies.

If life was found to be of an independent origin, then a novel biochemistry would be accessible, opening up questions and new lines of enquiry about the universality of biochemical pathways. Either way, the discovery of life would have enormously important implications for biology and ecology, which would become truly interplanetary sciences and more universal in their scope. It would also have significant ethical implications for how this life should be treated and how an ethic of protection might apply to it, if at all.

The discovery of extinct life (for example, fossils on Mars) could be more limiting (as scientists might be denied much detailed biochemical information, depending on the state of preservation) but it might still be possible to determine its relation to terrestrial life and it would, at the very least, indicate that another planetary body had transiently supported a biosphere. This too would substantially change the universality of biology and allied fields.

If the discovery of life was to come as a result of the detection of a signal from an intelligent source, this too would transform biological and allied sciences into fields with more universal application, but a range of other questions would be invoked, depending on whether the signal was sufficiently close to make a return communication plausible. Who would reach out and how? Should humanity try to communicate via radio signals – or is there an imperative to keep silent? If humans do communicate, what should be said – and how? Again, the ethical and societal implications would be hugely significant.

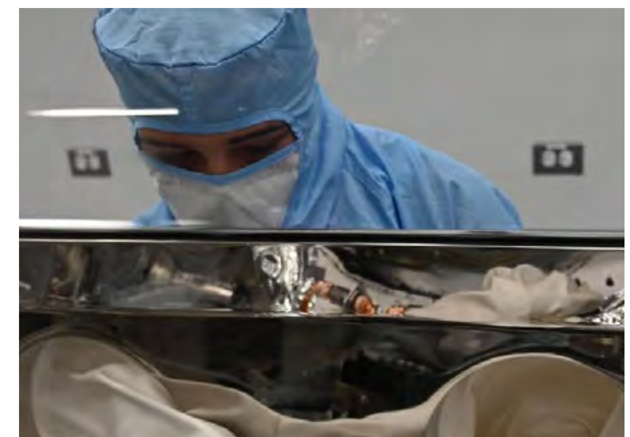
Right
A top-down view of one of the containers holding rocks and dust from asteroid Bennu, with hardware scale marked in centimeters. © NASA/Erika Blumenfeld and Joseph Aebersol.

The profundity of these outcomes varies, with communication with an external intelligence representing the most remarkable possibility. While the non-binding SETI Protocols, primarily covering the dissemination of information and the preparation of society for any developments and news, already exist, new practical protocols need to be agreed to manage the appropriate level of international response. For example, the discovery of microbial life may not elicit the need for global political action, although the scientific environment could change. However, intelligent extraterrestrial life would require international coordinated responses, potentially led by the United Nations Office for Outer Space Affairs (UNOOSA). Certain key issues would need to be considered such as the influence on biological sciences and the scope of its activity, scientific data sharing and through what means such data should be shared, and whether any legal or ethical codes would need to be applied to such life. With its strengths in research, life sciences, biosciences and international relations, the UK would be well placed to play a leading role in this process, helping to define the level and type of response needed in different scenarios.

If life is not found

Conversely, if after extensive research, no compelling evidence for life beyond Earth had been found, this conclusion would also have far-reaching implications. It could revive a Copernican view of the specialness of life in the universe, with implications for humanity's perception of itself.

The lack of life elsewhere might intensify the interest in life on Earth. It would raise questions as to why life occurred here and apparently not elsewhere and could provide added impetus to protect ecosystems on Earth, which could be potentially the only examples of life in our galactic neighbourhood.




Right
The sample capsule from NASA's OSIRIS-REx mission is seen shortly after touching down on the Department of Defense's Utah Test and Training Range on 24 September, 2023. © NASA/ Keegan Barber.

Views from the public on the search for life

In the Royal Society's public dialogue on space, participants viewed the search for life as both a profound scientific quest and a moral challenge.

Public dialogue participants expressed strong curiosity about the possibility of life beyond Earth. Many anticipated that if life is discovered, it would likely be microbial or microscopic in nature – yet the implications were no less significant. The discussions reflected awe at the scale of the universe and a broad belief that life elsewhere is probable.

"How many galaxies are there and in all of those galaxies there has to be one planet to have something similar to a caterpillar."
Workshop 1, Wrexham

But excitement was tempered by ethical reflection. A recurring concern was the risk of harming alien ecosystems through careless interference. Several participants drew parallels with historical mistakes made on Earth, such as the impact of colonial exploration on vulnerable communities.

"Why do we have the right to disrupt another planet's living life or anything, just for our own curiosity?"
Workshop 1, Wrexham

There was also deep interest in what different kinds of life might mean for our moral responsibilities.

"I think it depends what kind of form of life you're talking about… I think we all have different attitudes of the category of life [that] counts as life."
Workshop 1, Wrexham

Participants called for restraint, transparency, and international cooperation in the event of discovery – including agreed protocols and shared decision-making before any action is taken.

"If any life is found, there should be global collaboration and majority agreement about what action to take, if any."
Workshop 2, Cornwall

Read more about the Royal Society's Public Dialogue on Space conducted by independent research organisation Ipsos on page 180.

GOVERNANCE CHALLENGE

Managing the discovery of life

Regardless of the type of life found, it is important that the scientific community and national governments are adequately prepared to disclose its existence and disseminate information in such a way that minimises social disruption and the spread of misinformation amongst the general public, while preparing society for any relevant developments and activities.

International protocols, such as the SETI Protocols, for the discovery of life should be expanded on and developed to ensure that they are comprehensive for different scenarios of discovery, from microbial to intelligent life, and also set out an appropriate scientific, political and societal response. This should also establish appropriate thresholds of the robust scientific evidence required for a declaration of high confidence. A biosignature chemical signal from a distant exoplanet would be considered less reliable evidence than living microbial cells from a sample return mission, for instance.

There have also been instances of announcing false positives in the past, which can generate significant media attention and potentially result in distrust in science[20]. False positives could also be derived from contamination of sites with Earth-based bacteria and so Planetary Protection measures, including double-walled isolators in sample return spacecraft, will also be important to prevent forward contamination of samples.

Announcing the discovery of life may therefore be complicated, and should be managed sensitively, depending on the different types of actors involved in space missions. Such announcements could be particularly affected by new commercial actors in the space sector who may conduct their own science missions, where national governments may not be fully empowered to force transparency. These private actors may be involved in such activities and may seek to determine if there is commercial benefit to making use of the properties of these organisms.

Synthetic cells for space science and exploration

Supporting research

Regardless of whether life beyond Earth is found in the next 50 years, there are enormously interesting avenues to be pursued in investigating the potential for different forms of life using the power of engineering biology and allied biotechnological fields. The coming decades are expected to see greater integration between space-based and Earth-based science, with the two complementing each other in several fields. One recent focus of engineering biology is making synthetic cells: encapsulated complex biochemical systems that mimic the features of natural cells[21, 22, 23]. Such synthetic cells are now being used by researchers to study the possible origins of life on Earth, and that work can be extended over the next few decades to explore the kinds of life and cells that may exist elsewhere in the universe, particularly considering what biochemical properties would be needed for a life-like entity to thrive in an extra-terrestrial environment, such as one with almost no liquid water and with high radiation.

Being able to engineer microbes and cell-like biochemical systems to work in extreme environments in experiments on Earth could allow humanity to understand and predict what kind of life may be able to exist beyond this planet. Researchers could then ask fundamental questions such as whether there are alternatives to water as a solvent (for example liquid ammonia), and if non-carbon-based molecules, such as those based on silicon, can also perform the fundamental functions of life.

If any traces of non-Earth life were found elsewhere, engineering biology and synthetic cell research could be used to recreate findings in controlled terrestrial labs, possibly even before any extra-terrestrial organisms could be physically brought back to be studied. This might even be extended to make use of various biological properties of the life found and integrate them into biotechnologies with purposes on Earth.

GOVERNANCE CHALLENGE

Coordination of life sciences for space

The UK has recognised strengths in the life sciences in subdisciplines such as astrobiology, engineering biology, human health and genomics. However, currently many of these fields operate in a siloed way. Reviewing ways to bring these fields together could highlight synergies between them. Building links to space technology experts, both industry and academic, could enhance the UK's ability to influence life science applications in space. For example, synthetic biology can be applied to constructing organisms that can be used to investigate the limits of life and its capacities to survive in the radiation extremes of space environments (astrobiology). Thus, links exist between synthetic biology and astrobiology, both areas with strong UK efforts.

Extremophiles

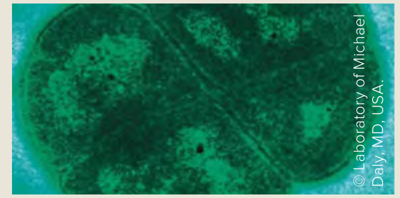
Organisms adapted for extreme environments

Organisms that already survive in extreme environments on Earth could also usefully support future space missions. Because of their unique survival characteristics, Earth's extremophiles have numerous properties that could be used to create custom organisms that can survive and thrive in the harsh conditions of other planetary environments, or even to survive dormant in the harsh conditions of space, such as extremes of temperature, pressure, radiation and ionic environments.

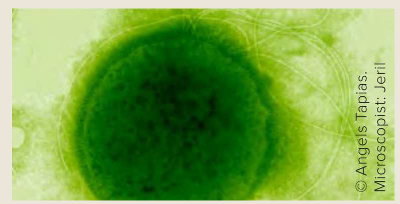
BOX 3

What are extremophiles?

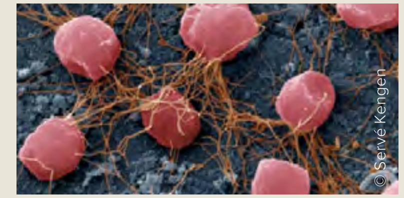
Extremophiles are organisms, primarily microorganisms, that have evolved to grow in conditions which are considered inhospitable to typical lifeforms on Earth. This includes extremes of temperature, pressure, radiation levels, minimal oxygen, a shortage of water or nutrition, or high acidity or alkalinity. The distinct biochemistry of Earth's extremophiles makes them interesting subjects for research because they can provide a glimpse into the origin and evolution of life from the harsh conditions of early Earth. Their ability to produce unique enzymes (extremozymes) makes them valuable for industrial procedures and research applications which operate in, or create, harsh conditions.



Deinococcus radiodurans
Polyextremophile bacterium that can tolerate extremes of radiation, cold, dehydration, vacuum and acid. Survived for three years in space during experiments on the International Space Station (ISS).

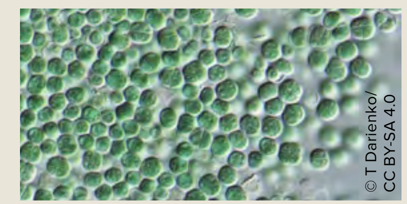


Thermococcus gammatolerans
Archaeon found in hydrothermal vents in the deep ocean. Thriving at temperatures of 88°C, it can withstand doses of ionising radiation that are 6000 times greater than the dose that would kill a human



Pyrococcus furiosus
Archaeon also found in the extreme conditions of hydrothermal vents. It can endure temperatures greater than 100°C. Some of the enzymes it produces contain rare elements such as tungsten and their high thermal stability has seen them utilised in biotechnological processes that are run at high temperatures such as the Polymerase Chain Reaction.

Chryseobacterium greenlandense
Bacterium that was recovered from a 120,000 old ice core in Greenland. Capable of surviving in high pressure, reduced oxygen nutrient poor habitats.



Chroococcidiopsis sp.
Photosynthetic bacterium which has been shown to be able to survive dormant for at least 13 million years in a desiccated form before being reactivated. It has been suggested that this sort of organism might have endured on Mars following the collapse of its atmosphere and loss of water.

BOX 3 (CONTINUED)

Earth's extremophiles can provide insight into how life might survive in different harsh space environments. For example, given that most bodies in the Solar System are very cold, the study of psychrophiles – extremophiles which live in cold conditions – could help scientists to understand how potential life could survive on cold bodies. It is also possible that life capable of withstanding high pressures could live in subsurface environments closer to the warmer core of planetary bodies. There is a rich and understudied subsurface ecosystem on Earth which may provide clues[24].

Radiation is a particular threat both for human health and damage to instruments wherever a magnetic field is not present to provide shielding. *Deinococcus radiodurans* has inspired the creation of a synthetic compound called MDP[25], made of manganese ions, phosphate and a small peptide which mimics the organism's ability to withstand high doses of radiation, up to 28,000 times a lethal dose for humans[26]. By acting as a powerful antioxidant, MDP could be exploited to provide radiation shielding for a variety of purposes on space missions.

Extremophiles could also be engineered to support space operations in other ways. Using knowledge of the biochemistry of extremophiles, it could be possible to create 'living tools' able to function in space. For example, synthetic microbes could support lunar mining by breaking down resources in a similar way to the use of natural microorganisms in existing operations on Earth.

The future of physical sciences in space

Space astrophysics grew rapidly with medium-scale dedicated missions, mostly developed from technology proved from sounding rockets or early test launch experiments. Many early success stories had the UK in bilateral or similar partnerships, providing a leading role eg International Ultraviolet Explorer (1978) and Infrared Astronomical Satellite (1983).

For smaller scale missions, affordable For smaller scale missions, affordable launches and available communications technologies have made dedicated space missions feasible on the cost and complexity scale of current ground-based astronomy research projects. This makes it feasible for individual research consortia to build and operate dedicated research facilities in space. Among the first targeted Solar System exploration missions, is the Venus Life Finder mission from the company Rocket Lab in collaboration with a team from Massachusetts Institute of Technology (MIT). This is a private fast-track single-instrument mission to study the chemistry, and potential habitability, of Venus' atmosphere. This style of research is likely to expand very rapidly.

Image
The JWST team in front of a real-size model of the JWST spacecraft on display in Dublin, Ireland. © ESA/Fennell Photography.

Learning from development of the James Webb Space Telescope (JWST)

Astrophysics missions have historically focused on a limited region of the electromagnetic spectrum, with later generation missions building on technological advances demonstrated earlier. An excellent example is infrared astronomy. The telescope and detectors must be cooled to close to absolute zero, to prevent thermal emission from the telescope swamping the astronomical signal. In early missions, the entire telescope was cooled inside a cryogenic tank, leading to small apertures and short lives, limited by the available liquid helium volume. In the 1980s, an Edinburgh scientist, Tim Hawarden, proposed passive cooling through multiple large radiation shields. After decades of growing enthusiasm, this became the design for the James Webb Space Telescope (JWST). Many years later, Tim Hawarden posthumously received the US National Aeronautics and Space Administration's (NASA) Exceptional Technology Achievement Medal for his Passively Cooled InfraRed Observatory Telescope (POIROT) concept, with the citation noting "the breakthrough concepts that made possible the James Webb Space Telescope and its successors".

This technology allows and will support future large-aperture long-lived astrophysics missions for study of the infrared and microwave sky. It is worth noting that the sensitive large array infrared sensors essential for this wavelength range have been developed almost exclusively at great cost driven by US military requirements. Improved, cheaper, more readily available infrared detectors of wide potential value beyond basic research and defence remain a limiting factor, subject to active research, linking astrophysics and nanotechnology.

The now proven technology and ability to observe the high-redshift very early Universe ensures continuing interest in and development of this astrophysical field. It is also interesting that the scale of missions such as JWST, and the very wide scientific interest, make them much more international than they might appear at first sight. JWST's cost and long timescale was set by an ambitious large telescope design, managed by NASA on a 'too-big-to-fail' approach. There are four instruments on board JWST, which deliver the science. European countries contributed to their design and construction: JWST is much more European than is often appreciated.

Such multi-national approaches to the biggest and most expensive observatories are likely to continue to develop, with the US, ESA, Canada and Japan established as major partners. However, political enthusiasm for global cooperation could wane and should be considered a risk when allocating funding. The future collaborative or competitive involvement of other spacefaring nations remains unclear. JWST is widely considered a great success and is a good example of the lead time required to develop modern instruments.

Astrophysics and its sub-disciplines use these instruments to consider the basic makeup and origin of the universe. Whilst a great deal has been learned about the universe, there are still many phenomena yet to be fully understood. A small selection of activities are described here with how they might develop out to 2075.

Instrument	Delivery team
NIRCam (Near-InfraRed Camera)	University of Arizona, Lockheed Martin, Teledyne Technologies, in cooperation with the U.S. Space agency, NASA
FGS-NIRISS (Fine Guidance Sensor and Near Infrared Imager and Slitless Spectrograph)	Designed by Canadian Space Agency and built by Honeywell
NIRSpec (Near-Infrared Spectrograph)	Astrium (now Airbus) Germany with subcontractors and partners spread over Europe and a contribution from NASA, operated by ESA
MIRI (Mid-Infrared Instrument)	Built by a European/US consortium co-led by the UK Astronomy Technology Centre, Edinburgh and University of Arizona

A new standard cosmological model

The current understanding of the contents of the Universe is that approximately 5% consists of what would be considered ordinary matter, the materials that stars, planets and people are made from. The remaining 95% consists of 27% dark matter – matter which does not emit or reflect electromagnetic radiation and is not made of ordinary atoms – and 68% dark energy – a mysterious form of energy that is causing the expansion of the Universe to accelerate. Although the identity of dark matter and dark energy is unknown, there is compelling evidence for their existence. Dark matter is required to explain the velocities of stars in galaxies and the velocities of galaxies in clusters which cannot be accounted for by the gravitational forces exerted by the ordinary matter that we can see. Dark energy is required to account for the observation that the rate at which the Universe is expanding is increasing rather than slowing down, as would be the case if there was only gravitating matter: dark energy is pushing galaxies apart at an accelerating rate.

Image
The Dark Energy Spectroscopic Instrument (DESI) is installed on the Nicholas U Mayall 4-meter Telescope at Kitt Peak National Observatory near Tucson, Arizona. © NOIRLab / KPNO/NSF / AURA / P Marenfeld.

These two dark components, dark matter and dark energy, form the basis of the standard model of cosmology, known as the 'Lambda Cold Dark Matter' model, where Lambda denotes a form of energy known as Einstein's cosmological constant and cold dark matter denotes a particular class of elementary particles formed soon after the Big Bang. This model is one of the great success stories of physics of the past 40 years: it accounts for a very large range of observed cosmic phenomena, from the properties of the microwave background radiation – the heat left over from the Big Bang – to the existence of galaxies and their spatial distribution on large scales.

Evidence has surfaced very recently from the largest galaxy map ever constructed using the ground-based 'dark energy spectroscopic instrument' (DESI) that dark energy may not be Einstein's cosmological constant after all but rather a form of energy that is declining in time. If verified by further observations, this conclusion would mark a paradigm shift in cosmology. The Nancy Grace Roman (NASA, though currently threatened by budget cuts) and EUCLID (ESA) telescopes, will create complementary 3D maps of the Universe by surveying the location of galaxies and determining their relative positions and velocities[27]. This will inform scientists of how the rate of expansion has changed over time and confirm or rule out the DESI result and provide clues about the origin and nature of dark energy. Roman and EUCLID's approaches are complementary: Roman will survey a smaller region of the sky in more detail due to its larger reflector enabling more distant observations whereas EUCLID will survey much more widely at slightly shallower depth. This is a useful illustration of two projects, one based in the USA and the other in Europe, that are complementary in their techniques and goals rather than in direct competition[28].

Astrometry

Astrometry, ie the measurement of distances and motions of stars through repeated parallax observations (the apparent shift in the position of an object when viewed from different angles or positions), underpins much of our understanding of the Universe. Absolute astrometry, to measure true distance, is possible only from space, as combinations of observations with a very wide separation are essential. This was first demonstrated on bright stars by the European Space Agency's HIPPARCOS mission (1983). The ambitious Gaia mission (launched in 2013 by the European Space Agency) built on this to map two billion sources. Two key technological developments were needed. First, an ultra-stable spacecraft, essentially an optical bench insensitive to thermal variations, was required. The material selected from which to fabricate this was silicon carbide, a light, strong ceramic with very low sensitivity to thermal expansion. Building Gaia involved developing the first large silicon carbide structure, a technology now already widely applied in subsequent spacecraft, and with enormous knock-on potential in aerospace and other industrial applications. Secondly Gaia required development of ultra-precise spin and precision control – micronewton controlled propulsion, needing only a small volume of propellant per day. This is a key technology for operation of free-flying spacecraft interferometers.

Right
Testing the Hipparcos satellite in the Large Solar Simulator, at ESTEC, prior to launch in 1989. © Michael Perryman.

BOX 4

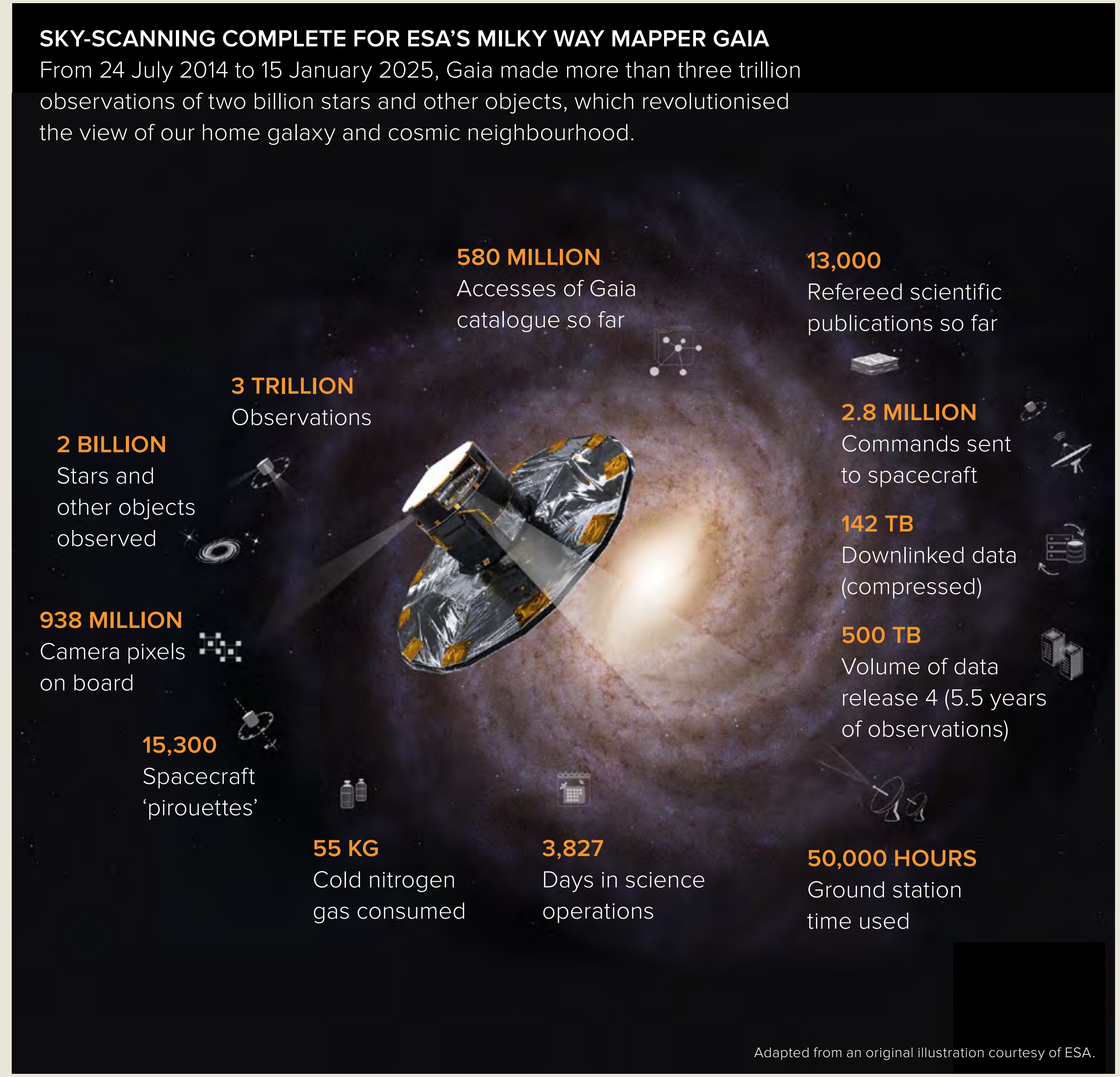
The success of Gaia[29]

In addition to its technology heritage, it is noteworthy that Gaia has the record highest publication impact for a space astrophysics mission. Whilst being a European Space Agency mission, with teams across Europe; UK researchers are overrepresented in its research outputs. One metric used to assess the success of science is the number of times a paper is cited by other researchers as it demonstrates that the findings are deemed important to build other research on. UK-based researchers led on 31% of the total papers produced from Gaia data but accounted for 46% of the total citations demonstrating the high quality science from academia in the UK.

Ultra-precision astrometry is now established as a new tool to map the Universe. A successor mission, delivering micro-arcsecond astrometry to map in real-time the local expansion of the Universe, can be anticipated.

The computing methods developed in the project have also been applied in the field of medicine on Earth, with the Gaia project team partnering with the Cancer Research UK Cambridge Institute and others. The UK's Gaia team has employed star map analytical techniques to study cancers and tumours with the aim of developing the world's first virtual reality cancer map.

The UK Space Agency commissioned a review of Gaia to learn lessons from its investment in the project to replicate successful outcomes for future investment in European Space Agency missions and demonstrate value for public money. Whilst space science represents less than 10% of the total space economy, missions such as Gaia demonstrate the potential wider benefits of funding basic research in space.



The huge potential of interferometry

Interferometry relies on the principle that waves, electromagnetic or gravitational, will constructively or destructively interfere with one another depending on their phase relationship. By measuring these interference patterns, scientists can gather precise information about the waves and their sources.

Interferometry in space can deliver sensitivity and spatial resolution far beyond ground-based possibility. This underpins much future science, ranging from detection of gravitational waves generated by merging super-massive black holes, to detailed imaging and spectra of exoplanets orbiting other stars. Interferometry requires either an ultra-stable single structure, or more ambitiously, precision control of, and communication between free-flying spacecraft. Both approaches are being explored and will dominate the most ambitious future astrophysical research.

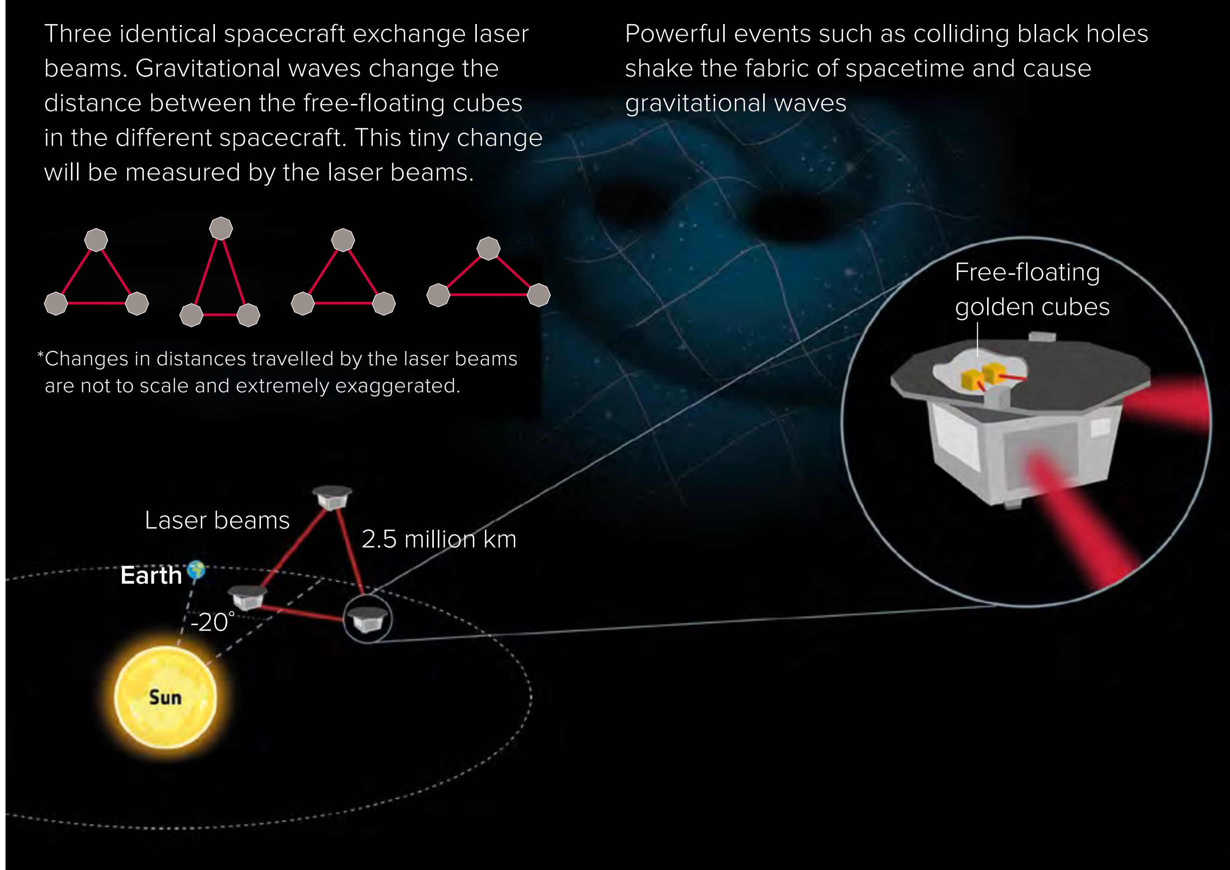
Free-flying space interferometry is being implemented through the European Space Agency-led LISA mission[30]. LISA will comprise three spacecraft flying in a triangular formation behind the Earth as our planet orbits the Sun. The spacecraft will sit in orbit around the sun, about 50 million km from Earth, with a distance of around 2.5 million km between each spacecraft.

LISA will detect ripples in spacetime (gravitational waves) through subtle changes in the distances between free-floating cubes nestled within each spacecraft. Changes in the relative distances between these golden cubes will be tracked with extreme accuracy using laser interferometry.

The very long timescales associated with new technologies in space astrophysics are notable. LISA was first seriously proposed in the 1990s, leading to a flight technology demonstrator (LISA Pathfinder, 2015); it was approved by the European Space Agency in 2024, and will be operational in the late 2030s. Application of free-flying interferometry technology to exoplanet imaging is anticipated soon after. For context, the first ground-based detection of gravitational waves took place in 2015 (LIGO-Virgo US/Europe)[31], with the required extreme precision also needing a long development path, with detailed plans emerging in the 1980s and construction starting in 1994. LIGO detected merging black holes that are 10-100x the mass of the Sun, whereas LISA will be able to detect gravitational waves at lower frequencies, enabling the study of black holes which are many millions times the mass of the Sun.

LISA – LASER INTERFEROMETER SPACE ANTENNA

Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between free-floating cubes nestled within its three spacecraft.



Adapted from an original illustration courtesy of ESA.

Broader lessons on space technology development

There are two lessons evident here. First, large ambitious space missions, focused on studies of the Solar System, astrophysics or missions focused on fundamental physics, are in a significant way technology development opportunities, with potentially broad commercial impact. This economic benefit is a prime motivator for government funding of basic space science. The high cost and long timescales are intrinsic to the activity. As such expensive mission opportunities are rare, so there is an inevitable tendency to make them multi-purpose and multi-instrumented where possible, driving the cost-duration cycle further.

Second, the complementary approach of small dedicated affordable mini-missions, can develop in numbers and applications very rapidly, meeting the scientific community's aspirations on a practical timescale. The major space agencies are responding by providing more 'fast' or 'explorer class' opportunities. It will be interesting to watch growth from competitive sources of missions and launches, and the impact on national space agency strategies. The opportunity for a much larger role for nationally funded and led mini-missions is evident.

Conclusions

- Human activity concerning the outer Solar System and deep space has been primarily scientific rather than commercial until now and that is expected to continue over the next 50 years.
- Missions using probes and telescopes take a long time to plan but are making incredible discoveries; they are only going to improve as new materials and techniques for taking measurements are developed.
- Funding arrangements for space science should be reviewed carefully to ensure that space science objectives can be achieved in the most efficient and timely ways possible.
- An enormous expansion can be expected in the number and scope of potential science facilities and experiments in areas such as astrophysics, geology, astrobiology and engineering biology, partly enabled by cheaper access to space and possibly including the development of laboratories in different locations in the Solar System. This will greatly expand the quality and quantity of scientific investigations across the Solar System in pure and applied science.
- By 2075 research may have answered the question of whether there is unambiguous evidence of life on a wide diversity of planetary bodies in and beyond the Solar System, which would have significant implications for humanity's sense of place in the Universe.

CHAPTER 2

The leap from Earth

This chapter considers how objects get into space – the leap from Earth. It documents the rapid changes in the space sector that have led to a rise in the rates of launches and sets out the range of plausible, and some more marginal, emerging launch technologies that are expected to develop in the years to 2075.

Earth has a strong gravitational pull that means a huge amount of energy is required to leave its orbit and travel out into the Solar System. Earth's escape velocity, the speed required to break free from its gravitational pull, is 40,000 km per hour[32]. If an object launched into space fails to reach this speed, it will not have sufficient energy to escape Earth's gravity and depending on how fast it is travelling, will either enter into an orbit around the Earth or fall back to the surface. Rockets using a variety of highly energetic propellants, are the tried and tested method used to generate the necessary thrust against Earth's gravitational pull and they have developed significantly over time.

Left
SpaceX Starship ignition during its launch on IFT-5. © Steve Jurvetson.

Timeline of launch technologies

Here a small range of the background of rocketry is presented to provide context for future activity discussed in this chapter.

1232 AD
Chinese solid fuel rockets used in battle of Kai-Keng.

1919
Robert H Goddard's pioneering work on the science of rockets, *A Method of Reaching Extreme Altitudes* is published.

June 1942
V-2 rocket the first to reach space (190km).

1947
First animals (fruit flies) sent into sub-orbital space on V-2 rocket.

19 June 1949
Albert II the rhesus macaque is the first mammal launched into sub-orbital space.

1970
Long March 1, the first of the Long March family of rockets is launched by China.

June 1971
Three cosmonauts die due to decompression of the Soyuz 11 rocket.

October 1971
The Black Arrow rocket becomes the first British rocket to successfully launch a satellite into orbit – Prospero, from Woomera, Australia. The Black Arrow programme had already been cancelled in July of the same year with no further launches to take place after October.

1981
NASA's Space Shuttle programme begins with the launch of STS-1 aboard the Space Shuttle Columbia.

1986
Space Shuttle Challenger disaster occurred due to failure of an O-ring seal in its rocket booster. A further disaster happened on re-entry of Space Shuttle Columbia in 2003.

2006
NASA founds its Commercial Orbital Transportation Services (COTS) to encourage the private sector to develop launch capability to support NASA missions. SpaceX and Rocketplane Kistler are awarded the first contracts.

2015
SpaceX Achieves First Successful Landing of a Falcon 9 First Stage. A key moment for reusable rocketry.

2018
The UK's Space Industry Act 2018 establishes regulatory framework for spaceflight activities, including the licensing of spaceports and the operation of space vehicles.

January 1923
Virgin Orbit's LauncherOne rocket fails after launching from Spaceport Cornwall in the UK. It experienced an anomaly during the second stage, causing it to fail to reach orbit. This mission was intended to be the first-ever orbital launch from the UK.

2023
SpaceX's super heavy launcher vehicle, Starship, fails on its first two launch attempts.

2024
SpaceX conducts four successful tests of Starship, including an eye-catching landing of its booster in a tower to be reused on another flight.

January 1925
Blue Origin's New Glenn rocket successfully reaches orbit on its first test.

Current position

Launch economy

Powerful rockets carry cargo (often referred to as a payload) to space for a variety of uses. There are trade-offs to consider: the heavier the payload, the more energy that is needed to lift it from the Earth's surface thus requiring larger rockets. In turn, larger rockets must carry more heavy fuel along the journey requiring more thrust – ie fuel is needed to carry fuel.

As such there has been a drive to reduce the mass of the payload to a minimum and to optimise the fuel efficiency and capacity of rockets to achieve the required orbit. Historically, the cost of launch has been the key driver for the price tag of a space mission and a major factor limiting activity in space.

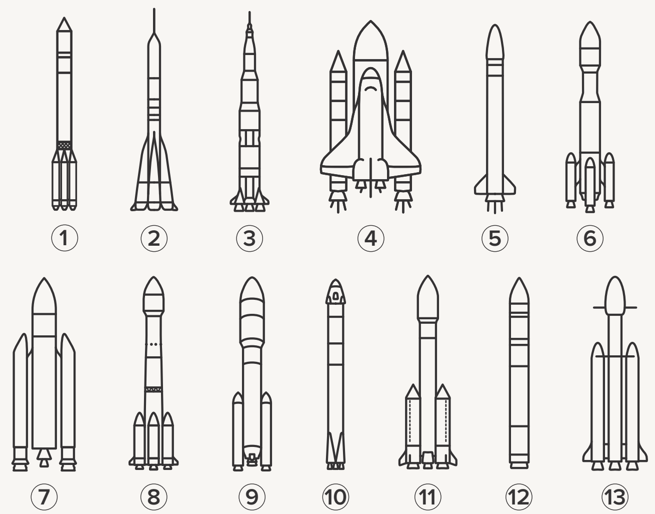
Until recently, launch systems were expendable, one-shot systems that are an expensive and wasteful way to get into space. When adjusted for inflation, NASA's Delta E rocket, used in the 1960s and 1970s, cost $177,900/kg of payload placed into orbit. Even the partially reusable Space Shuttle of the 1980s required expensive refurbishments following each flight, resulting in cost of $65,400/kg to reach low-Earth orbit. The Russian Soyuz launch vehicle used on many European Space Agency missions, is $17,900/kg. But none of these can compete with the value of modern rockets.

Launch was almost exclusively restricted to governments and their agencies due to the high costs and safety considerations, however the entry of the private sector providing competitive technological advances for launch services, such as reusable components and ridesharing of compact payloads, has dramatically changed the economics of access to space. SpaceX's partially reusable Falcon 9 rocket, is able to launch for $2,600 per kilogram.

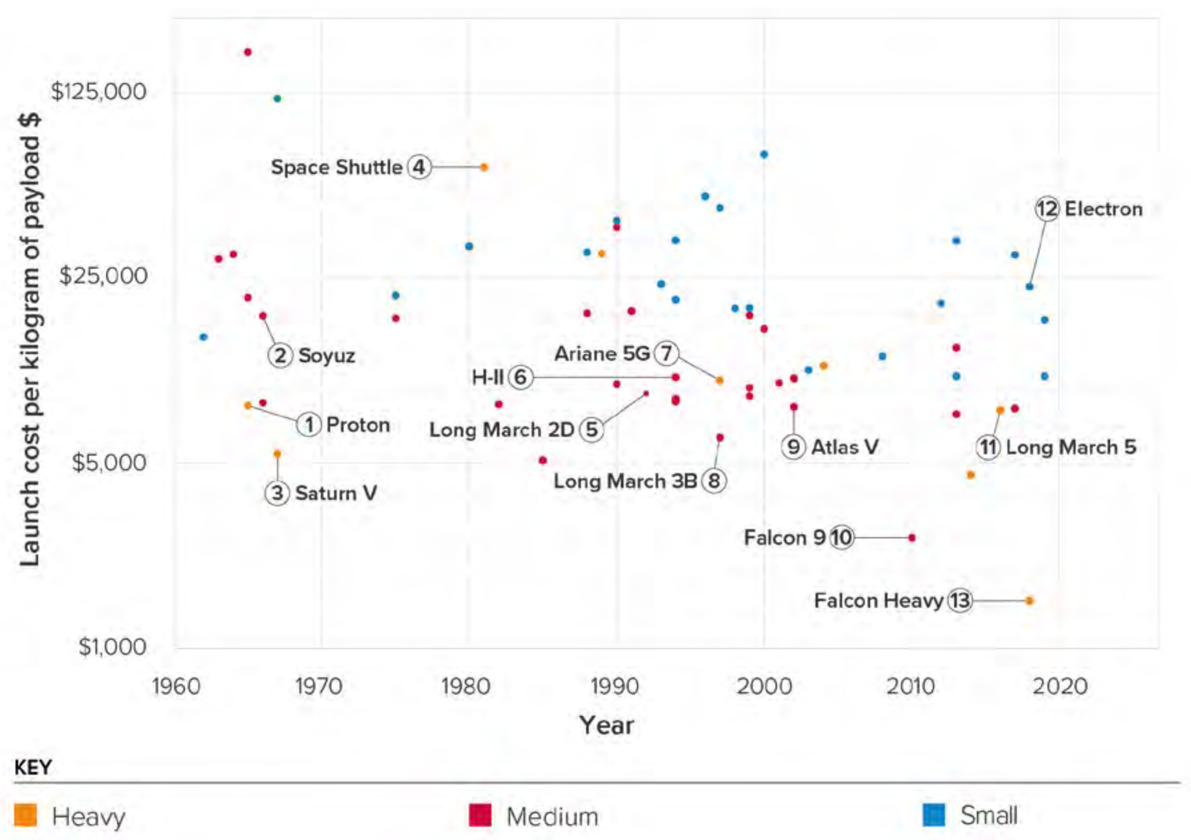
FIGURE 6

Cost to launch one kilogram of payload mass to low Earth orbit as part of a dedicated launch.

This data is adjusted for inflation. Small vehicles carry up to 2,000 kg to low Earth orbit, medium ones between 2,000 and 20,000 kg, and heavy ones more than 20,000 kg. These data are expressed in constant 2021 US$. A selection of notable launch vehicles of different sizes have been highlighted.



1. **Proton** Soviet Union/Russia | 53m
2. **Soyuz** Russia | 46 – 50m
3. **Saturn V** USA | 111m
4. **Space Shuttle** USA | 17m
5. **Long March 2D** China | 41m
6. **H-II** Japan | 49m
7. **Ariane 5G** Europe | 46 – 52m
8. **Long March 3B** China | 55m
9. **Atlas V** USA | 58m
10. **Falcon 9** USA | 70m
11. **Long March 5** China | 57 – 64m
12. **Electron** New Zealand | 18m
13. **Falcon Heavy** USA | 70m



Data source: CSIS Aerospace Security Project (2022).

GOVERNANCE CHALLENGE

The environmental implications of increased launch frequency

By themselves, rocket launches have been small contributors to overall atmospheric pollutants to date. The aviation industry burns 100 times more fuel each year than all of the rockets launched globally combined. However, there is a key atmospheric difference: aeroplanes fly in the troposphere whereas rockets fly through the stratosphere where combustion products (ie soot) remain 100 times longer and are 500x more effective at generating a warming effect when compared to the same pollution created at commercial aviation altitudes or at ground level[33, 34]. Some modern rocket designs use liquid oxygen and liquid hydrogen, producing only water vapour as a byproduct. This is a considerable improvement over hydrocarbon-based propellants such as RP-1 (highly refined Kerosene). However, water vapour in the upper atmosphere still traps and retains heat, just not nearly as readily as black soot, methane, or carbon dioxide.

With the dramatic increase in launch frequency over the last 3 years, driven in part by reduced costs and the demand for large constellations in LEO, the impact of space launch on the atmospheric environment has become more significant. Should this launch frequency trend continue, then harm to the atmosphere will become of increasing concern. A Falcon 9 rocket uses approximately of 273,620L of liquid oxygen and 163,000L of RP-1 fuel[35]. This is roughly equivalent to the amount used by a car to drive 2 million miles. In the UK about 300 billion miles are driven each year, so current launch rates will not make a dent. If, however, launch rates increase by a one order of magnitude, to 20,000 per year for instance, that is equivalent to 40 billion miles or 1/8th of the UK total.

The assessment of environmental impact of launch activities should, however, encompass all aspects: including launch sites, the manufacturing and building of infrastructure, the reusability of components, the type of propellant used, and the return and safe disposal of spent rocket stages and atmospheric ablation. Further studies are needed to assess the environmental impact of increased launch frequency, whilst technological solutions (eg clean propellants) and regulatory action will be important areas for further research.

UK-based launch company Orbex is developing a biopropane propellant for their Prime rocket, which minimises soot production which they claim leads to a carbon footprint that is 86% lower than comparable vertical launchers of the same size[36]. The company Skyrora has also explored the possibility of developing an 'Ecosene' propellant made from non-recyclable plastics to mitigate the need for new hydrocarbon fuels, though it is not clear what impact this would have on soot development[37].

Views from the public on space sustainability

In the Royal Society's public dialogue on space, participants emphasised that sustainability must be built into the governance of space from the outset – not added as an afterthought.

As discussions turned to the increasing volume of satellites, launches and orbital infrastructure, many participants expressed a clear sense of unease. There was a widespread view that space activity was accelerating faster than the systems designed to manage it.

"I think morally and ethically we have an obligation not to ruin everything as we have done on Earth."
Workshop 2, Leicester

This perspective extended beyond Earth's orbital environment. When imagining future activity on the Moon, Mars and beyond, participants raised concerns about carrying over the same destructive habits to other worlds.

"If we're going forward to other planets and this is a stepping stone, we really need to get the habit in of not trashing places."
Workshop 1, Cornwall

The idea of extracting resources from other planets provoked especially strong responses. While some saw potential benefits, many were uneasy about the ethics of exploiting untouched environments for Earth's gain.

"They should leave everything undisturbed, they should not go to different planets to mine for our own benefit."
Workshop 2, Cornwall

At the same time, participants recognised the complexities of balancing sustainability with urgent global needs. Some questioned whether there might be exceptions in extreme cases.

"If that planet is uninhabitable… but there's something very valuable there for us, then, should we not take it to help save Earth?"
Workshop 2, Leicester

Read more about the Royal Society's Public Dialogue on Space conducted by independent research organisation Ipsos on page 180.

Launch technologies – looking further ahead

Reusable rockets

Rockets have typically been designed with multiple stages, to allow the most efficient transit from Earth to Space. The stages are segments that contain their own engines, tanks and propellant which means when fuel is depleted in a particular stage, it can be jettisoned to reduce the overall weight and thus facilitate the remaining rocket stage(s) reaching orbital speeds. Traditionally, these stages have been seen as expendable, despite being highly engineered and expensive machines to produce.

Advances in production engineering, new materials and autonomous guidance and control systems have enabled spent rocket stages to be returned in a controlled flight in order to make precision landings. They can then be refurbished and reused on a later flight, rather than simply dumping them in the oceans. This approach has been pioneered by SpaceX who have achieved increasingly rapid turnaround, with many of their rocket stages being flown more than a dozen times to date. This has reduced the cost of launching to as low as $1,500/kg, a reduction of over 90% compared to a decade ago and a 40-fold reduction since the 1980s. Several organisations such as Rocket Lab and China Aerospace Science and Industry Corporation have demonstrated prototypes of similar systems.

Thus, more economical launches have become a reality and in the coming decade ever more capable and cost-effective transportation systems are set to be developed, primarily by the private sector, taking payloads more routinely and affordably to orbit, the Moon, Mars and beyond. It is forecast[38] that launch costs will reduce to less than $100/kg by 2040, a 200-fold reduction within a 30-year period. This will be realised with fully-reusable systems in which all stages of the propulsion rockets and payload cabins can return to Earth. The economics of this are of course contingent on there being sufficient competition between different suppliers capable of offering similar services to customers.

SpaceX's Starship, the world's most powerful rocket to date, is designed to be fully reusable and can carry 150 tonnes of material to low Earth orbit. This new capability will transform how space is used by enabling the transportation of large and heavy payloads into orbit for large-scale infrastructure projects, such as space-based solar power, large astronomical and scientific satellites, in-orbit manufacturing and a giant radio telescope on the far side of the Moon[39].

Moreover, lower costs mean that many more organisations across more nations – institutional, commercial and educational – can afford to access space. In turn, this enables further cross-sector collaborations.

In the coming decades, space launch could become a routine, reliable, affordable service, similar to that provided by airlines and major logistics companies today, commanded invisibly, at the click of a mouse.

UK Spaceports

In the 1950s-1960s, the UK developed the Skylark sounding rockets, which were used for scientific research and launched from Woomera, Australia. These rockets laid the groundwork for future space endeavours. The UK achieved a major milestone in 1971 with the launch of Prospero, the first and only British satellite to be launched using a British rocket (the Black Arrow, also from Woomera, Australia). Subsequently, the launch programme was cancelled and the UK focused instead on developing satellite technology and relying on other providers for access to orbit. This is set to change in the coming decades with recent developments for new UK launch capabilities.

The UK has been developing several spaceports to support its growing space industry, driven by the regulatory framework established by the Space Industry Act 2018. This act was designed to create a modern, flexible, and safe regulatory environment for commercial spaceflight activities, including satellite launches and sub-orbital flights. It introduced comprehensive regulations covering licensing, safety, security, and liability for spaceflight activities. The intention was to make the UK a leading destination for commercial space launches by providing a supportive legal framework that encourages innovation while ensuring safety and compliance with international obligations.

The act also facilitated international partnerships, such as the UK-US Technology Safeguards Agreement, allowing US companies to operate from UK spaceports. This has opened new markets and opportunities for the UK space industry.

GOVERNANCE CHALLENGE

International space traffic management

As spaceflight becomes more widespread and routine, the necessity for a robust mechanism for international coordination grows alongside it, as it did in the past with the development of commercial aviation. Space traffic management (STM) is first and foremost a governance challenge, rather than a technical one. The technological capabilities for manoeuvring satellites and space infrastructure are fundamental, they are reliant on continuous space situational awareness and vulnerable if there are no established, universal, mechanisms in place for operators to communicate and coordinate, including the sharing of critical data and information – irrespective of nationalities, political differences, and commercial interests.

Spaceport	Location	Launch mode	Orbital inclinations	Proposed departures
Spaceport 1	Scolpaig Farm, Isle of North Uist, Outer Hebrides, Scotland	Vertical, sub-orbital	N/A	In negotiation with launch providers
Space Hub Sutherland	A' Mhòine peninsula, Sutherland, Scotland	Vertical	Polar, Sun-synchronous	Formerly Orbex Prime, construction paused indefinitely
SaxaVord UK Spaceport	Lamba Ness, Unst, Shetland Islands	Vertical	Sun-synchronous, suborbital, orbital, polar	Orbex Prime, Orbex Proxima, ABL Space Systems, Rocket Factory Augsburg, HyImpulse, and potentially others
Spaceport Machrihanish	Campbeltown, Argyll, Scotland	Horizontal, vertical, high-altitude platform	Sun-synchronous, polar	In negotiation with launch providers
Glasgow Prestwick	Prestwick, South Ayrshire, Scotland	Horizontal (orbital)	Sun-synchronous (SSO), Polar, Molniya, other high inclinations (North and South)	Astraius and Spirit AeroSystems
Spaceport Snowdonia	Llanbedr, Gwynedd, Wales	Horizontal, vertical and rail	Sun-synchronous, polar, sub-orbital	Multiple including research, development, test and evaluation
Spaceport Cornwall	Cornwall Airport Newquay, Cornwall	Horizontal	Sun-synchronous, polar	Virgin Orbit LauncherOne Rocket (Cosmic Girl carrier aircraft) now defunct, no confirmed customers

Most of these spaceports are in a nascent stage of their development. They will need to attract sufficient commercial interest to create a thriving launch industry in the UK.

This can be a precarious business as the company Virgin Orbit discovered. Virgin Orbit used a modified Boeing 747, known as Cosmic Girl, which flew to 35,000 ft (11,000m) before releasing the LauncherOne rocket which was designed to carry payloads such as satellites into orbit. In January 2023, their first launch failed when LauncherOne suffered an anomaly and ultimately broke apart mid-flight. Investors subsequently lost confidence and the business was declared bankrupt in April 2023 with its assets sold off to other space companies.

Despite this setback, Virgin CEO, Richard Branson stated in March 2025[40] that he would be keen for operation of his other space company, Virgin Galactic to run operations from Spaceport Cornwall. Virgin Galactic operates space tourism flights taking passengers on journeys lasting approximately 90 minutes to around 96,000m[41] above the Earth's surface for approximately £350,000 per ticket. Flights currently operate from New Mexico and require a two-month turnaround time to make the reusable vehicle ready for its next flight. Branson claims that improvements to the craft could reduce this turnaround time to enable two flights a week, which would reduce running costs and hence the ticket price in the longer term.

Saxa Vord is the most advanced of the UK spaceports under development with multiple launch companies having invested in the site. This includes Orbex, a UK-based launch company who have two ongoing launcher projects, Prime, a small launcher and Proxima, a medium launcher[42]. The company's strategy should enable them to compete in the European Launcher Challenge being run by ESA to support development of European launch capabilities and to service institutional and commercial contracts, which may prove to be a more reliable business model to grow demand for the spaceport.

Spaceplanes

Vertical launch rockets have so far been the dominant method of sending payloads to space. However, looking out to 2050, it is likely that reusable 'single stage to orbit' (SSTO) spaceplanes will be developed and operational. These offer benefits of more 'airline-like' operations, with horizontal takeoff and landing on conventional (but likely extended) runway facilities. Spaceplanes could bring about benefits such as more rapid turnarounds between launches and a reduction in space debris accumulation with no part of the craft jettisoned during take-off as is the case with conventional multi-stage rockets. This could result in even lower operational costs and higher capacity. Conventional passenger aeroplanes rely on turbojet engines which are unable to operate at altitudes much higher than 12,000-15,000m. For context, space is considered to begin at the Kármán Line located at 100km. Turbojet engines require special adaptations in order to fly at the speeds required to reach greater heights.

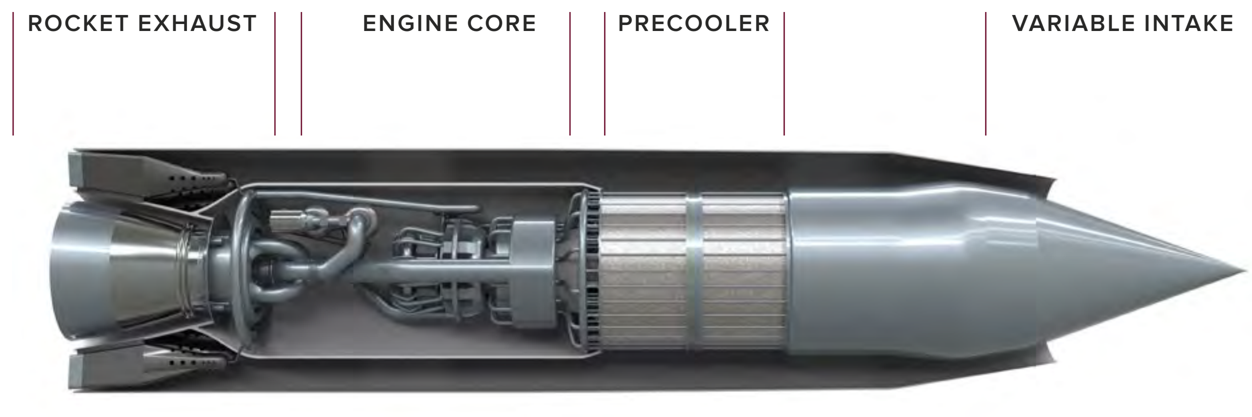
The atmosphere becomes less dense (hence less oxygen is in the air for combustion of fuel) and powerful cooling systems are required to cope with the high temperatures generated when providing and maintaining thrust. Designs by companies such as Reaction Engines[43] (now defunct) and Radian Aerospace[44] have tried to address these issues.

If SSTO concepts can be fully realised, so-called 'air breathing' rocket engines would be able to harvest atmospheric oxygen more efficiently for use during flights, instead of having to store it onboard in liquid form. This would reduce both costs and mass by exploiting aerodynamic lift during the atmospheric phase, rather than relying entirely on fuel stored on board. This could make SSTO spaceplanes a viable alternative to stored-propellant rockets for many activities, in addition to contributing to a much-reduced carbon footprint for the sector. However moving beyond the present research and demonstration phase will take considerable investment.

Aside from journeys to destinations in space for satellites and other space-based infrastructure, spaceplanes and other reusable launch vehicles that travel to sub-orbital space and back to Earth can provide ultra-fast connections between widely separated locations on Earth, potentially in as little as 1.5h for journeys which usually take significantly longer[45]. Commercial sub-orbital passenger spaceflight could revolutionise large segments of the traditional long-haul travel market, but impacts on travellers with different medical status would need to be carefully studied given the G-force involved in accelerating to top speed[46].

FIGURE X

SABRE™ synergetic air-breathing rocket engine



GOVERNANCE CHALLENGE

UK Launch capability

The UK took a strategic decision in the 1970s to cancel its launch programme and instead to rely on other partners to provide this capability. This had the advantage of being a cost-saving measure but the disadvantage of leaving the UK reliant on others without a sovereign launch capacity of its own.

UK spaceport projects that have been established in seven locations across the UK represent a review of the previous position and a desire to expand activity in this area. Spaceports will require support to become sustainable businesses. There is a 'chicken and egg' issue with establishing a spaceport. Spaceports require customers, but customers need infrastructure to make it attractive to invest in a given site. Ayrshire council recently cancelled a £50m road infrastructure project around the Prestwick Spaceport due to pressures on funding. Similarly, Orbex had exclusive access to the Sutherland spaceport site promising 300 jobs in the area which are now in jeopardy as Orbex has moved its main operations to Saxa Vord with further development on the Sutherland site on pause. There has been some pressure on Orbex to cede its exclusive rights to the site to try to attract other launch providers. It may be the case that it is sensible to review whether investing in the most promising sites would represent a more effective strategy for expanding UK launch capabilities if activity at some sites is failing to ignite.

There could be some strategic benefit to a UK spaceport for some operators, especially in the defence sphere as it enables access to polar orbits. Alternative bases in Norway and Alaska do not offer as direct a route to orbit and so the UK is well-positioned to invest in this strategic benefit.

High risk and high reward launch technologies

Reaction Engines received significant government funding to support its development but was unable to generate significant revenue. Eventually investors lost confidence and the business, short of £20m, went into administration in 2024 after 35 years of operation. This was not a large amount of money in terms of development of a technology which could have been transformative for the space industry and point to point travel on Earth. It is a useful example of the high development costs involved in space sector development. Reviews of the long-term strategic benefits of space technology should be considered when evaluating business cases for government investment.

SpinLaunch

Alternative launch methods are being explored that avoid the need for chemical propulsion. The company SpinLaunch conducted research into an electric-powered vacuum-sealed centrifugal kinetic launcher as an alternative to conventional rockets. Initial 1/3-scale tests have achieved altitudes of around 10km, however, it is not yet practicable to achieve the necessary 7km/s velocity required for low Earth orbital insertion without the use of a second stage chemical rocket. The sustained acceleration forces of ~10,000g create challenges for rocket and payload design, though may suit launch of raw material and other non-complex payloads for in-space manufacture.

Space elevators

A space elevator, brought to mainstream attention by science fiction author, Arthur C Clarke in the 1970s but with roots in scientific thinking in the late 19th Century, is a theoretical structure designed to transport materials from Earth's surface into space via a car on a cable line. The primary idea is to use the space elevator for transporting payloads, such as satellites or cargo, into space without the need for traditional rocket launches.

Central to most space elevator concepts is an ultra-strong lightweight tether cable which is anchored to a point on the equator and stretches up to geostationary orbit or beyond. The cable is kept taught by an orbiting counterweight, such as a space station, and a 'climber' ascends the cable with its payload. Whilst space elevators have been the subject of a number of technical studies by NASA and other agencies, for the foreseeable future they remain within the realm of science fiction, there being no currently conceivable practical material with the tensile strength/weight ratio required, though some proponents have explored the potential of carbon nanotubules and graphene. If the principles are ever deployed in practice, it is likely in the first instance to be between objects in space over relatively short distances[47, 48].

GOVERNANCE CHALLENGE

Space elevators: international legal issues

Besides the materials production and engineering challenges, an infrastructure project of this size will have an equally large price tag, most likely requiring joint investment from many nations, organisations and companies. It will require diplomatic efforts to decide where the ground terminal is located, possibly in international waters. Reaching consensus on managing risks, responsibilities and liabilities will be challenging, such as the tether becoming a dangerous obstacle for aeroplanes and satellites, with implications for global air and space sector operations, and thus ensuring it is resilient to any collisions.

Conclusions

- Advances in materials and manufacturing in competitive commercial settings have created a new class of reusable launchers that have significantly reduced the cost of access to orbit. This has facilitated the recent emergence of NewSpace companies and a dramatic increase in launch frequency
- Single-stage-to-orbit (SSTO) spaceplanes could significantly reduce cost to orbit, launch carbon footprint, and create new intercontinental transport business models.
- Other methods of reaching orbit are being researched and could provide alternatives to traditional rockets

CHAPTER 3

The evolution of orbit

Earth orbit is the area of space where humanity has been most prolific. This chapter looks at how the range of industrial, commercial and scientific activities taking place in orbit could evolve in the decades to 2075. The space economy was valued at $630bn[49] in 2023 and the majority of this concerns activity in Earth orbit, dominated by communications, navigation and Earth observation services. The space economy is anticipated to grow to $1.8tn by 2035 due to increasing commercial activity.

An orbit is a regular and repeating path that an object like a planet takes as it travels round a larger primary body like the Sun. Objects in orbit are called satellites and they include the Moon, a natural satellite of Earth, as well as the moons of other planets. However, the term ‘orbit’ is also commonly used to refer to the area of space that immediately surrounds the Earth. Earth orbit, from about 200km to 50,000km, is where most commercial activity in space resides today and human activity on Earth has grown to be dependent on the vital services located there. As of 2025, there are more than 10,000 artificial satellites orbiting the Earth which serve a variety of purposes such as communications; remote sensing; space science and position, navigation and timing (PNT). This number has accelerated dramatically since 2020 and is expected to continue in the coming years with decreasing launch costs resulting from reusable rockets making orbital projects and services more affordable than ever before.

Left
In a joint project between Philippine and Japanese universities, the DIWATA-1 satellite is deployed.
© NASA/ESA/ Tim Peake.

Timeline of activity in orbit

Here a small selection of activity in orbit is presented to provide context for future activity discussed in this chapter.

4 October 1957
Sputnik 1 launched by Soviet Union becomes the first satellite to orbit Earth.

3 November 1957
Sputnik 2 launched the first animal into orbit, Laika the dog.

31 January 1958
Explorer 1 becomes the first American satellite, discovering the Van Allen radiation belts.

1959
NASA satellite Explorer 6 took the first ever satellite image of Earth at an altitude of approximately 27,000km.

26 April 1962
Ariel 1 (UK): First British satellite, conducted research in the ionosphere, part of Earth's upper atmosphere.

1968
The Soviet Union conducts the first anti-satellite weapon (ASAT) test that involved destroying another object in orbit, one of the Soviet Union's own satellites.

1971
The first ever space station, Salyut 1, is launched into orbit by the Soviet Union.

May 1973
The USA's Skylab space station is launched and occupied for 24 weeks.

1975
Representatives from the United States and the former Soviet Union shake hands when an Apollo module docks with a Soyuz module. Key demonstration of space as a diplomatic tool in a period of high geopolitical tension between the two countries.

22 February 1978
First of 76 satellite launches for GPS.

1978
Donald Kessler, publishes paper titled *Collision Frequency of Artificial Satellites: The Creation of a Debris Belt* setting out the principle of what would later be known as Kessler Syndrome, whereby the likelihood of satellite collisions would increase as more spacecraft are launched.

1985
US conducts first ASAT test to impact one of its own satellites creating 288 pieces of debris.

20 February 1986
Soviet Union's Mir space station launched.

1995
First laser communications from space (Japan).

20 November 1998
An international collaboration of five space agencies from Europe, Canada, Japan, Russia, and the USA launches the first module of the International Space Station.

2001
First laser communications between spacecraft (France + ESA).

2007
China ASAT test creates record amount of debris in orbit (3,537 pieces).

May 2019
SpaceX's Starlink programme begins with 60 satellites launched into orbit providing high speed internet coverage by November 2020.

24 January 2021
SpaceX sets record for the most satellites launched (143) on a single rocket during the Transporter-1 mission. This mission was part of SpaceX's Smallsat Rideshare Program, which aims to provide affordable access to space for small satellite operators.

29 April 2021
The core module of China's Tiangong Space Station is launched.

November 2021
Russian ASAT test creates 1,808 pieces of debris and forces the ISS to make an evasive manoeuvre.

May 2024
EarthCARE satellite is launched. A joint venture between the European Space Agency and the Japan Aerospace Exploration Agency. It will gather data on the effects of clouds and aerosols on solar radiation reflection to improve the precision of climate models.

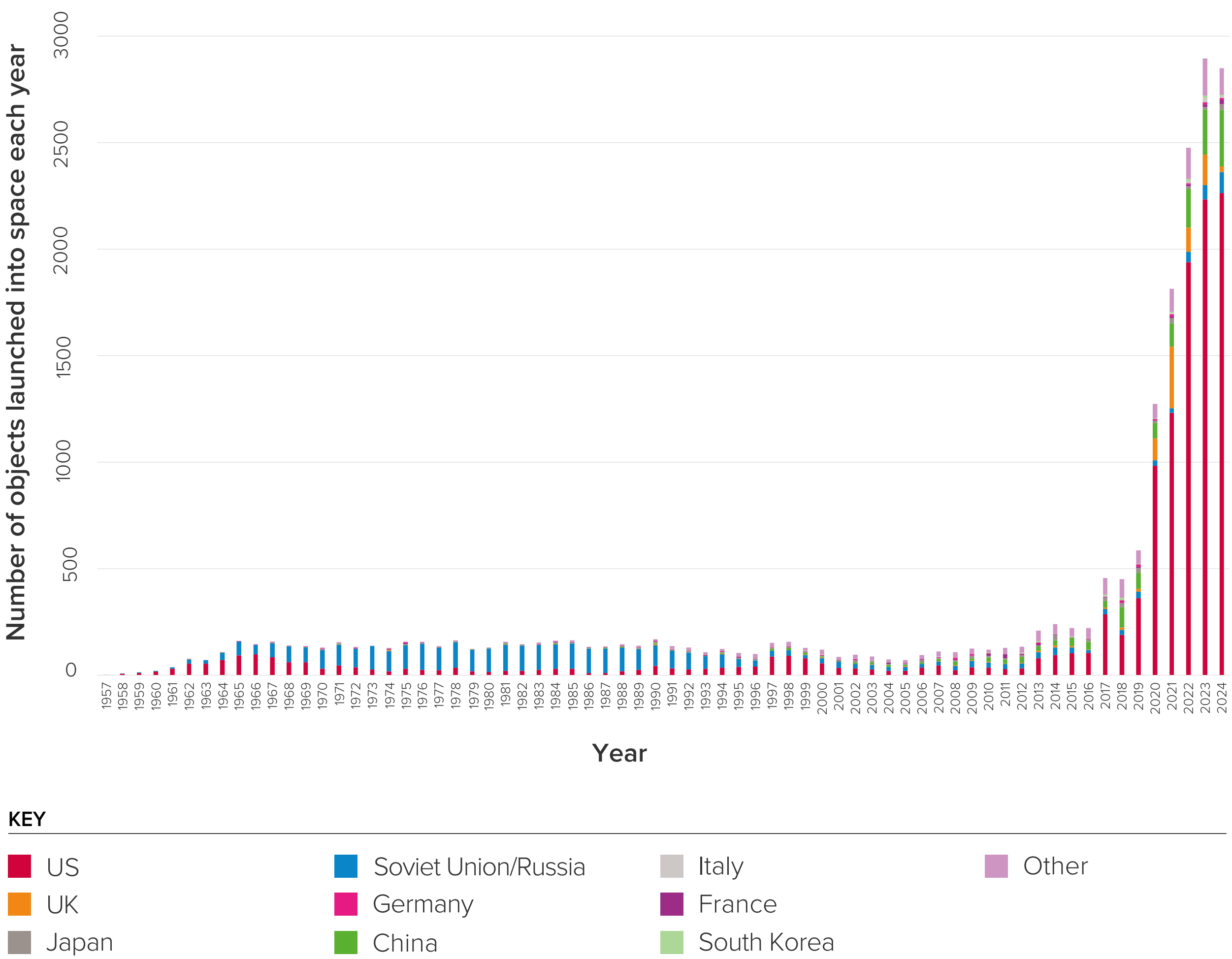
Current position

The pace of activity in orbit has accelerated dramatically over the last 5 years. More satellites were launched since 2020 than the total of all satellites launched between 1957 to 2020 combined.

This trend is set to continue, with other emerging and enabling technologies expanding the scope of what is possible in space with significant implications for security, industry, science and the environment.

FIGURE 8

Number of objects launched into space per year 1957 – 2024

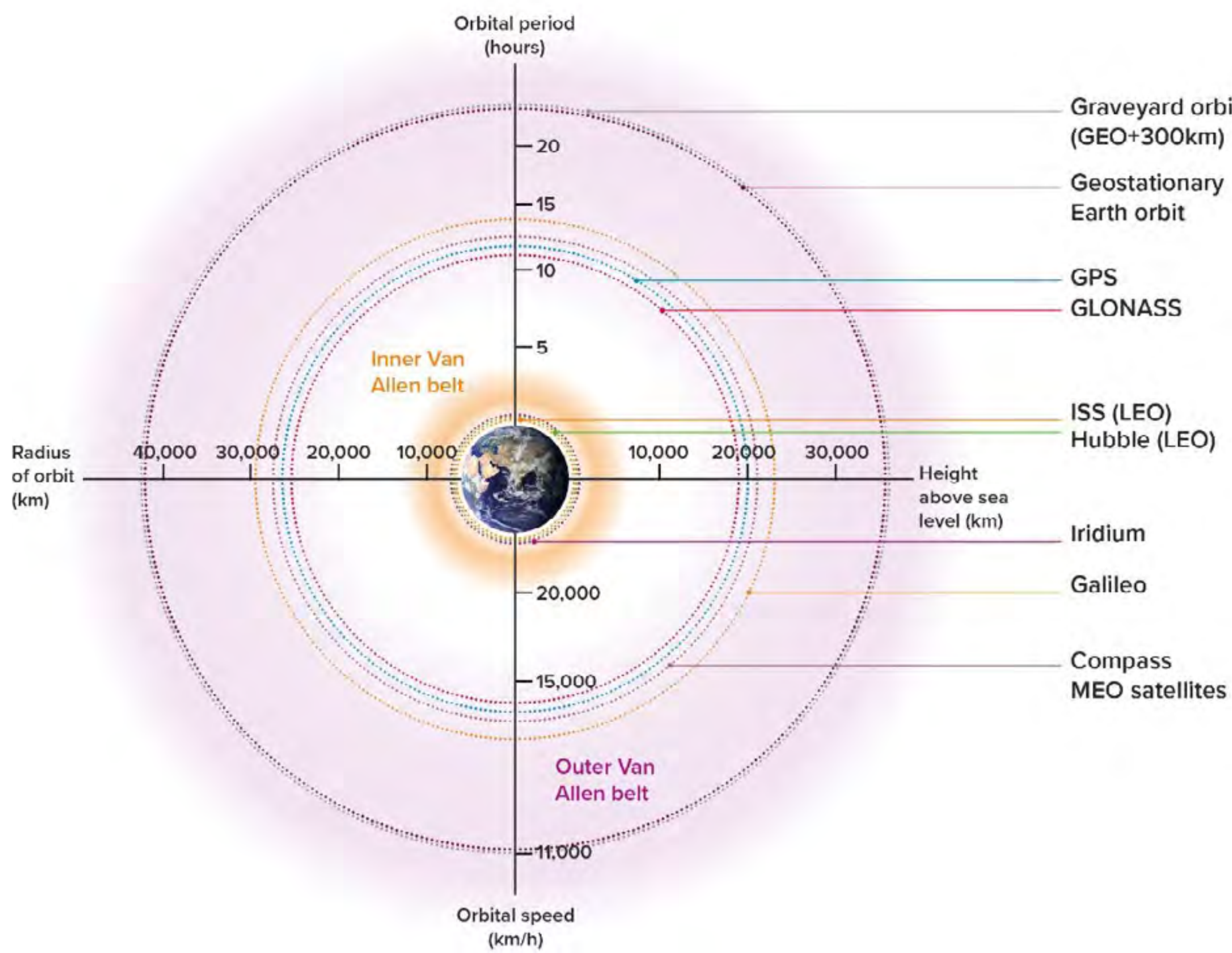


Satellites can be positioned at different altitudes in Earth orbit and there are advantages and disadvantages to each, dependent upon the mission objectives.

The majority of satellites are found in low Earth orbit (LEO) which is located between 200km to 1,600km above the Earth's surface.

FIGURE 9

Altitudes of different orbits around Earth and examples of some key satellites



Earth observation satellites

Observing the Earth from the high vantage point of orbit allows human activity and its effects to be monitored and quantified, and for the impacts of policy interventions to be monitored. Earth observation and remote sensing satellites cover a broad range of applications and technologies involved with providing data on the physical, chemical and biological systems on Earth and within its atmosphere.

The most common type are satellites that take optical images (such as photographs). Optical images rely on capturing electromagnetic wave signals collected passively from reflected sunlight or other sources of light/radiation in visible, infra-red and ultraviolet wavebands. These are interpreted to measure variables such as temperature and the presence or absence of certain chemical signatures. They have many applications from geological and topographical mapping and agricultural planning; to surveillance for law enforcement and strategic defence objectives. Other satellites use different active remote sensing technologies, such as forms of radar that have the advantage of operating day or night and independent of weather.

Satellite imaging of Earth from different orbits, using a variety of sensing techniques is now constant, detailed and pervasive. Planet Labs' Doves constellation consists of more than 150 satellites which generate 350 million square kilometres of images in a 24h period. Global Earth observation in real-time from geostationary orbit (GEO) is currently operational. However, high-resolution low-latency Earth observation from low Earth orbit (LEO) in real time is not yet available but is to be expected very soon. Earth observation satellites have become critical in the international effort to combat climate change with the unique ability to provide global, real-time coverage of the planet. The Global Climate Observing System records over 50+ measurable Essential Climate Variables (ECVs) across land, air, and sea. More than half of these ECVs can only be measured from space[50]. Long-term data collection enables scientists to identify trends and refine climate modelling and forecasting techniques. Accurate forecasting models provide the strongest foundation for policymakers to make robust plans for climate change mitigation and adaptation. The European Space Agency and Japan Aerospace Exploration Agency satellite, EarthCARE[51], is supporting development of more accurate models. It is using sophisticated atmospheric lidar and cloud profiling radar instruments to gather data on both the role that clouds and aerosols play in reflecting incoming solar radiation back into space, as well as how infrared radiation emitted from Earth's surface gets trapped in the atmosphere.

Satellite observations have been used for a long time to forecast the weather. However it is anticipated that new instruments and the ability to analyse large datasets using artificial intelligence, will provide the ability to forecast weather-related disasters and monitor them as they unfold, including wildfires, droughts, hurricanes, tsunamis, floods landslides and avalanches. This provides critical insights for early warning systems and disaster response. Other examples of how EO can support policy implementation include monitoring fishing in protected waters, land use including farming and deforestation, and sea ice levels.

BOX 5

Earth Observation Data Hub

The Earth Observation Data Hub (EODH) in the UK is a pathfinder project designed to provide a single access point for Earth observation data by drawing on various public and commercial sources.

The EODH project was initiated to address the fragmentation of Earth observation data sources and services in the UK. It aims to make data more accessible and usable for researchers, industry, and government. The project is funded by the Natural Environment Research Council (NERC) through the Department of Science, Innovation and Technology's Earth Observation Investment programme. Key stakeholders include the UK Space Agency, Met Office, and several industrial partners like Airbus Defence and Space.

Features of EODH

Centralised Access
EODH provides a centralised software infrastructure, enabling users to access and develop new EO services and tools based on standardised services.

Data Integration
The hub integrates data from distributed public and commercial centres, reducing the need for extensive data downloads and storage.

Community Building
By the end of its initial phase, EODH aims to have a community of researchers, industry professionals, and government entities working together to innovate and utilise EO data in new ways.

Support for Decision-Making
The hub supports commercial and government decision-making by providing insights derived from space-based data.

Communications satellites

Radio waves used for communication essentially travel in straight lines and, at very high frequencies (VHF), are not able to transmit across the curvature of the Earth. At lower shortwave frequencies radio waves can be reflected off the ionosphere above the atmosphere, but long-distance communications using this propagation method is highly variable, often unpredictable, and prone to fading and interference.

Using a satellite in orbit as the intermediate relay of a signal that needs to be transmitted between two or more distant points on Earth has enabled much greater communications coverage and enabled more remote parts of the world to receive reliable, high-quality radio, television and data services. The use of tightly focused microwave transmissions to/from satellites achieves far greater communications capacity and allows greater exploitation of finite radio frequency resources.

The first four decades of the space age have used satellites in geostationary orbit located 35,786km above the equator, which has the advantage that they appear stationary in a continuous, fixed position in the sky as viewed from a communications terminal on the ground, and they do not need to use steerable or tracking antennas. The 70,000km round trip to/from the satellite and the ground terminal does introduce a ¼ second (250ms) delay, which affects two-way voice conversations and some data services but has no practical impact for one-way direct-to-Earth services (such as television).

Advances in both satellite and ground terminal technologies in the last 5 years have enabled satellites in low Earth orbit to provide an alternative to geostationary systems, offering reduced delays (~10-20ms) and improved coverage at high latitudes but requiring large constellations and complex traffic hand-over from satellite-to-satellite to provide continuous communications. SpaceX's Starlink is leading the way with a constellation of more than 6,900 satellites providing high speed (>100mbps) mobile data transfer and internet access worldwide.

Global Navigation Satellite Systems (GNSS)

Global Navigation Satellite Systems (GNSS) are groups of satellites, generally in medium Earth orbit (MEO), that generate and transmit very stable and accurate timing signals generated by atomic clocks. Comparison of these timing signals received simultaneously from several GNSS satellites in different locations in their orbits enables the receiver to generate location data that can be used for precise positioning and navigation. The GNSS timing signals are also widely used to control and synchronise many energy utilities, banking transactions and transport systems to the extent that GNSS now underpins essential infrastructure and the everyday lives of citizens.

A number of countries now have their own Position, Navigation and Timing (PNT) satellite systems offering global coverage, such as the US Global Positioning System (GPS), European Galileo, Russian GLONASS or regional coverage such as the Japanese Quazi-Zenith Satellite System (QZSS) and Indian Regional Navigation Satellite System (IRNSS).

Mobile phone users use GNSS-derived PNT combined with urban cellular systems to provide consumer services through applications such as Google Maps. Anonymised datasets from mobile phone movement have a diverse range of applications but proved valuable when determining public health guidance based on citizen movements during the COVID-19 pandemic[52] and by aiding in tracing contacts of those who contracted the virus[53].

Military space

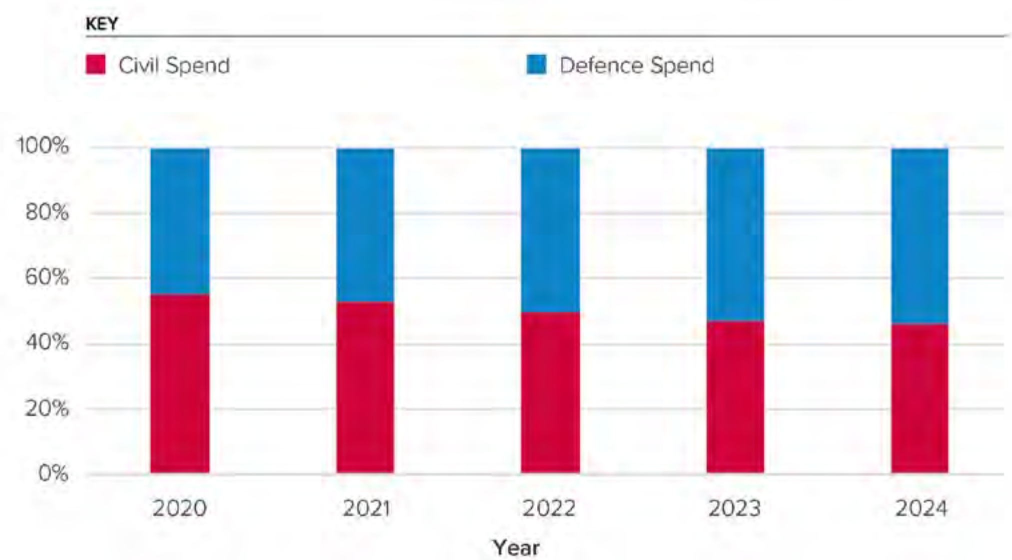
The initial driver for access to and exploitation of space in the 1960s came from military applications, such as the use of high vantage points from orbit to observe adversaries and communicate with dispersed forces on land, sea and in the air. The need to observe deep into adversaries' territories without infringing sovereign airspace stimulated the development of sophisticated (but costly) military remote sensing satellites. As early as 1962, US reconnaissance satellites provided the essential information that supported US intelligence-gathering during the Cuban Missile Crisis. Geostationary satellites have been a communications backbone of defence and military organisations since the first satellites were launched. Space-derived position, navigation and timing (PNT) information has been a key component of location and navigation of forces, operation of drones and missile guidance systems.

Although space provided crucial surveillance information and communications channels to military commanders, it was regarded as a useful supporting function rather than a primary capability until the Gulf War of 1991. This is often referred to as the world's first "space war" where space-based observation and positioning systems played a critical role in military operations. Since then, space has become an increasingly essential component of defence and military strategy, although the increasing reliance on space capabilities can create new potential vulnerabilities as space-based functions have become increasingly layered and interdependent. The same is true of services and facilities in complex urban environments which rely on space-based functions that become increasingly layered and interdependent. Technology vulnerabilities can manifest themselves through cascading failures[54] that may become harder to predict and mitigate, particularly if legacy systems are not maintained. Older satellites and systems can also be more vulnerable to cyberattacks[55] and indeed the same vulnerabilities also exist for civilian services and facilities, especially in complex urban environments, with implications for the military supply chain.

With geopolitical tensions increasing, since 2020, the share of defence vs. civil spending in space globally has increased from 45% to 54%[56].

FIGURE 10

Share of civil versus defence spend as a proportion of GDP globally.



Source: European Space Agency

Major space stakeholders have funded and launched their own national satellites, whilst other nations have often shared communications services with their allies. In 2024, some 31 countries have satellites in orbit that have either dedicated military use or, increasingly, military/civil/commercial use. Originally such assets were referred to as 'dual use' but they are now described more specifically across a range of flexible architectures such as 'space-as-a-service', 'commercial integration', 'commercial augmentation' and 'hybrid framework'. As governments make increasing use of private sector commercial space assets to support military capabilities and objectives, there is a blurring of the distinction between civil and military use provided by companies that increases the risk of private sector commercial space assets being treated as military targets.[57]

However, in the last few years, space is no longer considered to be a benign or neutral environment. It has become "congested and contested" and now recognised as a 'warfighting domain' with space powers demonstrating complex manoeuvres in orbit and increasing technical skill with direct implications for surveillance of other satellites and potential attacks. Preparations to achieve control over space to protect national capabilities now consist of both defensive and offensive actions.

UK perspective

The UK government's Ministry of Defence has owned and operated a strategic communications satellite system called SKYNET since the 1970s, to transmit defence communications securely to its forces and allies across the globe. The UK Government has committed a further £5bn to develop SKYNET 6 to improve this service over the next 10 years.

In 2024, recognising the growing importance of an independent national capability for space intelligence, surveillance and reconnaissance (ISR) alongside satellite communications, the UK military launched its first dedicated imaging satellite called TYCHE, as a demonstrator that will be able to image troop positions on battlefields. TYCHE will be followed shortly by a second ISR small satellite, JUNO, and then larger radar satellites in a network of future ISR satellites capable of imaging through clouds and eavesdropping on radio transmissions.

Space weather

The environmental conditions in space are influenced by the Sun's activity cycles. Solar winds, the streams of charged particles and magnetic field released from the Sun's corona and Coronal Mass Ejections, expulsions of plasma from the Sun's corona, can result in large geomagnetic storms around Earth. In addition, solar flares, which are sudden bursts of electromagnetic radiation from the Sun's surface and solar energetic particle events, which are bursts of high energy particles accelerated by shock waves emitted from the Sun, can result in radiation storms. Geomagnetic activity and geomagnetic storms are disturbances in the Earth's magnetosphere which are also responsible for the magnificent light displays of the Aurora Borealis phenomenon. Together with radiation storms they can also result in significant damage to electronic equipment such as satellites resulting in disruption to communications, GPS signals and aviation. Geomagnetic storms can also increase atmospheric drag and change the orbits of satellites and space debris in low Earth orbit, increasing the risk of collisions. They can even damage Earth-based infrastructure such as transformers on the electricity grid depending on the intensity of the storm. The Carrington Event of 1859, saw the largest geomagnetic storm in recorded history, with geomagnetically-induced currents resulting in significant disruption to telegraph lines, in some cases giving operators electric shocks, and sparks generating fires. A similar event today would be significantly more disruptive given the expansion of electrical equipment both on Earth and in orbit and many vital pieces of infrastructure would be vulnerable.

One research group identified a potential risk in the older electrical signalling systems found at more than 50,000 points on British railways[58]. Geomagnetic storms caused by space weather could be capable of activating these signalling switches potentially leading to accidents. Mitigating this risk is possible with resistant components which are gradually being rolled out at key points. However, replacing older signalling systems on the entire railway network would be a very costly intervention to prepare for an event that only occurs once every 100 years. The most important concerns are the risks to power supplies from geomagnetically induced currents during a geomagnetic storm, and that a storm could trigger a cascading set of collisions between objects in orbit (Kessler Syndrome, discussed further below).

GOVERNANCE CHALLENGE

Security and resilience – protecting orbital assets, ensuring the continuity of services, and preventing disruption

If orbital systems are disrupted by a malicious attack, an unsustainable orbital environment, or an extreme space weather event then all the services they provide could be compromised. The space-based satellite services which society heavily relies on could become limited or completely disrupted. Scientific research infrastructure like space stations or space telescopes could become inoperable. Without position, navigation, and timing (PNT) services, for example, large sections of the economy could be set back decades. If GNSS services alone were lost for seven days, this would result in the loss of a £7.6 billion contribution to UK GDP[59, 60], an economic shock comparable in scale to the impacts of the COVID-19 pandemic. Alternative terrestrial solutions to satellite services might not prove to be adequate replacements. Similar disruption to Earth observation satellites could reduce the capacity to measure and monitor environmental changes and render humanity blind in its efforts to protect Earth's climate.

Objects in orbit therefore need to be protected from physical risks in the orbital environment and built with advanced, radiation resistant components. They must also be able to avoid collision with other objects in orbit. Collision could disrupt services to their customers, potentially even wiping their data. They could also require regular, potentially expensive, servicing for maintenance and refuelling – though new forms of propulsion and improvements in automated robotic servicing could make these far less significant as limiting factors.

Threats to space-based infrastructure and service continuity include:

- Attacks from bad actors (eg physical or cyber-attacks)
- Extreme space weather events
- Physical risks (debris/collision)
- Electromagnetic interference (light and radio noise)
- Absence of redundancy systems

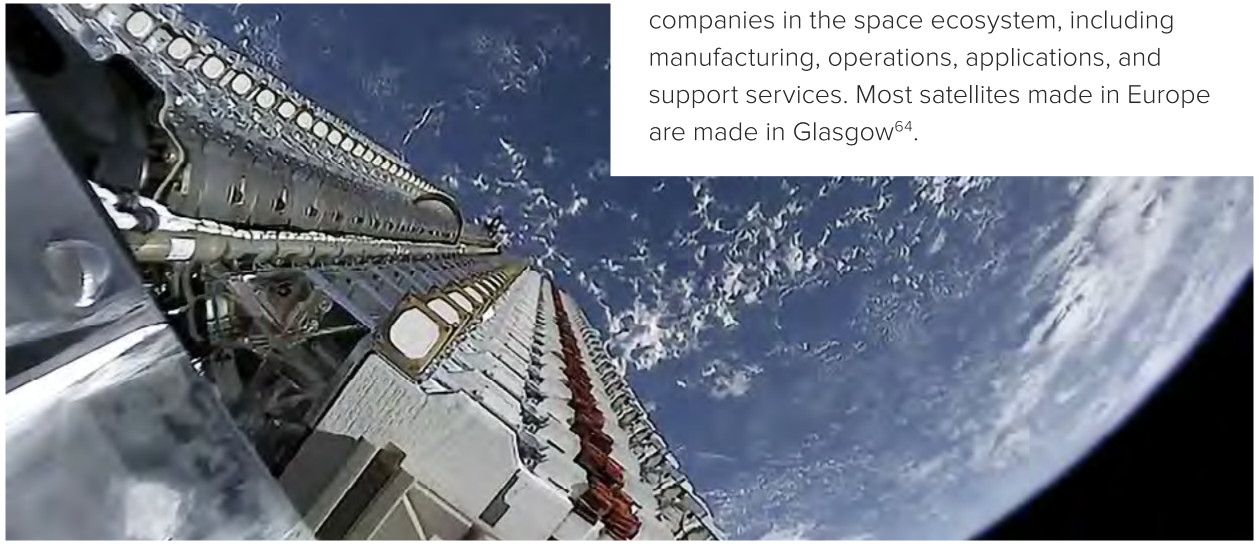
Reviewing dependency on these systems and determining what Earth-based capacity could replace them in event of their loss will be important. This has been explored with ground-based quantum clocks for instance as an alternative to satellites which provide timing information.

Equally, space can offer an alternative to ground-based infrastructure in the event of emergencies. Satellite communication systems could be used for transmission of essential data in the event of undersea data cables (which transmit 95% of internet data) being cut either by accident or with malicious intent. Reviewing the extent to which existing satellite systems could compensate for the loss of such cables is of fundamental importance for resilience.

Recent trends in the satellite sector

In 2023, the global civil space economy was valued at around $630 billion[61], and could be as much as $1.8 trillion by 2035. While national government expenditure is included in this total, over 75% of worldwide space-based economic activity now takes place in the commercial sector, with revenue generation being dominated by the supply of ground equipment, such as antenna farms (large commercially operated ground stations which transmit signals to and from satellites), control centres, consumer equipment such as GPS receivers and satellite and launch services that support wider economic activity on Earth[62]. In the UK, space-related services underpin around 18% of UK GDP[63] or £370 billion annually as non-space organisations are becoming more aware of the possibilities of using space data, with uses from precision farming to city planning and traffic management, opening new commercial possibilities for both service providers and consumers.

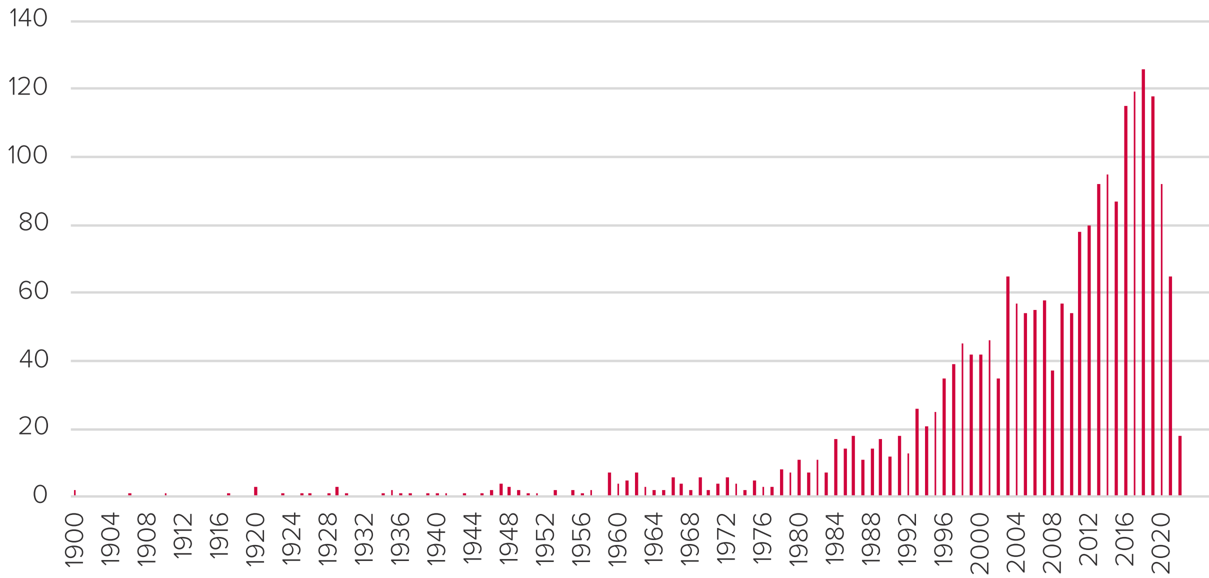
Below
A stack of 60 Starlink test satellites atop a Falcon 9 rocket, close to entering orbit. © SpaceX



In the last decade, the satellite sector has expanded dramatically with increasingly affordable launch and the shrinking of satellites. Small satellites, or 'smallsats', have taken advantage of the combination of miniaturisation and increased capability of microelectronics to create highly capable yet physically small and relatively inexpensive satellites ranging from 100kg microsatellites down to 10kg nanosatellites. These small satellites can also be launched in large batches on a single rocket, even ridesharing on a rocket as a secondary payload. SpaceX currently holds the record for launching 143 satellites on a single rocket. These developments have stimulated many new start-up companies and smaller businesses offering both innovative hardware and services whilst also creating affordable opportunities for scientists, universities and even students to put their own spacecraft in orbit. This change is now often referred to as 'NewSpace', although its origins have developed steadily since the 1980s, and has greatly broadened involvement in space and stimulated new ideas. This worldwide trend has been matched by activity in the UK. Figure 11 shows the increasing number of UK companies in the space ecosystem, including manufacturing, operations, applications, and support services. Most satellites made in Europe are made in Glasgow[64].

FIGURE 11

UK space companies by incorporation date over time



Source: DataCity

There remain requirements for large (and costly) satellites for certain missions where either large power requirements or massive scientific instruments are necessary. To meet future requirements, many satellite communication companies now have, or are planning to have, multi-orbit solutions with geostationary satellites continuing to provide secure back-up and communication services where latency is not an issue, whilst the low Earth orbit satellites will be used for mobile, time critical low-latency requirements[65]. Whilst recent developments have been towards satellite constellations, in time this will likely be complementary to geostationary orbit services as each orbit carves out specific niche applications.

The increased ease of launching satellites is enabling larger companies to produce constellations of thousands of satellites. So-called mega-constellations have thus far largely focused on efforts to provide low latency internet connections around the globe. Signals are transmitted either to a ground-based antenna, or increasingly, direct-to-device (D2D). Companies such as Apple and Google have invested in satellite infrastructure and are designing mobile phone hardware to receive signals from satellites. The advantage of satellite internet services is that locations that are hard to reach with traditional cable and mobile phone mast infrastructure can get the benefit of internet without having to wait for installation of cable networks to reach their area. This should enable ubiquitous high-bandwidth access to critical services such as education, healthcare, finance and entertainment, irrespective of population density. It also means that internet signal can be provided during commercial passenger flights – a deal was announced between SpaceX and Air France in September 2024 to provide customers with rapid internet speeds for free mid-flight.

Examples of growing mega-constellations in LEO include Starlink from SpaceX with more than 6,900 satellites comprising over 60% of the total satellites currently in orbit. SpaceX ultimately plans to have 42,000 satellites in its completed Starlink constellation. Currently, the next largest constellation is Eutelsat's OneWeb with 630 satellites in orbit, which is complete, but yet to have started commercial services. Other anticipated mega-constellations which are in an earlier stage of deployment, include Amazon's Project Kuiper which has been granted permission to launch a constellation of 3,236 satellites and China's Thousand Sails project which is aiming for a constellation of 14,000 satellites, with over a thousand scheduled to be launched in 2025.

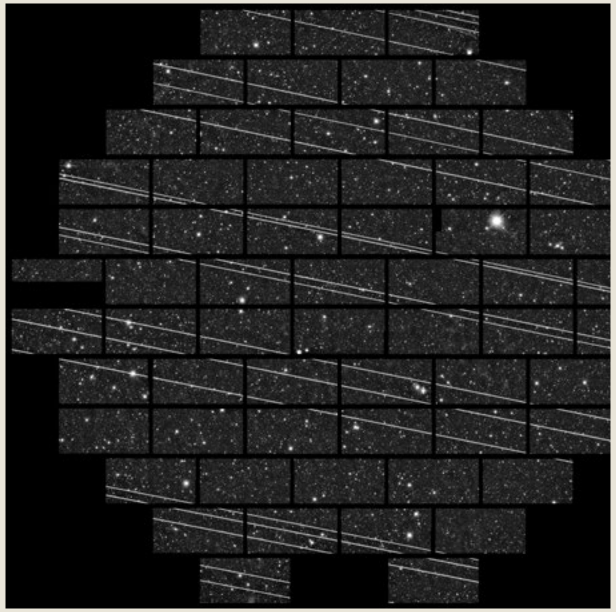
The commercial requirement for such large quantities of satellites has driven a change in production approach, with greater standardisation, robotic assembly, stimulation of the component supply chain and the use of automated spacecraft operations in orbit. It has also raised concerns about the rapidly growing number of objects in low Earth orbit in particular and the need to protect the space environment by means of industry best practice guidelines, regulation and standards.

GOVERNANCE CHALLENGE

Orbital congestion

More satellites are being launched now than ever before. In 2020 there were 2,000 active satellites in orbit in total; but in 2022 the United Nations Office for Outer Space Affairs (UNOOSA) received more than 2,000 new satellite registrations for that year alone. There are now over 10,000 satellites in orbit and the frequency of objects launched is expected to continue rising at unprecedented rates. Consulting firm, McKinsey & Company estimates that by 2030, there could be 27,000 satellites operational in orbit[66], exacerbating existing risks and issues. However, it could be as many as 65,000 satellites if all proposed constellations materialise.

The increasing number of satellites being launched into space has led to congestion in certain orbital regions, particularly in certain low Earth orbits. This is raising concerns about the increased risk of collision and about how access to radio frequency spectrum is managed and governed by the International Telecommunications Union (ITU).



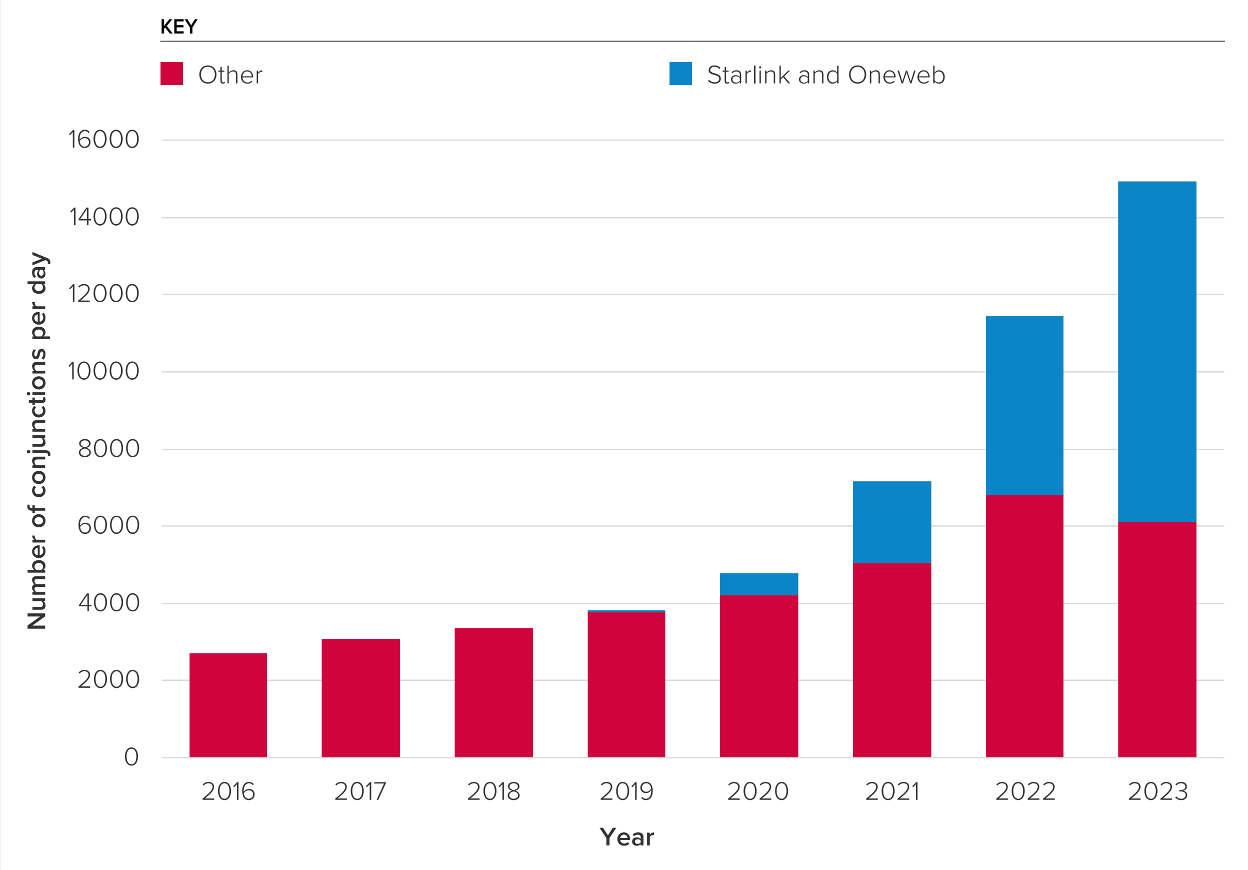
Collision avoidance manoeuvres

The United States Space Force 19th Space Defense Squadron (19 SDS) operates a Space Situational Awareness (SSA) system, that constantly monitors objects in orbit and alerts satellite operators to risks of collisions between their objects and another target. Approximately 600,000 alerts are generated each day which is an increase of 200% over the past three years, demonstrating how the rapid increase in satellites in orbit has resulted in greater risks of collisions[67]. When notified, operators will conduct avoidance manoeuvres of their satellites, which require using onboard propulsion systems to change course. The typical threshold of risk tolerated by operators is a one in ten thousand chance of a collision, but SpaceX uses a 1 in a million chance. It is thought that this stricter threshold is followed due to the size of its constellation. With more than 6,900 satellites, the cumulative risk of different collision events and hence threat to the constellation overall could add up quite quickly. This has rapidly increased the number of avoidance manoeuvres made (see Figure 12) and complicates the process of SSA. The issue is compounded by the fact most satellites in low Earth orbit use ion propulsion systems which provide low thrust and hence make it slow to change course. The SpaceX constellation orbits at 550km above the Earth. The greatest probability of a collision comes when satellites must cross this orbital height.

Left
Starlink satellites impacting a DELVE survey telescope image. Photo Credit: CTIO/NOIRLab/NSF/AURA/DECam DELVE Survey. © M Lewinsky/CC-BY-2.0

FIGURE 12

Most alerts are received by operators of existing large constellations ie SpaceX and OneWeb



Credit: Professor Hugh Lewis.

Improvements in SSA techniques will help operators to identify more precisely when assets are at risk. Companies like LeoLabs are developing advanced radar technology which can detect and track objects that are 2cm in size. This will help to improve the accuracy of collision probability calculations. However, international research and collaboration is still required to understand the carrying capacity of different orbits and ensure that they are not exceeded.

Satellite insurance

The first satellite insurance policy was placed with Lloyd's of London in 1965. It was designed to cover physical damage on pre-launch of Intelsat 1 – known as the Early Bird. This was the first commercial communications satellite to be placed in geosynchronous orbit. Despite this milestone happening early in the space age, only a very small proportion of satellites are insured today. The risk of collisions from crowding in certain low Earth orbital altitudes has led to some space insurers refusing to insure satellites in low Earth orbit and other insurers carefully considering which satellites should be insured or whether particular orbital altitudes are becoming too much of a concern[68]. With so much commercial activity taking place in low Earth orbit, the concern is that if insurers do not have the confidence to offer to insure satellites, finance may not be made available to support the commercial venture. If this were to happen, it could seriously hamper commercial developments (except for certain operators) especially if there were to be a collision in low Earth orbit which would highlight the concerns.

The impact of a crowded orbit on astronomy

Crowding of orbit with satellites emitting radio frequency EM radiation and visible light also interferes with the work of ground-based astronomers. Ground based telescopes are designed to be highly sensitive to detect distant cosmic signals. With the satellites being much closer, they can significantly interfere with what these telescopes are able to capture as the distant signals are overwhelmed by radio noise from satellites[69]. Similarly, visible light reflected off the constellations of satellites in orbit can create streaks in telescope images, compromising what can be seen.

This has galvanised a movement in the scientific community calling for 'Dark and Quiet Skies'. In 2023, SpaceX reached an agreement[70] with the US National Science Foundation to mitigate interference by implementing new design features in satellites that minimise reflected light and hence brightness of satellites in the sky eg by use of new black paint as a surface coating. Also included was a provision to open radio frequency bands for ground based astronomers outside of the 10.6-10.7GHz range protected by the ITU for research purposes[71]. The Dark and Quiet Skies Bill was introduced with bipartisan support to the US Senate in 2024 which sought to formalise some of these protection efforts in law by expanding research on these conflicting uses of space[72]. The Bill did not pass before the end of the session in Congress, but could be revived in future.

Right
Starlink Satellites pass overhead near Carson National Forest, New Mexico. © NSF's National Optical-Infrared Astronomy Research Laboratory/CTIO/AURA/DELVE.

Monitoring asteroids

It is not only scientific benefits that could be lost. Ground based telescopes are important for monitoring the location of asteroids which could impact Earth. In 2019, the football pitch-sized, 2019 OK asteroid made a close approach to Earth (within 65,000 km), equivalent to one fifth of the distance from Earth to the Moon[73]. Asteroids of this size are estimated to hit Earth once every 100,000 years, but smaller asteroids are predicted to impact more frequently and could still cause significant damage eg the 18m asteroid that exploded over Chelyabinsk, in 2013 with 112 people hospitalised.

2019 OK was only detected a few days before its closest approach indicating the need for more robust mechanisms for discovering and monitoring asteroids. The Double Asteroid Redirection Test (DART) conducted by NASA demonstrated that the course of asteroids can be diverted if necessary to protect Earth[74] and the mission's success is being built upon in the European Space Agency's Hera project[75]. Even so, it is critical to ensure that asteroids can be identified and monitored so any risks can be dealt with as they arise. As orbit becomes increasingly crowded with planned satellite constellations, it could interfere with the ability to monitor such threats.

FIGURE 14

The hunt for dangerous astroids

Use of Very Low Earth Orbit (VLEO) spanning between 100 – 450km may offer a way to address some orbital sustainability concerns. VLEO orbits are attractive as their closer proximity to the Earth's surface enables more precise imaging and reduces latency for communication satellites. VLEO orbits are sometimes referred to as 'self-cleaning' because satellites can be programmed to deorbit at the end of their productive lifespan and burn up in the atmosphere more easily, leaving less debris behind. Satellites operating in this region are sometimes referred to as 'skyskimmers' and can also be made to be more fuel-efficient by employing 'air-breathing' engines which make use of oxygen in the upper atmosphere for propulsion. The downside is that maintaining orbital position in the drag of the atmosphere requires more energy overall and with the closer position to Earth they cannot cover as large an area as satellites deployed at higher altitudes. Lifespans can be increased further by implementing advanced coatings to reduce drag and erosion caused by atomic oxygen in the upper atmosphere. However, these coatings often contain heavy metal elements and further research will be required to assess the environmental impacts of these coatings at end of life.

Above
Europe's space freighter ATV Jules Verne burning up over an uninhabited area of the Pacific Ocean at the end of its mission.
© NASA/ESA.

GOVERNANCE CHALLENGE

Satellite disposal

Once satellites reach the end of their effective lifespan, then they essentially become junk that must be dealt with. Their lifespan is usually determined by a number of factors, for instance, the technology they possess has become obsolete, they have become damaged or they run out of fuel to maintain their orbital position.

The Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines set a timeline of 25 years for objects to be removed from LEO and the US Federal Communications Commission (FCC) rules expect them to be removed within five years.

There are currently two widely practised options for disposal of satellites. The first is to move them into less crowded, less useful, so-called graveyard orbits around Earth where they are less likely to interfere with other functional satellites.

The alternative approach is to allow defunct satellites to re-enter Earth's atmosphere in either an actively controlled or uncontrolled manner (allowed to passively fall out of orbit). As satellites are travelling at such high speeds, the friction from air resistance generates sufficient heat to burn them up. Graveyard orbits are typically used for satellites that are located in geostationary orbit. For the majority of satellites, located in low Earth orbit, the policy of burning them up in the upper atmosphere is the typical approach. Whilst this strategy is essential for efforts to reduce the risks posed by inactive satellites which essentially represent orbital debris if their course can no longer be adjusted, it is unclear if this strategy could pose other risks.

It has been demonstrated that 10% of the heavy metals found in the upper atmosphere[76], including up to 20 different elements including lithium, aluminium, copper and lead, are associated with the process of satellites burning up. The remaining 90% come from meteorites burning up in the upper atmosphere but given the rate of expansion of activity in orbit, this distribution could soon shift. At present, it is unknown what influence the increased amounts of these metals might have on processes like ozone formation for instance. Ozone is a vital protector from the sun's rays and increased commercial activity in orbit could undo the successful efforts directed by the UN Environment Programme's Montreal Protocol 1987[77]. The protocol significantly reduced the impacts of harmful chemicals such as chlorofluorocarbons (CFC) which had been depleting the ozone layer previously. Pre-emptive research would help to determine if metal accumulation threatens the ozone layer in any way, or unintentionally reflects sunlight away from Earth (thereby cooling the planet like geoengineering) which could stimulate a review of the chemicals to be controlled under the auspices of the Montreal Protocol.

In-Orbit servicing

Active debris removal and in-space servicing

It is estimated that over 36,500 pieces of space debris over 10cm in size exist around Earth, some of them remaining for decades after launch. These range from entire non-functional satellites to tiny pieces of space junk that have fallen off rockets or spacecraft or because of collisions. If any craft is hit by a piece of debris over 10cm in size that is moving at relative speeds greater than 14,400 km/h, it will likely be destroyed[78]. Impact velocities in orbit will vary but become faster the closer the orbit is to Earth (figure 9). Objects in the same orbit as the International Space Station move at 27,612km/h, more than 10 times the velocity of an average bullet shot on Earth. In 2016, a tiny fleck of space junk, only a few thousandths of a millimetre across, gouged a quarter-inch dent in the glass window of the International Space Station (ISS)[79]. Whilst this is far from causing any critical failure, it demonstrates how even minuscule objects can cause visible damage when moving at high speeds. Any object greater than 1cm in size could rip through shielding on the ISS. Space Domain Awareness (SDA) has become an important activity to map, monitor and inform satellite and space station operators of risks, providing the information necessary to conduct avoidance manoeuvres. Companies such as LeoLabs can monitor debris of 2cm in size with radar technology. Oxfordshire-based company First Light Fusion is also repurposing technology it designed for fusion reactors, which fires objects at comparable speeds to space debris. This will be used by NASA and the Open University to test the resilience of various materials to impacts at these speeds.

FIGURE 15

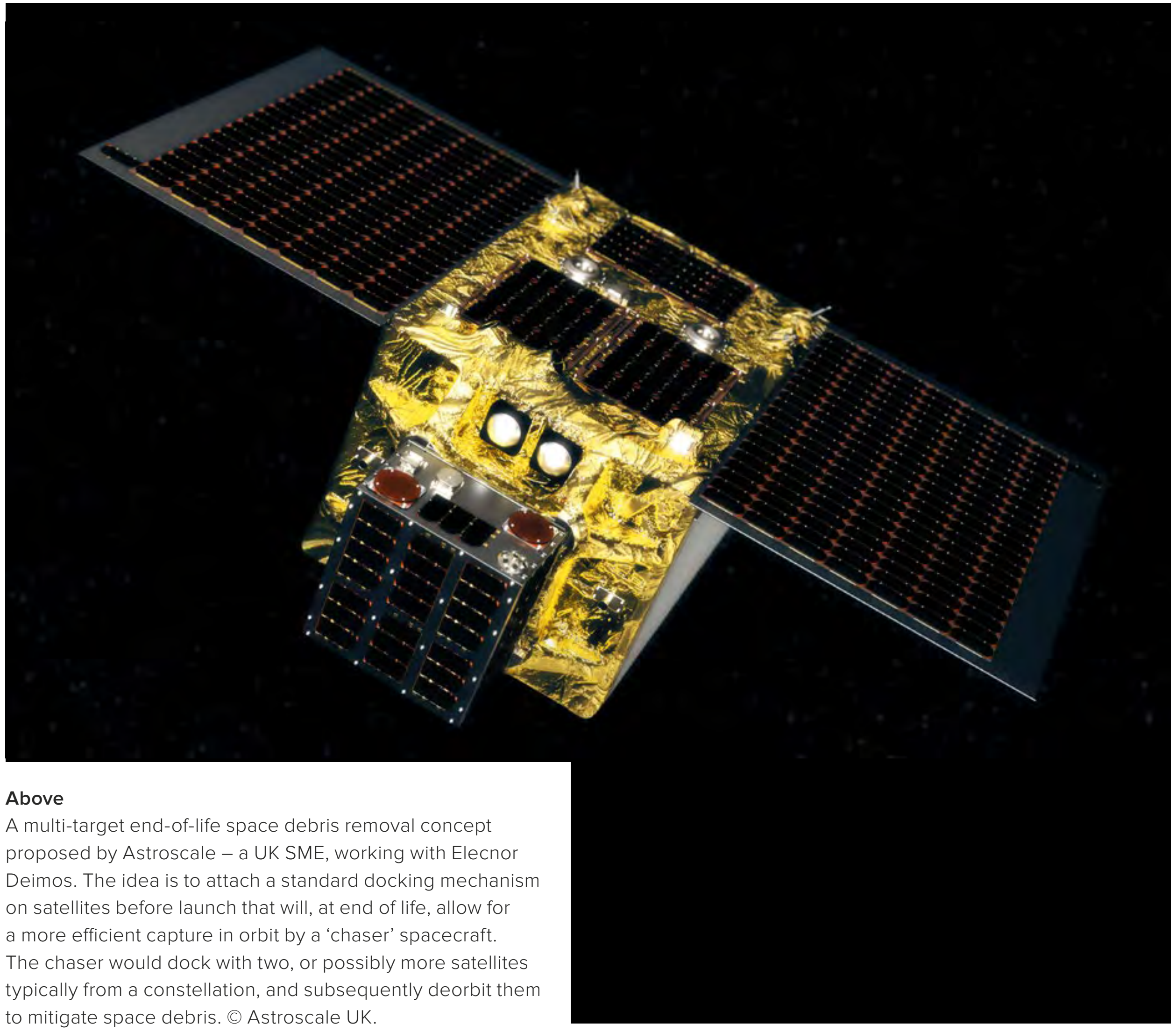
Image of crack in ISS window taken by British astronaut, Tim Peake.

"I am often asked if the International Space Station is hit by space debris. Yes – this is the chip in one of our Cupola windows, glad it is quadruple glazed."

Tim Peake

Active debris removal (ADR) is the process whereby defunct satellites and other potential major debris risks are taken out of Earth's orbit to avoid congestion or risk of fragmentation or collision. It is, not yet feasible to clean up the whole debris field, but the risk of a 'chain reaction' (the Kessler syndrome) caused by multiple collisions can be reduced by removing large or unstable defunct objects.

Several companies including Astroscale are offering commercial services for debris removal, however this is a costly operation, with several risks and no legal framework; and at present it is restricted to major threats. There have been demonstrations of techniques to capture and de-orbit pieces of debris eg Astroscale's robotic craft, 'End-of-Life Services by Astroscale' (ELSA-d) and 'Cleaning Outer Space Mission through Innovative Capture' (COSMIC).



Above
A multi-target end-of-life space debris removal concept proposed by Astroscale – a UK SME, working with Elecnor Deimos. The idea is to attach a standard docking mechanism on satellites before launch that will, at end of life, allow for a more efficient capture in orbit by a 'chaser' spacecraft. The chaser would dock with two, or possibly more satellites typically from a constellation, and subsequently deorbit them to mitigate space debris. © Astroscale UK.

There is increasing pressure on satellite operators to dispose of their satellites safely at their end of life by deorbiting or moving into unused 'graveyard' orbits. ADR will be an important component of any space sustainability measures and requires clear standards for operations accepted internationally and to manage and mitigate technical and security concerns. Such technology could be used by malicious actors to remove another operator's satellite from orbit and misunderstandings over rendezvous operations could escalate tensions between different operators and so must be handled with care.

In the longer term, an option to consider is that space debris is recycled by autonomous robotics as part of novel in-space manufacturing processes. Recycling debris would provide a source of essential raw materials and components that would otherwise have to be expensively launched from Earth. Such services would feed back into satellite manufacture if they were recyclable by design.

There are specialised servicing and refuelling robots which are capable of semi-autonomously seeking out and reviving defunct satellites to extend their effective lifespan such as the Northrop Grumman Mission Extension Vehicles (MEV-1 and MEV-2), which have extended the life of satellites in geostationary orbit. Such maintenance robots will reduce the need to risk astronauts for such tasks and result in fewer satellites being launched, increasing the value and yield of each satellite while reducing overall costs and mitigating any potential risks of heavy metals impacting the upper atmosphere as they burn up.

GOVERNANCE CHALLENGE

Orbital debris and Kessler Syndrome

The European Space Agency's Space Debris Office, has estimated the existence of 36,500 objects larger than 10cm, 1 million objects between 1-10cm, and approximately 130 million objects between 1mm to 1cm. Larger items include intact defunct satellites, or spent rocket stages, whilst smaller items are the fragments and broken parts of a variety of space assets. There is little in the way of legislation or guidance on appropriate behaviours in orbit and some space operators engage in practices which are unsustainable eg failing to deorbit defunct satellites or not providing adequate information about their spacecrafts' movements, creating uncertainty and risk in space operations. Whilst operators can make evasive manoeuvres to avoid other satellites, large items of debris represent the greatest collision risk[80].

Destructive Anti-satellite (D-ASAT) weapon tests involving the deliberate destruction of spent satellites, also generate a substantial amount of space debris and heighten tensions in space. Historical examples have generated between 1000-3000 pieces of debris. Debris is a hazard for all assets in orbit. The International Space Station (ISS) had to make evasive manoeuvres more than 30 times since 1999 to avoid such debris that could cause damage which could be highly dangerous for those aboard.

Some have warned that orbits can only sustain a finite capacity of objects before a collision sets off a chain reaction, or a 'collision cascading effect', known as the Kessler syndrome. Whilst not yet at this stage, with each subsequent collision, the risk continues to grow exponentially until a given orbital height (most likely, certain regions in LEO) around the Earth becomes an unnavigable cloud of debris that would destroy any asset in orbit or any spacecraft flying through it. There are some who argue that the early stages of Kessler syndrome are already evident, though before the exponential growth curve of risk and collision. The result of this would be to deny the effective use of space to everyone, potentially for decades, as cleanup operations would have to take priority. The situation right now is manageable – but this could change at any moment. International agreement, practices and standards, such as those being developed by the Earth Space Sustainability Initiative (ESSI), Astra Carta and others like it, which call for space activities to protect common and mutual interests into the future are essential.

Re-entry of debris into Earth's atmosphere
Over time, pieces of space junk, without active means of propulsion to maintain their orbital positions, will descend in orbit via Earth's gravitational pull. This means they will eventually re-enter Earth's atmosphere.

Smaller objects will typically burn up from the friction of air resistance in the atmosphere. However, the material, size, shape and speed of the debris as well as the altitude at which it breaks up will affect its fate upon re-entry. Some larger objects such as rocket bodies, of which there are more than 2,300 already in orbit[81], pass through largely intact and travel in an uncontrolled way through Earth's atmosphere towards the surface of the Earth.

There are risks associated with this, it can be difficult to predict where these objects will land and whilst most of them land in the ocean or other uninhabited areas, there have been incidents of objects landing close to human populations. A 0.7kg piece of waste jettisoned from the ISS crashed through a Florida home at high speed in March 2024, tearing through two levels of the house whilst residents were inside, illustrating the potential dangers of uncontrolled re-entry of debris.

In November 2022, a 20 tonne Long March 5B rocket body re-entered the atmosphere and was estimated to land over Europe. Authorities responsible for flights in this area were notified of the risk and as such 645 aircraft were delayed. Precautionary closures of airspace has significant costs for airlines and their passengers, estimated to be in the order of tens of millions of dollars despite being caused by the space industry[82]. Determining who should be responsible for such costs eg the launch state, the airline, or consumers, requires further negotiation at international level as there may be some limitations to the effectiveness of the Liability Convention (1972) in covering all types of economic damages.

Anticipated growth in frequency of rocket launches coupled with commercial airline traffic expected to increase by a third to more than 36,000 craft by 2034, suggests that the probability of similar incidents occurring will only increase[83].

BOX 6

Saving Hubble

A key example that supports the case for servicing and life extension of an asset in space has been the Hubble Space Telescope. Originally launched in 1990 at a cost of $4.7 billion (at 2020 prices), the telescope was designed to be serviced – an important characteristic for the future as most space assets in space are not currently built with servicing in mind.

Between 1993 and 2009 the Hubble Space Telescope was visited by astronauts five times to replace limited-life components such as batteries, and to upgrade scientific instruments including replacement of components and installation of new cameras which have improved EOs. These missions have not only extended the life of this expensive asset but have also improved its quality and value to science.

These repair and servicing missions were completed by astronauts ferried by the Space Shuttle craft, costing NASA $1.1 billion to repair in 1993. Over the next decade, advanced robotic technicians could become a cheaper and safer alternative – and combined with reusable and more affordable launch systems, the repairing and upgrading systems of significantly lower value than Hubble could become commonplace.

Although it is difficult to quantify the return on investment from the repairs and upgrades, in-orbit servicing has extended Hubble's scientific mission to over 30 years, allowing it to continue to provide humanity with insights into the Universe – and stunning imagery that captures the imagination.

More recent concerns for Hubble revolve around the fact that it is naturally deorbiting over time, slowly falling towards Earth due to the slight atmospheric drag. There is a 50% chance that Hubble will naturally deorbit by 2037. To maintain the instrument, NASA signed a non-exclusive and unfunded Space Act Agreement with SpaceX in 2022 to study the possibility of boosting its orbit.

Left
Images from Hubble Space Telescope before and after servicing.

A maturing satellite ecosystem

Satellite services are likely to continue to evolve in the coming decades. Higher resolution imagery, pinpoint navigation precision, faster data transmission rates, lower latency, expanded coverage and more secure connectivity will ensure that satellite services become even more central to the Earth economy. Annual growth is forecast to be 11%, leading to a $1 trillion economy by 2040. Space-derived services are also likely to converge and integrate with emerging terrestrial services to create a seamless infrastructure.

Satellite services – convergence with emerging technologies

Artificial intelligence

One emerging form of enhancement to satellite services is the use of artificial intelligence (AI) to address bottlenecks in the processing of the huge quantities of data gathered by satellites each day. For example, the EU's fleet of Copernicus satellites provides over 20,000 gigabytes of new data each day that is beyond the capacity of human-directed analysis and AI is now being used to process these vast quantities of data through machine learning and deep learning techniques. These include image classification to identify objects or phenomena, super resolution enhancement for more detailed imagery, data fusion to combine different datasets from different types of sensors, and the identification of correlations or effects that would escape human detection. AI also enables EO satellites to be more selective in gathering information by making independent decisions about which phenomena to track.

AI could also be used to complete satellite data analysis in orbit ie edge computing. Downloading vast data sets in full for processing on the ground is less efficient than automating analysis of results in-situ and transmitting only essential information, which may well be sufficient for lots of purposes.

AI tools can also be used to package data into products and services, providing real-time weather services and predictive modelling and forecasting trained on historical data. Eartheye Space, a company founded in 2022 is exploring ways to combine multiple sources of data from more than 475 satellites and send customers the analysis from machine learning processes. SpaceChain's programme, I-Sat is also capable of using natural language processing similar to OpenAI's ChatGPT to enable users to make requests without requiring technical expertise. Requests are then interpreted and trigger analysis of satellite image data in real time. They have demonstrated how this can be used to estimate yield for sugar crops in Brazil. In the future, the combination of satellite data, ground sensors, and AI may be able to create a 'digital twin' of Planet Earth. This is currently being explored by the European Space Agency for applications such as modelling Antarctic ice sheet melting, water resource management and crop irrigation.

AI could also be used to make satellite manoeuvring more autonomous, similar to self-driving cars, which could be useful to adjust their orbit to avoid debris or other satellites in a congested space. The use of AI will lead to issues around the responsibility for such space activities, similarly to issues arising terrestrially.

GOVERNANCE CHALLENGE

Privacy

If unregulated, super-high-resolution, real-time, 24/7, complete global coverage observation of the Earth coupled with advanced AI data processing could bring about serious privacy concerns for citizens.

As observation instruments advance and integrate with other emerging technologies like AI, the ability to monitor individuals at scale could increase substantially and even become a fully automated process.

Quantum satellite technologies

Emerging quantum technologies for sensing, communication and encryption could benefit space science and exploration, as well as satellite services closer to home. The UK is developing capability in this area in a number of ways including via the Quantum Communications Hub[84] and QEPNT, the UK Hub for Quantum Enabled Position, Navigation and Timing[85].

BOX 7

Quantum misconceptions

Quantum communication relies on the phenomenon of quantum entanglement whereby the quantum states of two particles become interlinked regardless of how far apart they are. While it is true that entangled particles exhibit instantaneous correlations regardless of distance, this DOES NOT imply the possibility of communication faster than the speed of light or real-time interplanetary communication as is sometimes the subject of science fiction. In the context of quantum communication, classical (non-quantum) information is necessary to coordinate the measurement outcomes. For example, Quantum Key Distribution (QKD) and quantum teleportation (the transfer of quantum state from one particle to another) still require the transmission of classical information to establish a shared key or transfer quantum states, which is done using conventional means like laser communication, hence limiting communication to the speed of light.

Quantum communication

Quantum Key Distribution (QKD), using the phenomenon of quantum entanglement or single-photon transmission, can ensure secure communication between satellites as well as between satellites and ground stations. It safeguards sensitive data and commands during space missions. This is partly because any eavesdropping on the signal would be detectable due to the nature of quantum technology.

Satellites can also serve as platforms for implementing long-distance and even global quantum communication. For example, the Micius quantum satellite led by researchers at the University of Science and Technology of China[86], used QKD to demonstrate transmission of a secure message using quantum entanglement distribution 1,000km apart. This was subsequently extended to using the Micius satellite as a trusted relay for an intercontinental QKD between Beijing and Vienna over a distance of 7,600km.

However as Micius resides in low Earth orbit, it cannot cover the whole Earth directly. The team behind Micius are developing a quantum science satellite in geostationary orbit which will be launched around 2027. This satellite will implement QKD and entanglement distribution over 10,000km to enable more efficient satellite-to-ground quantum communication.

Quantum sensing (or quantum metrology)

Besides QKD, the proposed geostationary satellite also provides a new platform for the study of quantum metrology. With the help of global entanglement distribution, it will be possible to combine photons from distributed telescopes worldwide by quantum teleportation in space. In this way, a quantum-enhanced telescope array can be constructed with an interference baseline length that can reach tens of thousands of kilometers, which would greatly enhance the spatial resolution of the telescope. For example, it could even be possible to read a number plate floating in the orbit of Jupiter from Earth[87].

The satellite would also carry an ultra-precise optical clock with fractional instability of 10^{-18} – 10^{-19}. This means that it would take between 0.3-3 billion years for the clock to deviate in its frequency, which is about a billion times more stable than current GPS clock systems. Such clocks would enable even more precise timing information sharing among intercontinental ground stations, thus providing a new standard measure for the definition of a ‘second’. It might be possible to improve this even further in outer space where magnetic and gravitational noise are negligible, so the fractional instability of optical clocks could even reach 10^{-21}, deviating once every 0.3 trillion years.

Specialised facilities – future industries in orbit

Space-based solar power

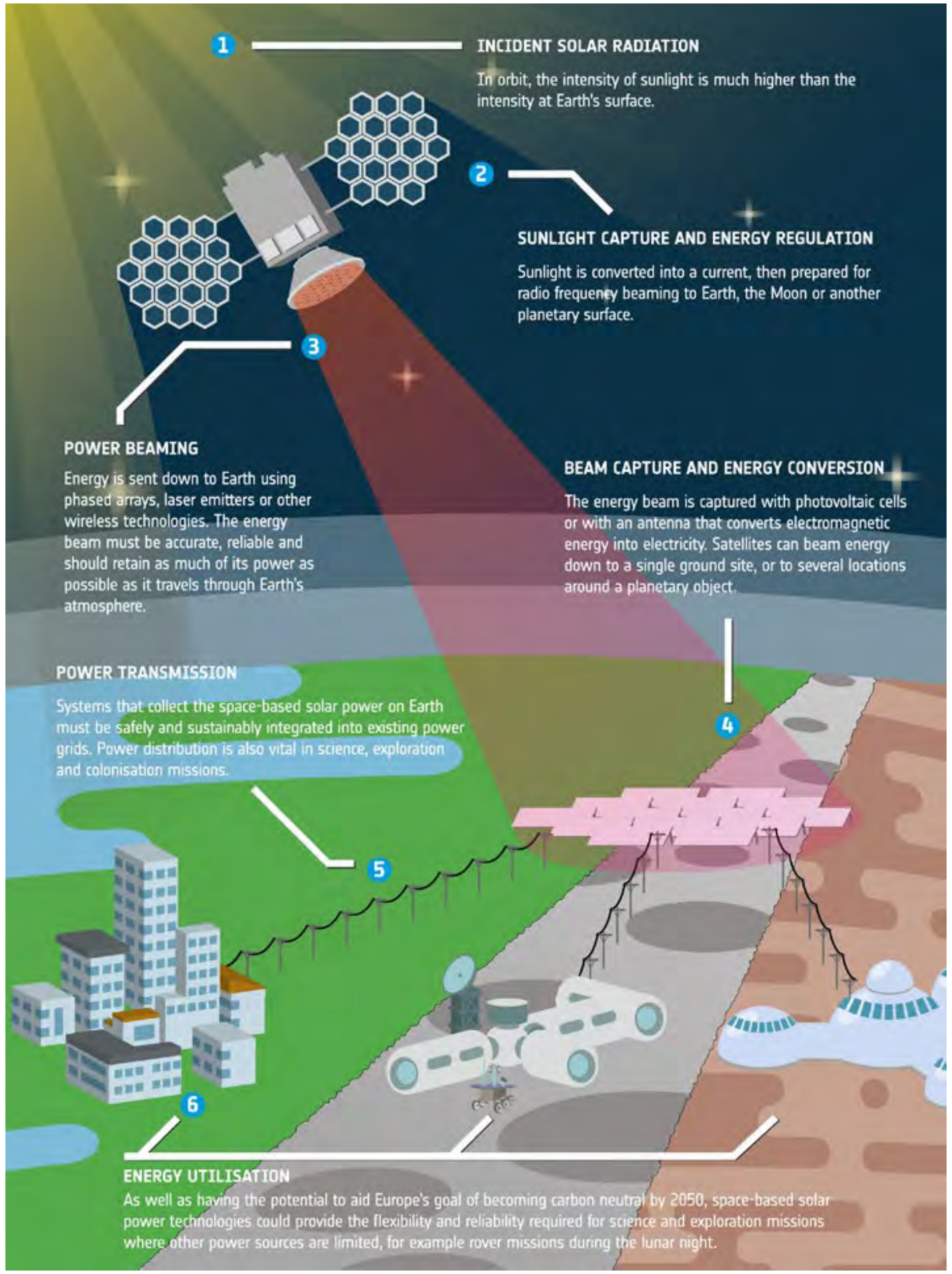
Space-based solar power (SBSP) is an ambitious concept to harvest solar energy in space using kilometre-scale satellites in geostationary orbit which could gather sunlight almost all the time, providing continuous power to Earth day and night and in all weather.

Space-based solar power satellites would convert solar energy into microwaves or lasers and beam it to Earth-based receivers where it could be converted back to electricity. Advocates of this technology argue that electrical power from space could address the intermittency of terrestrial renewable power, by providing energy to places that are experiencing low levels of sunlight and wind, and could provide energy resilience in the case of natural or man-made disasters by beaming it directly to the point of need. Studies commissioned by the UK Government suggest that space-based solar power as part of the energy mix could lead to reductions in the cost of energy[88]. However, this study focuses on power transmission and distribution costs in a UK scenario but does not consider the full range of associated costs including ongoing maintenance of the system and the costs of space-to-Earth transmission.

Space-based solar power could also be used for space-to-space applications, such as providing energy for future lunar bases and mining operations. It could also be used in orbit for delivering electricity to satellites such as synthetic aperture radar systems and space stations. Having companion satellites which could beam energy to such spacecraft would reduce the need to carry as many solar panels and optimise the primary objectives of such payloads. Indeed this is likely more straightforward than implementing such systems to provide energy on Earth and companies such as Star Catcher are trying to develop such infrastructure in orbit

FIGURE 16

Space-based solar power



With the urgency and huge challenge of delivering Net Zero energy production on Earth, whilst keeping energy reliable and affordable, several governments are looking into SBSP. A feasibility study commissioned by the UK government suggests the technology is potentially technically and economically viable, with a carbon footprint estimated in one study to be half that of terrestrial solar power for every unit of electricity provided, including the carbon emitted during launch of the infrastructure[89]. However, the assumption is that carbon payback for SBSP as assessed in this study, would take six years. An alternative estimate for terrestrial solar power, suggests carbon payback of just one year[90] and so further analysis is necessary to determine the relative benefit of SBSP from this perspective. NASA estimated that SBSP could be online from 2050 onwards[91], but some companies have more ambitious aspirations to contribute to the energy mix within the 2050 Net Zero timeframe. In the UK the Space Energy Initiative (SEI) is a coalition of industry, academia and government, bringing together the energy and space sectors to advance the development of SBSP. The UK company Space Solar is developing and commercialising SBSP with industry partners. Space Solar announced a partnership with Icelandic companies Reykjavik Energy and Transition Labs in October 2024 to fly a demonstrator satellite by 2030 which will be capable of powering 3,000 homes[92].

SBSP requires a major engineering development programme to de-risk, scale up and demonstrate this technology in the space environment.

Several challenges need to be addressed to make a space based solar power system viable:

Constructing large infrastructure in space
Building very large structures in space will present new challenges, though lessons can be drawn from experience of constructing the ISS as well as robotic operations in harsh terrestrial environments from sub-sea assembly and nuclear decommissioning.

Solar panel technology and power to weight ratio
The most commonly used solar panel in space is the III-V multijunction solar cell. These are very expensive but have high durability and relatively high power generation per weight launched (approx. 1.2W per gram) compared to silicon solar cells. Other options are in prospect such as perovskites, with a theoretical power to weight ratio of 74 – 94W per gram. However, may have lower durability and are as yet untested in the space environment.

Resilience (debris and security)
Size of the panels are likely to be substantial (approximately 3,000 times the size of the ISS). Whilst most existing plans for SBSP would situate the collecting satellite in geostationary orbit, where there is less space debris, this would still pose a risk given the area covered and other objects such as meteorites could cause damage. Given the distance from Earth (35,786km), servicing and replacement would be challenging and expensive. Though modular construction designs could help to mitigate this risk.

Ramifications for scientific research
Some astronomers have argued that the large area of the collecting satellite would also contribute to light pollution, inhibiting Earth-based science, while others have countered that its light would not be visible from Earth.

Health and safety on Earth for people and the environment
There are also open questions about the risks associated with beaming power back to Earth, including potential damage to human health. Designers of the technology highlight the fact that receivers would be sited offshore, and the beams would also not be powerful enough to harm humans as the low power density levels are well within today's regulation limits. Public acceptance of a new energy technology involving beamed power is nevertheless an important consideration.

The wavelength chosen is important because at certain microwave frequencies they can be harmful to life. Examples include the impacts of homing mechanisms in honeybees[93]. However if the wavelength is very long, the business of collecting the energy at the rate at which it is being generated, and converting it back to electricity, becomes challenging. Understanding the impacts of passing energy through the atmosphere should also be assessed.

Security implications
It has been suggested that the beam technology at optical frequencies in the form of lasers could be used as a space-based weapon. That said, safeguards could protect against military applications, such as using a secure pilot beam directed to specific locations. International agreements will be key to mitigate risks of misuse.

Efficiency of power conversion
There are very significant challenges in beaming power to Earth. The efficiency of power transmission using microwaves through the atmosphere is very low.

Distribution and storage
SBSP has similar challenges in terms of supply and demand of power as ground based alternatives. Determining the best approach to handle unneeded power and finding a way to store or dissipate it safely will need to be addressed.

Situating rectenna
The ground based rectenna (a receiver that converts electromagnetic radiation to electricity) is very large, and whilst much smaller than equivalent ground based solar or wind farms, they will require careful siting and planning, together with a major boost to their conversion efficiency to be competitive for large scale deployment. This means that unlike conventional solar power systems and wind power, they cannot be installed almost anywhere. The systems will need new international regulations to be agreed ensuring they are developed and operated sustainably and responsibly.

Addressing all of the above challenges will have costs which should be factored into a full life-cycle analysis (LCA) comparing the different options, as well as a techno feasibility study.

Orbital data centres

The capacity to generate electricity in space could lead to power-hungry digital operations such as big data processing and cryptocurrency mining being relocated to orbit to avoid raising energy consumption on Earth. Data centres around the world currently consume more energy than the whole of the UK. This is projected to increase, with digital data storage anticipated to account for 14% of greenhouse gas emissions by 2040. Orbital facilities for data processing and storage, powered by abundant and clean solar energy, while taking advantage of the cold environment for a boost in efficiency, could help to address some of these concerns. Traditional cooling systems for Earth-based data centres usually involve circulation of air or liquid coolant which are not practical in a vacuum and in microgravity conditions. There may be limits to the extent to which heat can be radiated out of such data centres into space, depending on the size of the data centre which would need to be considered.

Data centres in orbit could integrate with other emerging technologies, providing a more sustainable option for energy intensive terrestrial activity such as AI model training. As space-based networking bandwidth and latency improves, it might also prove a more effective hosting environment for existing terrestrial 'cloud' services which are occupying ever more capacity as demand has grown significantly. Orbital data centres could also be used to support other digital activity, from the Internet of Things (IoT) to blockchain.

Space-based data centres are likely to be most useful to analyse the huge quantities of data in space itself. Florida-based OrbitsEdge plan to put a small number of data centres into orbit to store vast volumes of data sent from larger groups of satellites at lower orbits, some of which would also relay data back to Earth. Meanwhile, Japan's NTT and SKY Perfect JSAT plan to launch an orbital centre to store and process data in 2025, using photonic chips which use light rather than electronics to transfer information which consume less power. Thales Alenia Space intends to construct a constellation of 13 satellites with processing power of around 10 megawatts (MW), comparable to a medium-sized, ground-based data centre, with 5,000 servers. Other companies such as Lonestar Holdings have successfully tested a small data centre on the Moon[94], which they claim would offer a higher security alternative to Earth-based infrastructure. Lunar data centres could also support scientific analysis with high computing power requirements on future lunar missions.

Data centres on Earth are shielded from solar radiation by the Earth's geomagnetic field. Placing data centres in orbit or on the Moon would therefore require radiation-tolernductor devices and architectures, particularly in the case of larger space weather events.

Space stations

Space stations are specialised spacecraft designed to be operated by human crews and to sustain those crews for extended durations in orbit. They provide an environment for experiments largely free from the effects of Earth's gravity and also to prepare and assess the necessary technologies, procedures, and human endurance issues to lead the way for missions to the Moon and to Mars.

Space stations have existed since the 1970s when the former Soviet Union and US each launched their own orbiting laboratories –Salyut and Skylab. However, the first truly internationally collaborative space station emerged in 1998 through an agreement between these two leading spacefaring countries and several other international partners such as the European Space Agency and Japan.

The resulting International Space Station (ISS) became the largest international civil space programme to date. The assembly of the ISS was a monumental task spanning a decade and requiring over 30 missions, bringing together five space agencies and 15 countries. It is the most expensive human artefact ever created, with a cumulative cost that has been estimated at $150 billion[95]. The European Space Agency share of this figure amounts to approximately €1 per citizen for every year of the ISS's existence[96].

The space station is now approximately the size of a football pitch, weighing 460-tons, orbiting 400km above Earth once every 90 minutes. It provides a platform for sustained human presence in space and is a unique setting for microgravity experimentation. For most of its existence, scientific research onboard the ISS has been reserved for government initiatives, but in recent years opportunities for commercial and academic uses have been made available. The BioAsteroid experiment at the International Space Station, an experiment to study how microbes can process and digest asteroidal material, was the first UK science experiment to be launched to the space station through a commercial route, and the first customer of the Bioreactor Express programme[97] (managed by Kayser Space Ltd), illustrating how scientists can now access these growing commercial routes for carrying out science beyond Earth. The ISS is due to be decommissioned by 2030 due to the limited lifespan of its structure. However the US is currently supporting the development of three new commercial space stations due to launch by the end of the decade.

China has recently completed the assembly of its own space station, Tiangong ('Heavenly Palace'), operational since 2022. Unlike the collaborative ISS project, which China was not involved with, Tiangong is built and run entirely by China after building up the know-how over the last decade. Despite this, Tiangong has become the first space station open to all UN Member States.

Commercial space stations are likely to be very costly and the accumulation of asset value of the station plus the visiting spacecraft may easily exceed the amount of space insurance that is available in the market. This happened with third party liability insurance in the US many years ago when the US was looking for $2 billion of cover and had to step in when only $500m of cover was available in the insurance market. The availability of insurance could be a real-life impediment to these (and many other) projects and may require government backed schemes if the levels of cover needed exceed the amount of insurance available.

A renewed focus on the need for in-orbit third party liability insurance may also follow as larger commercial structures are built in orbit, some of which may involve multiple countries. Absence of a functioning commercial insurance market could hinder such commercial development.

Research in microgravity

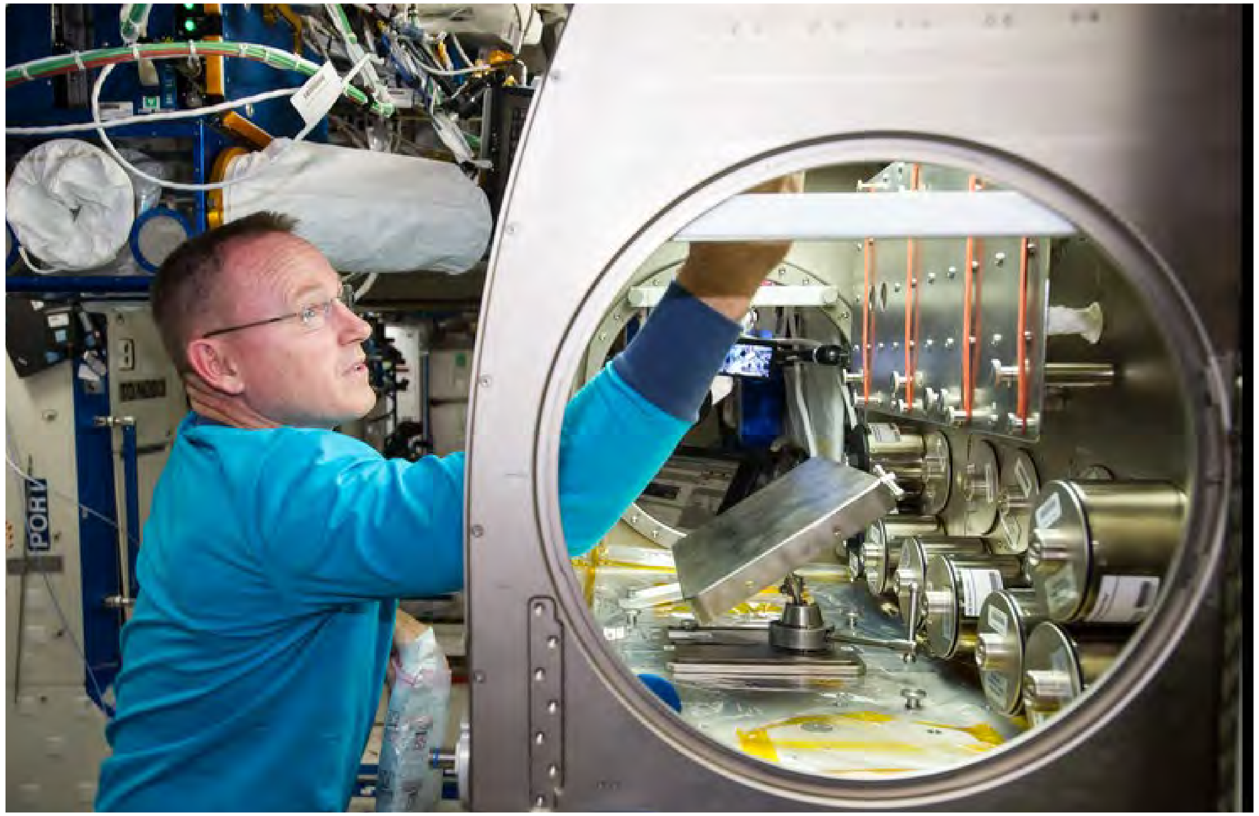
Whilst parabolic aircraft flight can support very short duration microgravity experiments (for up to 20 seconds or so) it is only in space that microgravity research of real significance can be undertaken for extended periods. Whilst the gravity experienced in low Earth orbit is approximately 90% of that which is experienced on Earth, objects in orbit are in constant freefall giving the sensation of weightlessness. Gravity is reduced on planetary bodies of lower mass than Earth eg the Moon and Mars. Further out into space true weightlessness can be achieved as the influence of Earth or other planetary bodies diminishes. Different microgravity environments can offer unique opportunities for science.

Most microgravity experimentation in the last few decades has been conducted onboard the ISS. The ISS has so far been the perfect location for experimenting with microgravity, equipped with scientific laboratories for this purpose, and maintaining a continuous flow of astronauts and payloads. The decommissioning of the ISS by the end of the decade represents a huge loss of research potential. However, the three new commercial space stations being supported by NASA represent an effort to fill this void before the ISS is deorbited.

Right
NASA astronaut Barry Wilmore setting up the Rodent Reseach-1 Hardware in the Microgravity Science Glovebox aboard the International Space Station. © NASA

The space environment supports unique basic research fields and applied research with direct benefits on Earth in areas such as biology and medicine. For example, some microorganisms replicate faster in space, speeding up the process of research and testing which could allow development of therapies such as vaccines to be accelerated.

Microgravity also offers new opportunities for materials science as it changes processes such as crystal growth, fluid mixing, heat transfer, solidification and combustion. A number of physical and chemical processes also change in the absence of gravity, providing the chance to examine boiling, melting and fluid and gas mixing in ways that are impossible on Earth. In space, hot air does not rise and flames become spherical. These differences enable scientists to investigate processes that are strongly influenced by gravity on Earth and thus to determine what the influence of gravity is on the fundamental scientific processes.



Manufacturing

The microgravity conditions found in orbit provide an environment to produce very high-performance products such as semiconductors, fibre optic cables, structural materials, and pharmaceuticals, avoiding the risk of impurities. There are certain physical and chemical processes which do not happen in microgravity, such as convection, sedimentation and buoyancy which cause disruption in Earth-based manufacturing. Instead, diffusion is more important and allows for more uniform mixing to occur. Surface tension also dominates, enabling more precise products to be formed as similar compounds adhere to each other more readily[98].

Companies such as Redwire Corporation (formerly Made in Space) have developed technologies such as additive manufacturing of small components in microgravity. Others such as Cardiff-based company SpaceForge are targeting in-space manufacturing of high value, niche application semi-conductors with delivery back to Earth, increasing in frequency from monthly in 2025 to daily in 2030.

In space manufacture would allow more flexibility to adapt to changing mission needs without having to rely on new launch of finished products (the challenging ad hoc fixes used for the damaged Apollo 13 mission may have been easier with in-flight manufacture capability). There are significant challenges in developing and validating this technology, but it has interesting potential.

Space may also provide optimal conditions for the delicate process of 3D bioprinting human organs. Potential benefits include enabling medical emergencies to be resolved more easily in space environments and studying the impact of space on different organs when exposed to radiation and microgravity. On Earth, when material leaves a 3D printing dispenser it is pulled down into position through gravity. While this is useful when printing with materials like concrete, where the material sinking downwards is an advantage, some items, such as artificial human organs, are much more challenging to 3D print on Earth as they require each individual molecule or cell to be positioned precisely to avoid the structure collapsing[99]. Synthetic blood vessels currently collapse on themselves when 3D printed on Earth, but in space it is possible to construct the scaffolding of the organ without each cell falling out of place.

Microgravity conditions enable the potential creation of materials which cannot be made on Earth. For example, the process of crystallisation can be different in the absence of gravity. Making use of this, ZBLAN, a type of optical fibre used for high-speed telecommunications networks has been made on the ISS on a trial basis and this has avoided imperfections caused by crystals that form when manufactured on Earth due to the slower process of crystal formation in microgravity conditions.

Views from the public on industry in space

In the Royal Society's public dialogue on space, participants recognised the potential of future space industries – but stressed that these must be shaped by clear rules, public benefit, and protection for workers.

Participants expressed a mixture of excitement and caution when discussing future industries such as asteroid mining, solar power generation, and space manufacturing. The commercial promise was evident – but so were the risks of inequality, exploitation, and environmental harm.

"Space mining for me is a real concern I think… initially you can control it. But what happens when it becomes much more prominent… [It] gives [corporations] access to colossal resources of very precious metals. I think it will artificially create wealth in places where it maybe shouldn't be, and it almost seems like a cheat to start getting resources from elsewhere."
Workshop 1, Glasgow

Others raised concerns about the role of powerful private actors in shaping the future space economy. With the rich being able to exploit space and its resources first, and controlling the infrastructure, concerns were expressed over widening inequality, as well as the power and influence this could grant such actors back on Earth.

"You basically get three billionaires that are leading the charge in terms of the commercialisation of Space … How do you govern against something so vast? … What is there going to be, like, a customs station in Space or whatever, to check what they're bringing back? How do you stop it and how do you stop the rich just getting richer?"
Workshop 1, Glasgow

Participants stressed the need for activity motivated by values and purpose value – not just by technical capability and the drive for profit.

"The question should always be asked, 'Should we be doing this?' Not, 'Can we do it?'"
Workshop 1, Glasgow

The wellbeing and rights of future space workers were also central to discussions. Participants were clear that protections must extend to all space workers.

"Not all the jobs are going to be [equal], some of them are going to be more menial, but it doesn't mean to say that my minimum quality of life should be any less."
Workshop 2, Cornwall

Read more about the Royal Society's Public Dialogue on Space conducted by independent research organisation Ipsos on page 180.

Large-scale infrastructure construction in orbit

Reduced launch costs and the advent of large fully reusable commercial rockets (eg, Starship) will likely increase the frequency of launching modules for space stations and the construction of large space-based telescopes. This, coupled with the prospect of 3D printing large structures in-situ, will mean more diverse uses of space stations with an increase in those owned and maintained by commercial enterprises. Space stations could become more than simply dedicated scientific research facilities, with the emergence of manufacturing in microgravity, solar power generation and other space based commercial endeavours.

In-space assembly

At present, the necessity to fit a complete satellite within the payload fairing (protective capsule) at the end of a launch rocket places significant limitations on what can be put into orbit. Although some satellites are designed to unfold once in orbit, their size is still limited to tens of meters. Assembly in space liberates spacecraft from the constraints of volume and vibration associated with launch and enables much larger, more complex and fragile structures to be built.

Advances in robotics and autonomous systems[100], exemplified by terrestrial manufacturing in the automotive and other industries, has increased the potential for of robotic assembly of large structures in orbit. Initially this may comprise assembly of telescope instruments with apertures larger than can be accommodated in a single rocket and then the assembly of space station components and eventually large structures supporting, for example, solar power farms in space.

In the long term, it is possible that the entire process of space station assembly could be moved off Earth, using space resources launched as raw or partially processed materials, and those recycled from defunct satellites or mined from the Moon before processing and construction in orbital factories.

NASA's On-Orbit Servicing, Assembly, and Manufacturing 2 (OSAM-2) project successfully tested building of large structures in a space-like environment, though the project was cancelled before it could be tested in space itself.

Freeing designers of satellites and other space structures from the volume limits and the vibration constraints imposed by launch vehicles would be revolutionary in expanding what is possible in space. As such similar project ideas are likely to be pursued over the next 50 years.

The first examples of large structures built in orbit are likely to be commercial space stations. Companies such as Blue Origin, Starlab, Voyager Space and Axiom Space have ambitious plans to develop in-space habitats for space science and elite space tourism. China has proposed an ambitious plan for a mile-long spaceship assembled in orbit while India plans to construct a space station in 2035. Such structures may serve as test platforms for in-space manufacturing and servicing. The first of these is expected to be in operation by 2030. This could see commercial alternatives to the International Space Station, driving down the cost of microgravity science and enabling different groups to develop commercial services for science and materials development in space.

Inflatable components could make construction of large facilities more straightforward. An air bladder surrounded by high strength but light materials such as Kevlar, can be transported in its collapsed state and then inflated at the target location, significantly improving payload efficiency. The Large Integrated Flexible Environment (LIFE) designed by Sierra Space is currently undergoing testing and there are plans to use multiple units in construction of Blue Origin's Orbital Reef space station, scheduled to be operational by 2027.

Sustained human exploration of the Moon and later Mars will require the robotic construction of substantial habitats. Initially these will be modules manufactured on Earth, however these may later be manufactured and assembled in orbit where the energy needed to transfer them to trajectories to the Moon or Mars is far less.

In the distant future it may be possible to assemble much larger spacecraft for travel further into the Solar System and beyond. Manufacturing these craft in orbit using large-scale 3D printing technologies could eventually offer efficiencies for some applications over launching large completed components from Earth.

Space tourism

In recent years, commercial companies have started to offer space tourism experiences with short voyages into sub-orbital space. Virgin Galactic and Blue Origin conducted maiden flights with paying customers in 2021, while SpaceX's made the first private charter flight to the ISS in early 2022. SpaceX has since completed the Polaris Dawn mission in September 2024, funded by billionaire Jared Isaacman. The mission involved the first privately funded spacewalk, conducted at 700km above the Earth's surface. Space tourism is currently affordable only for the ultra-wealthy, and while costs are likely to fall as the industry matures, it is highly likely that it will remain a niche for the ultra-wealthy.

It is likely by 2075 that there will be niche demand for more adventurous space tourism experiences beyond short-duration flights. One company, Orbital Assembly, is aiming to have a 'space hotel' in operation by 2027 – but several similar projects have already fallen flat.

While space tourism has the potential to generate revenue, develop and refine launch systems, create jobs and provide an opportunity to advance research on human spaceflight, such excursions are likely to remain niche high risk 'adventurism' for the foreseeable future. Adverse public perceptions about the exclusivity of space tourism, its potential risks to the environment and human health may yet stifle this emerging market.

Right
Sierra Nevada's Large Inflatable Fabric Environment (LIFE) habitat inside the Space Station Processing Facility high bay. The habitat is an expandable habitat. Expandable habitats have the benefit of greatly decreasing the amount of volume it takes to launch the habitat, which can then inflate once it is in space. © NASA/Kim Shiflett

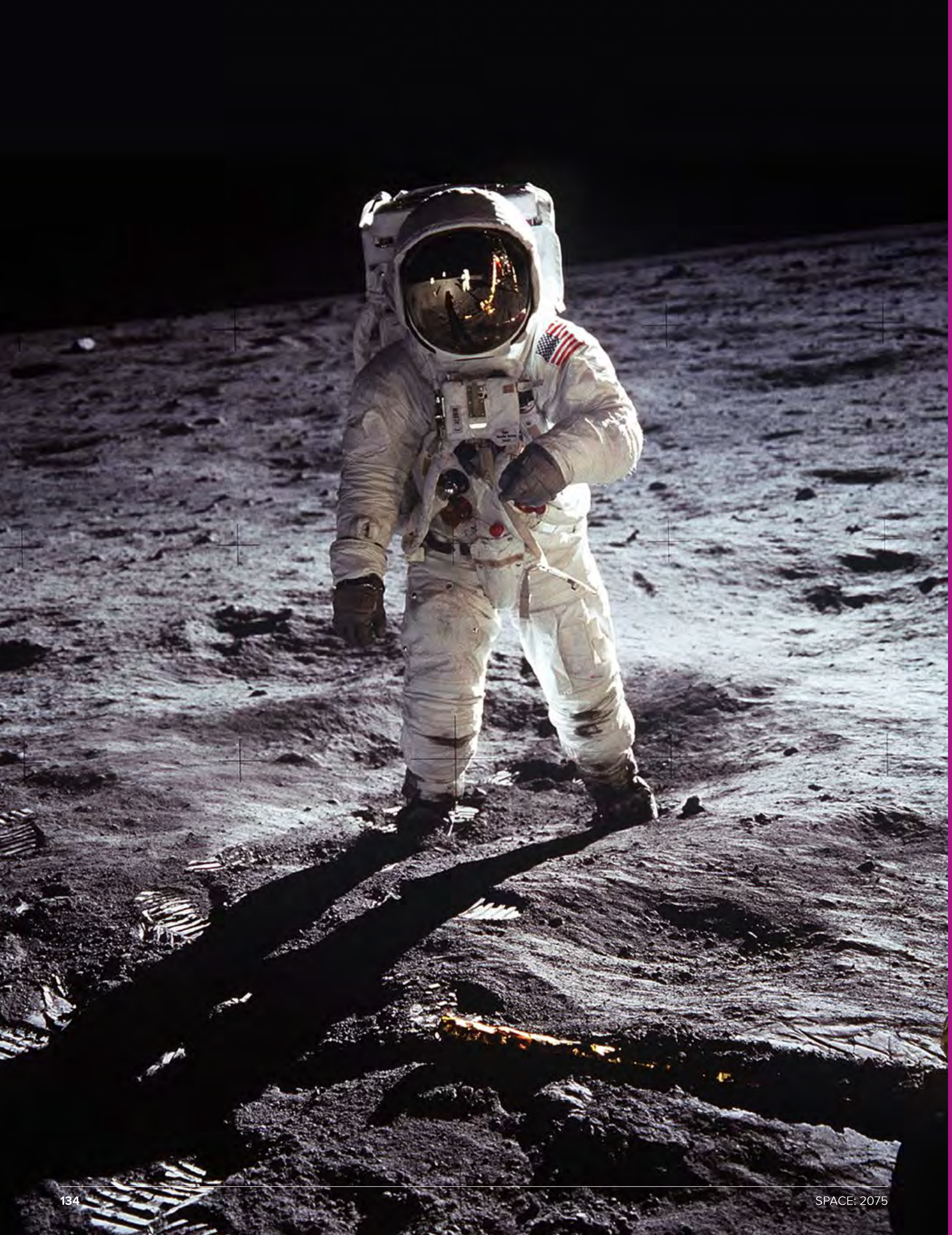
GOVERNANCE CHALLENGE

The safety of space tourism

Increasing numbers of private citizens travelling to space, with diverse physiologies and medical needs presents clear risks. There is a need to improve research on a wider range of physiologies, improve treatments and emergency procedures, and ensure standards and regulations are in placed to protect human health. Commercial space tourism companies will need to bear responsibility for the health and safety of their customers. New legal frameworks will also need to be developed to make this a commercially viable and insurable market, given the risks. Space medicine to date has also focused mostly on studying and treating highly trained and physically fit professional astronauts. Future space tourists will have a diverse set of physiologies and medical needs which require further study.

Conclusions

- Advances in satellite and launcher designs ('NewSpace') and reduced launch costs have accelerated the numbers of satellites being launched dramatically. This is creating new businesses and opportunities for wider participation in space activities worldwide.
- This has necessitated greater attention to limiting additional space debris and in removing defunct satellites and rocket stages posing a risk of fragmentation, coupled with improved space domain awareness monitoring.
- The fusion of advances in satellite communications, remote sensing, and timing (PNT) capabilities may create a case for a unified Earth-space infrastructure for both civil and military use. Quantum techniques applied to space will have a major impact.
- The combination of new materials, automated processes and robotic assembly could enable large structures to be manufactured and assembled in orbit removing significant constraints on design and manufacture.
- In the timescale considered in this report, these advances will result in space manufacturing of unique products for terrestrial applications, such as generation of space-based power, and the robotic construction of stations in orbit and on the Moon.
- Many commercial developments will require the availability of finance and insurance. Such markets are currently small and will need to develop if they are to support some of the projects contemplated within this report. Good governance and the sustainability of the space environment will continue to be paramount to give space insurers the confidence to continue to underwrite space risks and to therefore make sure finance remains available.



CHAPTER 4:

Exploring the Moon, Mars and beyond

With a series of Moon missions planned for the next decade, activity there is set to grow, including scientific research, while explorers also set their sights on the next frontier, Mars. Establishing permanent bases on these planetary bodies is a priority for a number of space agencies and commercial entities. Both the Moon and Mars are extremely harsh environments and so protecting health and wellbeing in these locations creates very significant challenges but will offer immense scientific and technical opportunities.

Left
Astronaut Buzz Aldrin on the moon.
© Neil A. Armstrong.

Timeline of human spaceflight and activity on the Moon and Mars

Here a small selection of activity concerning human spaceflight and missions to the Moon (crewed and uncrewed) and Mars (uncrewed).

1959
Project Mercury begins in the USA, the first human spaceflight programme.

1959
The Soviet Union's Luna 1 becomes the first spacecraft to reach the vicinity of the Moon and the first human-made object to enter a heliocentric orbit (orbit around the Sun).

12 April 1961
Yuri Gagarin, the Soviet cosmonaut, becomes the first man to enter space. Aboard Vostok 1, he completes one full orbit of the Earth before safely landing on Earth.

July 1969
Apollo 11 lands the first men on the moon.

1971
NASA's Mariner 9 becomes the first orbiter around another planet, Mars. Mariner 9 mapped over 70% of the Martian surface and studied the planet's atmosphere and moons Deimos and Phobos. Soviet orbiters Mars 2 and Mars 3 closely followed in the same year.

1972
Apollo 17 leaves the Moon, representing the last time humans set foot there.

1975
Viking 1 and Viking 2 (NASA) launched: were part of the Viking program, which included landers that successfully touched down on Mars for the first time. They provided detailed images of the Martian surface and conducted atmospheric studies.

2003
Launched in 2003, the European Space Agency's Mars Express orbiter has been studying the Martian atmosphere, surface, and subsurface, as well as searching for signs of water. Carried the UK-led Beagle 2 probe on it, Beagle is lost after deployment.

2005
Mars Reconnaissance Orbiter (MRO) (NASA): Launched in 2005, MRO has been providing high-resolution images of the Martian surface, studying the planet's climate and weather, and searching for evidence of past water activity.

2014
Mars Orbiter Mission (Mangalyaan-1) (ISRO): Launched by the Indian Space Research Organisation in 2013, this mission aimed to demonstrate technological capabilities and study the Martian atmosphere and topography.

2015
Beagle found in images taken by the MRO, confirms first soft landing from European craft.

2016
ExoMars is an astrobiology program led by the European Space Agency (ESA) in collaboration with Russia's Roscosmos. The primary goal of ExoMars is to search for signs of past life on Mars and to understand the planet's water and geochemical environment.

2019
First soft landing on the far side of the Moon was made by China's robotic spacecraft Chang'e 4.

2021
China's Tianwen 1 and the Emirates Mars Mission (Hope) arrive in orbit of Mars.

2021
The SpaceX Inspiration4 mission becomes the first all-civilian mission to orbit Earth, collecting data about the effects of space on non-professional astronauts.

November 2022
Artemis 1 launched, demonstrating the new Space Launch System (SLS) rocket and Orion spacecraft without a crew as a precursor to crewed missions.

2023
Chandrayaan-3 (India) achieved a soft landing near the lunar south pole, marking a significant milestone for India's space program.

February 2024
Intuitive Machines' Odysseus lander, successfully landed near the Moon's south pole, marking the first time a private company achieved a lunar landing. It carried both commercial and NASA payloads as part of the Commercial Lunar Payload Services initiative.

June 2024
Chang'e 6 successfully brought back the first samples from the far side of the Moon.

September 2024
SpaceX Polaris Dawn mission conducts the first ever commercial spacewalk.

Current position

Humans have not set foot outside low Earth orbit (LEO, extending between approximately 160 – 1,600km in altitude above the Earth's surface, see Chapter 3) for more than 50 years. The Apollo missions, which saw the first human footsteps on the Moon, concluded in 1972. The race to touch down on the Moon was partly driven by geopolitical competition during the Cold War as the USA and former Soviet Union vied to achieve the feat first. As tensions subsided in subsequent decades, efforts were refocused on crewed missions to Earth orbit; Moon voyages were deemed prohibitively expensive. However, in recent years, with improvements in propulsion and material technologies, as well as the emergence of new commercial players in the space sector, mission costs have become more affordable.

The ambitions of emerging space nations and modern geopolitical super-power tensions have reignited the competitive streaks in spacefaring nations, leading them to be more expansive in their strategies, much encouraged by commercial industry.

As the nearest celestial bodies to Earth the Moon and Mars are two of the best options for creating human facilities beyond Earth. In the case of Mars, there are substantial reserves of water ice which could be used as a resource.

The Moon is just a bit longer than a day-trip away, whereas Mars is up to a 1,000-day round trip, depending on the relative positions of the two planets at the time. So it makes sense to develop and test the technologies and procedures for extended human endurance in space on the Moon and other local missions before embarking on a journey to Mars.

At an average distance of 384,400 km from Earth, the Moon is the furthest humans have ever travelled into space. Mars is considerably further away at 54.6 million km even when closest in its orbit to Earth. Much has been learned from telescopes and scientific instruments on board rovers, orbiters and other uncrewed landers which has helped to prepare for planned crewed missions in the coming years.

FIGURE 18

The Moon and Mars: key features for exploration

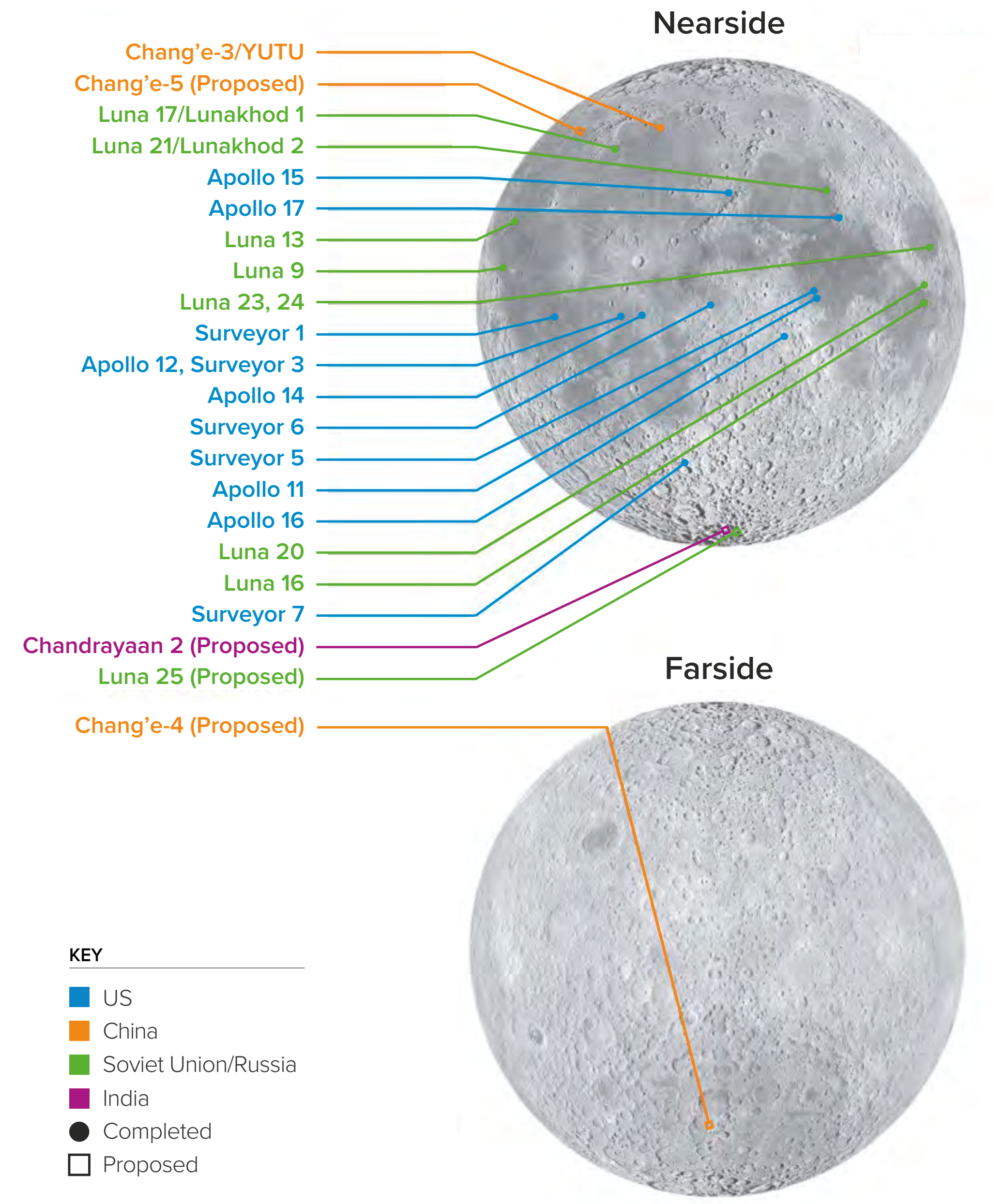


FIGURE 18 (CONTINUED)

Viking 2
NASA lander
Launched: 9 Sep 1975
Landed: 3 Sep 1976
Last contact: 11 Apr 1980
Utopia Planitia
47.643°N, 134.288°E, −4495m

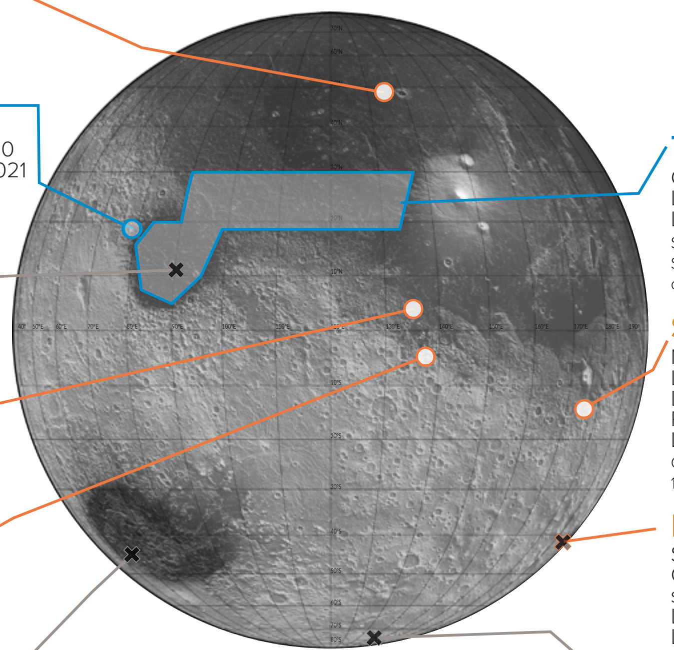
Perseverance
NASA rover
Launch: expected 17 Jul 2020
Landing: expected 18 Feb 2021
Jezero Crater
18.4386°N, 77.5031° E, −2640m

Beagle 2
ESA lander
No contact since separation
Launched: 2 Jun 2003
Last contact: 25 Dec 2003
Isidis Planitia
11.5288°N, 90.4314° E, −3725m

InSight
NASA lander
Launched: 5 May 2018
Landed: 26 Nov 2018
Elysium Planitia
4.502°N, 135.623°E, −2613m

Curiosity
NASA rover
Launched: 26 Nov 2011
Landed: 6 Aug 2012
Roved >22km
Gale Crater
4.5895°S, 137.4417°E, −4501m

Mars 2
Soviet lander and rover
Entered atmosphere too steeply
Launched: 19 May 1971
Crashed: 27 Nov 1971
Hellas Chaos
Near 45°S, 58°E, −5000m



Tianwen-1
Chinese rover
Launch: expected July 2020
Landing: expected early 2021
Site 1: Chryse Planitia 20–30°N, 310-330°E
Site 2: Elysium Planitia 19–30°N, 90–134°E
or within Isidis Planitia 4-20°N, 80-98°E

Spirit
NASA rover
Launched: 10 Jun 2003
Landed: 3 Jan 2004
Roved 7.73 km
Last contact: 22 Mar 2010
Gusev Crater
14.5692°S, 175.4729°E, −1936m

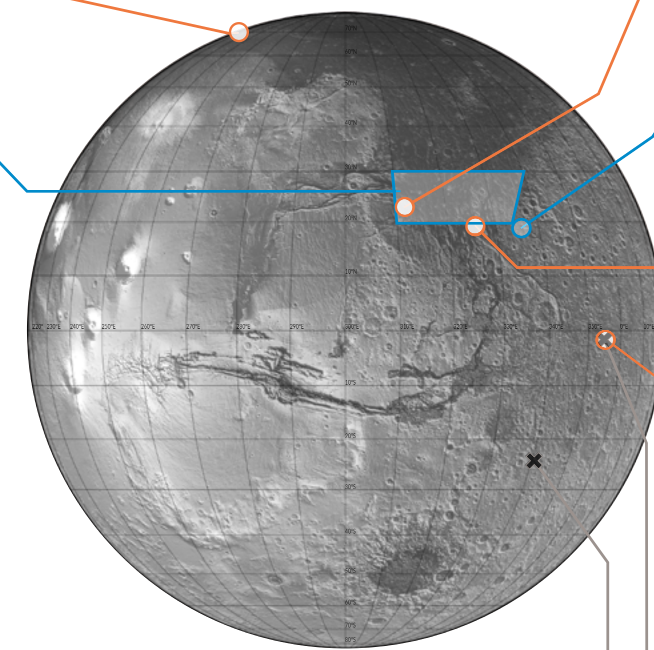
Mars 3
Soviet lander and rover
Contact lost after
successful landing
Launched: 28 May 1971
Last contact: 2 Dec 1971
Terra Sirenum
45.044°S, 202.019°E, +1626m

Mars Polar Lander
NASA lander
No contact since entry
Launched: 3 Jan 1999
Last contact: 3 Dec 1999
Planum Australe
Near 76.57°S, 165.2°E, +3000m

Topography
Relative to Martian Datum
1 degree of latitude on Mars = 59.3 km

Phoenix
NASA lander
Launch 4 Aug 2007
Landing 25 May 2008
Last contact: 2 Nov 2008
Vastitas Borealis
68.2188°N, 234.2508°E, −4130m

Tianwen-1
Chinese rover
Launch: expected July 2020
Landing: expected early 2021
Site 1: Chryse Planitia 20–30°N, 310-330°E
Site 2: Elysium Planitia 19–30°N, 90–134°E
or within Isidis Planitia 4-20°N, 80-98°E



Viking 1
NASA lander
Launch 20 Aug 1975
Landing 20 Jul 1976
Last contact: 13 Nov 1982
Chryse Planitia
22.269°N, 312.048°E, −3637m

Rosalind Franklin & Kazachok
ESA rover & Russian lander
Launch expected
Aug –Oct 2022
Landing expected
Apr or Jul 2023
Oxia Planum
Near 18.14°N, 335.7°E, −3000m

Pathfinder & Sojourner
NASA lander & rover
Launch 4 Dec 1996
Landing 4 Jul 1997
Last contact: 27 Sep 1997
Ares Vallis
19.33°N, 326.47°E, −3681m

Opportunity
NASA rover
Launched: 8 Jul 2003
Landed: 24 Jan 2004
Roved 45.16km
Last contact: 10 Jun 2018
Meridiani Planum
1.9462°S, 354.4734°E, −1387m

Schiaparelli
ESA lander
Contact lost during descent
Launched: 14 Mar 2016
Crashed: 19 Oct 2016
Meridiani Planum
2.0524°S, 353.7924°E, −1444m

Mars 6
Soviet lander
Contact lost upon landing
Launched: 5 Aug 1973
Last contact: 12 Mar 1974
Margaritifer Sinus
Near 24°S, 340.5°E, −500m

References

Landing location data compiled by E. Lakdawalla for The Planetary Society in May 2020. For failed landers whose crash sites have not been identified, actual sites could be as far as 150 km (2.5 degrees) radially from given location.

Base map by P. McGovern from MOLA GTDR [P. Smith et al. (2001) DOI: 10.1029/2000JE001364].

Beagle 2: Location: J.C. Bridges et al. (2017) DOI:10.1098/rsos.170785. Elevation: Peter Grindrod, personal communication.
Curiosity: E. Lakdawalla (2018) ISBN:978-3-319-68144-3
InSight: M. Golombek et al. (2020) DOI:10.1038/s41467-020-14679-1
Mars 2 & Mars 6: P. Stooke (2012) ISBN:978-0-521-76553-4. Landers have never been found.
Mars 3: Tom Stein and Feng Zhou, personal communication (hereinafter abbreviated SZpc).
Mars Pathfinder: Location: P. Stooke (2012). Elevation: SZpc.
Mars Polar Lander: P. Stooke (2012). Lander has never been found.
Opportunity: Location: Arvidson et al (2004) DOI: 10.1126/science.1104211. Elevation: SZpc.
Perseverance: J. A. Grant et al. (2018) DOI:10.1016/j.pss.2018.07.001
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Rosalind Franklin: M. A. Ivanov et al. (2020) DOI:10.1134/S0038094620010050
Schaparelli: A. Aboudan et al. (2018) DOI:10.1007/s11214-018-0532-3
Spirit: Location: R. E. Arvidson et al (2004) DOI:10.1126/science.1099922. Elevation: SZpc
Tianwen-1: Possible landing regions read from map posted at planetary.org/blogs/guest-blogs/china-2020-rover-sites.html in November 2018, credited to a Chinese National Space Agency presentation to the United Nations Committee on the Peaceful Uses of Outer Space in June 2018.
Viking 1 & Viking 2: National Space Science Data Center, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/displayTrajectory.action?id=1975-075C and id=1975-083C, accessed 11 May 2020.

Suggested citation: E. Lakdawalla (2020) "Every Mars Landing Attempt, Ever: Successes, Failures, and Future (version 1.3)." Poster published by The Planetary Society, Pasadena, CA, USA.

Apollo makes way for Artemis

The Artemis Program is a US-led exploration programme including the Artemis Accords, to which the UK is a signatory and key contributor, which has set out the goal of achieving a human presence on the Moon before 2030 and eventually extending exploration to Mars in the next decade. Though there is currently interest in the US government in accelerating the timeline for crewed missions to Mars. Regardless of how this timeline plays out, the growing interest in a human lunar presence from other state actors (eg India, China) together with the commercial capabilities to reach the Moon, makes human presence on the Moon highly likely in the coming decades.

Commercial contracts for rocket boosters have been issued for 13 Artemis missions. However detailed plans have only been set out for the first six so far. These primarily involve testing equipment, re-establishing a human presence on the Moon and constructing the Lunar Gateway space station from various component modules to facilitate longer Lunar missions. A range of subsidiary missions will accompany these main missions and provide necessary equipment and scientific instruments for Lunar exploration. Recent NASA proposals may result in some of these missions being curtailed or cancelled entirely in favour of developing a programme of crewed Mars missions.

Artemis also demonstrates a change in approach to human exploration, with new commercial players making vital contributions to the project. SpaceX, Blue Origin, Axiom Space and others are providing various components including components of launch systems, landers and space suits and it is anticipated that this trend of collaboration between public and private partnerships will continue with the expanded market reducing overall mission costs.

So far, Artemis 1 (2022) was completed as planned. This was a flight test of the Space Launch System (SLS) and (empty) crew capsule, Orion, which was placed into lunar orbit before safely splashing down on Earth. Artemis 2 will follow, completing the same mission, this time with astronauts on board. Artemis 3 plans to land astronauts on the Moon for the first time since 1972, including the first woman and the first person of colour. An agreement between the space agencies of the US (NASA) and Japan (JAXA) will land a Japanese astronaut on the Moon by 2030, followed by a pressurized lunar rover called Lunar Cruiser.

NASA's commitment to public-private partnerships has also been strengthened with its Commercial Lunar Payload Services. This a well-funded fast-growing activity, commercial though bidding mostly for government contracts. This has led to a number of initiatives to send privately funded landers with a variety of payloads to the Moon. Despite a previous attempt by Intuitive Machines, Blue Ghost from Firefly Aerospace, became the first lander from a commercial company to successfully touch down on the Moon on 2 March 2025, within 100m of its target site. It carried 10 scientific experiments for NASA and other commercial companies which will examine, amongst other things, the properties of lunar regolith and the effects of solar winds.

A new competition for the Moon

China too has established an ambitious lunar exploration programme and plans to land humans on the Moon by 2030.

This has been preceded by a series of robotic exploratory missions, in the Chinese Lunar Exploration Program, also known as Chang'e, named after the Chinese Moon Goddess.

The Chang'e missions, alongside relay and scientific satellites orbiting the Moon, represent preparations for a planned International Lunar Research Station, a major project concept that China has proposed to other nations such as: Azerbaijan, Belarus, Egypt, Ethiopia, Kenya, Pakistan, Russia, South Africa, Thailand, Turkey and Venezuela.

Both India and the UAE have active Moon and Mars robotic missions and ambitions to grow these in the coming decades to include human exploration.

CHANG'E MISSIONS

Chang'e 1 (2007)
Scanned the entire moon in unprecedented detail to create a high definition 3D map of the lunar surface.

Chang'e 2 (2010 – 2012)
Conducted further lunar mapping in even greater detail.

Chang'e 3 (2013)
Successfully landed on the Mare Imbrium (the deepest lunar crater) in 2013 and deployed a rover that explored the surface.

Chang'e 4 (2018 – 2019)
Successfully landed on the far side of the Moon in 2019.

Chang'e 5 (2020)
Sample return mission carrying 1.7kg of lunar samples back to Earth.

Chang'e 6 (2024)
Assessed the topography, composition and subsurface structure of a basin on the far side of the moon. Conducted a sample return mission collecting material from the lunar far side for the first time.

Chang'e 7 (proposed)
Aim to explore the Moon's south pole with a "mini hopping probe" and a water-molecule analyser.

Chang'e 8 (proposed)
Will land on lunar south pole and deploy a lander, a rover, and a robot exploring in-situ resource utilisation and 3D printing.

GOVERNANCE CHALLENGE

Managing an expansion of actors and activity

Safe and sustainable human activity on the Moon and Mars

Significant damage or disruption to the lunar or Martian environment could come about as new types of activity expand. There is a need to minimise damage to the environment whilst ensuring the safety of operations for all present. Unsustainable activity could threaten pristine sites of scientific interest and heritage areas such as the Apollo Moon landing sites and landing sites of probes on Mars. It could also cause physical harm to humans who are present in bases and damage to surrounding infrastructure. To that end, guidelines, practices and standards are required to be adopted at international level and implemented at national and commercial level. A desire to conserve the Moon has been recognised by the World Monuments Fund (WMF)[101].

> **"[…] We have carried our artifacts and created sites on the Moon in what is only the blink of an eye in the archaeological record. All cultures through early time have narratives, traditional practices and relationships to the night sky and the Moon, in particular. The WMF seeks, as our Scientific Committee does, to view the Moon as belonging to humanity and to advocate for the preservation of significant places within an international framework, inspired by previous preservation efforts done through the Antarctic Treaty and 1954 Hague Convention as well as other global treaties and agreements. […]"**
>
> Professor Beth O'Leary, ICOMOS International Scientific Committee on Aerospace Heritage

Promoting international cooperation and collaboration whilst avoiding unhealthy competition and conflict

Collaboration on major missions to the Moon and Mars is practical and cost efficient. The financial burden is shared between many nations and each partner can dedicate its time and resources into specialising in a specific area. This level of cooperation is also beneficial for science, enabling projects at a scale unachievable by any single nation alone, permitting scientists and scientific institutions from smaller nations to participate in otherwise unaffordable ventures, whilst inherently promoting scientific data sharing. It also helps build trust and confidence between potentially competing nations, contributing to the ongoing success of a project.

Regulating use of land in space

The Outer Space Treaty (OST) was established in 1967 during the Cold War with the express intention of preventing existing tensions on Earth from spilling out into the space domain. However, in terms of use of land in space, its provisions require more clarity in their interpretation. Specifically, ambiguity in Article II of the OST.

> **"Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means."**
>
> Article II of the Outer Space Treaty, 1967

Interpretations of this article vary based on definitions of appropriation and lack of any clear proscription of using and owning resources on celestial bodies. The Artemis Accords developed by NASA, take a more permissive view of what is allowed. They entitle private citizens to extract and own resources in space. They also establish the principle of safety zones, regions of exclusion around bases operated by particular nations or entities. The Accords do not specify the range of the safety zone which could create complications if a safety zone extends a long way and interferes with the objectives of another party. Likewise, safety zones must be temporary, but there is no detail to limit the length of a mission and so temporary is defined as when a mission is completed. If open ended, this could mean a particular group is entitled to stay on land and exclude others indefinitely. This raises questions about whether this effectively amounts to territory ownership in all but name. More than 20 countries have signed the Accords including the UK and they are likely to be important in establishing customs of behaviour on the Moon. Further dialogue at international level is needed to provide clarity on the more ambiguous provisions in the OST and Artemis Accords if they are to become the norm.

Learning from other examples of regulating commons

Other locations on Earth which do not belong to nation states, represent good examples to learn from how commons areas like space could be regulated. For example the Antarctic Treaty System (ATS) and The Protocol on Environmental Protection to the Antarctic Treaty which entered into force in 1998, designates Antarctica as a "natural reserve, devoted to peace and science" (Art. 2).

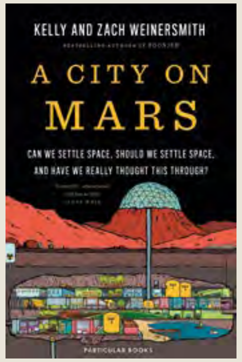
Article 7 prohibits activities related to exploitation of Antarctic mineral resources, except for scientific research. The ATS also prohibits new claims of territory in Antarctica.

Another commons environment which could provide useful lessons is for undersea mining regulations set out by the United Nations Convention on the Law of the Sea (UNCLOS) and the International Seabed Authority (ISA). Deep-sea mining regulations require permission to be sought from the ISA in order for extraction in a given region to take place.

Both frameworks promote sustainable resource management, ensuring activities do not deplete or damage ecosystems. Similar principles could be applied to prevent harmful impacts on space environments, such as the Moon or asteroids.

Serious consequences can also arise by leaving commons regions unregulated. On Earth, the example of illegal, unreported and unregulated (IUU) fishing has led to collapse of certain fish populations; habitat destruction and marine pollution from damaging bottom trawling methods; and biodiversity loss from bycatch of undesirable species, some of which can be endangered.

For those keen to learn more about space governance, *A City on Mars* by Kelly and Zach Weinersmith, winner of the 2024 Royal Society Trivedi Science Book Prize, sets out the different interpretations of space regulation and various disputes regarding territory ownership in more detail.



Views from the public
on governing the Moon and Mars

In the Royal Society's public dialogue on space, participants called for early international collaboration to prevent conflict and ensure fair, inclusive governance of lunar and Martian settlements.

Participants considered future scenarios involving long-term settlements on the Moon and Mars. There was widespread concern about the risks of territorial control, corporate dominance, and repeating Earth's colonial past.

Many favoured a global licensing or leasing model to regulate activity without conferring permanent ownership – administered by a neutral international body.

"If you had to divide it up, I'd want it more like a lease basis. Then it's yours to use, but you don't own it… whatever this governing body looks like, the UN equivalent or whatever, they would grant you the right to use it."
Workshop 2, Leicester

Participants pointed to existing frameworks as useful precedents – particularly those built around shared access, scientific cooperation, and long-term stewardship.

"These exterior bodies should be managed under some form of international control, possibly with licensing to extraction industries… [similar to] the deep-water treaties, and the Antarctic Treaty…"
Workshop 2, Glasgow

They stressed the need for binding rules before large-scale activity begins, with strong emphasis on avoiding competitive land grabs and exclusion.

"We should be building bridges rather than walls… It feels like laying claim to area, territory, land, whatever it is, it's just building walls around it, and inviting conflict."
Workshop 2, Glasgow

Equity was a recurring theme, with calls for governance frameworks that reflect global participation – not just spacefaring powers.

"If we're saying that Space belongs to everybody… it should be the richer nations combining together to do these projects for the benefit of everybody on Earth."
Workshop 1, Leicester

Read more about the Royal Society's Public Dialogue on Space conducted by independent research organisation Ipsos on pg.180.

Looking further ahead

The Moon as a stepping stone to Mars

With a significantly lower escape velocity than Earth, the Moon is a critical stepping stone for future missions to Mars. NASA's Artemis Program, China's International Lunar Research Station and many enterprises that will emerge in the coming decades, will serve as a proving ground to develop the necessary technologies for crewed exploration beyond the Moon. Though NASA may adjust plans and work towards missions to Mars sooner, by dropping elements of the Artemis programme. The first crewed missions to Mars are expected to follow the pattern of upcoming Moon programmes by establishing the wider infrastructure to support initial missions, testing the techniques and technologies for more permanent bases, and exploring the potential for the use of Martian materials to support mission efficiency and endurance by not having to set out on the mission carrying 100% of all required materials and supplies.

Initial Human Missions to Mars

Although NASA has successfully landed several rovers on Mars, it has not yet planned specific human missions to Mars. However they have expressed a desire to begin exploration in the coming decade. The round trip to Mars would be significantly longer at up to 1,000 days, compared to the 25 days it took to complete the Artemis 1 lunar flyby.

China has prepared for the exploration of Mars with successful landing of the Tianwen-1 with the rover Zhurong, and has a Mars sample-return mission planned to launch in early 2029 that will include in-situ resource utilisation tests – for example, extracting subsurface water or generating oxygen.

All this is in preparation for a platform for initial human missions, starting with an orbital facility, then landing on the planet's surface and finally constructing a Mars base. The third and final stage envisages forming a so-called 'econosphere', facilitated by a large-scale Earth-to-Mars fleet, large-scale development and utilisation of resources.

Alongside data from various probes and rovers about the conditions on the Martian surface, experiments have been conducted to simulate astronaut survival in the tough Martian conditions. NASA's Crew Health and Performance Exploration Analog (CHAPEA) concluded in July 2024 (with further mission phases planned), after four astronauts spent 378 days inside a 3D-printed habitat (Mars Dune Alpha) located in a simulated Martian environment on Earth. The mission aimed to replicate as many of the challenges of living on Mars as possible, including environmental stressors such as resource limitations, isolation, equipment failure, significant workloads and a 22-minute communications delay. The crew conducted simulated spacewalks (making use of virtual reality), communications, crop growth, meal preparation and consumption, exercise, hygiene activities, maintenance, science experiments, and sleep. Analogue missions such as this are intended to provide NASA and other space agencies with a better understanding of how humans will need to be supported on long duration missions on Mars. However, whilst they can be informative about individual astronauts' ability to cope with long duration missions, there are many aspects that cannot be simulated effectively eg the effects of microgravity over an extended period of time.

Establishing human bases on the Moon and Mars

These initial missions represent ways that space agencies and commercial companies are preparing for expanded activity on the Moon and Mars. In the next 50 years it is anticipated that these locations will represent new targets for sustained human presence in space in the form of facilities similar to the International Space Station or the permanent Antarctic research stations.

Science on the Moon and Mars

The only professional scientist to have set foot on the Moon is Harrison Schmitt, a geologist who was part of the crew on the Apollo 17 Moon landing. The next 50 years could see many more scientists of different disciplines staffing dedicated research stations on the Moon and Mars. These scientists will arrive through programmes such as Artemis, China's International Lunar Research Station (ILRS) and other state and private initiatives.

Scientific research can take advantage of the unique properties of the Moon including its lack of atmosphere, low gravity, cold conditions, and freedom from terrestrial radiofrequency and light pollution. The Moon's South Pole is attracting significant interest because its craters are permanently shadowed, potentially retaining stores of high-value water ice, and could form ideal sites for low-temperature science or manufacturing. The far side of the Moon, facing away from Earth, is ideally suited to radioastronomy as it is shielded from the radio signals generated on Earth. These characteristics make it an interference free, 'radio-quiet', location compared to Earth[102].

However, there are already plans for navigation and communication satellites in lunar orbit, including the European Space Agency's Moonlight Programme, for which the UK and Italy are leading partners. Comprehensive orbital communications are a critical precursor to extended lunar use and are planned by many national and commercial organisations. Carefully managing future lunar activity, including satellites in lunar orbit, will be necessary if the scientific potential of these locations is to be preserved in the long-term. The Moon also experiences significantly less tectonic activity than on Earth, and tectonic activity can disrupt sensitive instruments such as detectors for gravitational waves[103]. There are proposals to situate such a detector on the Moon's poles which are in constant darkness and hence under extraordinarily low temperatures which helps to stabilise the experiments[104]. Such a detector would be complementary to LISA discussed in Chapter 1, operating in the sub-kilohertz range and hence detecting black holes before they merge[105]. There are calls to preserve these locations, often referred to as Sites of Extraordinary Scientific Importance (SESI)[106].

GOVERNANCE CHALLENGE

Managing lunar orbits

Currently there are only a handful of satellites orbiting the Moon, but with the anticipated rise in activity, more satellites will appear around the Moon, providing essential imaging and communications services to support missions.

Applications for lunar communications licences for lunar radio spectrum to the International Telecommunication Union are growing rapidly, especially from companies in the US and China. This would make the radio quiet far side of the Moon far more 'noisy'. This would threaten the prospect of the benefits of a proposed giant lunar telescope situated there and so the science that could be lost would have to be weighed against the potential benefits of lunar satellite missions. There may be a compromise position which could be negotiated between different interests.

A separate challenge for lunar orbits is disposing of them at end of life. With no atmosphere to burn up satellites at the end of missions, there are challenges associated with safe disposal. The options are as follows[107]:

1. Uncontrolled landing on the lunar surface – allowing an orbit of a satellite to decay naturally after the mission end point which would result in it crashing onto the surface. This might disrupt lunar dust which could have risks for instrumentation on the surface. It might also become unviable as and when human bases appear because crashing satellites in an uncontrolled way could pose a risk to human safety and potentially be perceived as an aggressive action between different states.
2. Controlled landing on the lunar surface – this might be deemed preferable to enable parts to be recycled. However, it would mean that satellites would have to be equipped with sufficient propellant to provide the energy for a controlled landing which shortens the lifespan of missions, which could ultimately make them more costly.
3. Return satellites to Earth orbit to be burned up in atmosphere – this solves the issue of affecting the lunar surface but adds additional burden to the Earth. This option would also require additional propellent to be carried, and, as mentioned, it is unclear if this approach is problematic.
4. Graveyard orbits – some stable cislunar orbits have been identified where defunct satellites could be deposited at end of life. It is not clear how easy these orbits are to achieve and whether there are any long-term safety risks if the satellite does not stay in this location.
5. Leave Earth-Moon system – ie sending the satellite beyond cis-lunar space. Again requires energy to adjust trajectory to leave and it would require assessment of whether the satellite could one day return and pose a risk to future activity on the Moon or Earth.

Much further ahead, similar scientific facilities will likely emerge to exploit the unique features of Mars. This could include scientific instruments which require very cold temperatures. Evidence of previous water on Mars and a more Earth-like atmosphere, make it a more interesting location in the search for traces of life. Several landing sites have been identified, such as the Jezero crater[108, 109], the site of a former large lake 3.8bn years ago for example, which are promising locations to explore this possibility. Recent interest has again refocused on the search for extant life on Mars. The recognition that micro-habitats could exist on the planet where conditions are transiently favourable[110] for life, and that conditions in the subsurface may be more clement, has brought the search for present-day life back onto the agenda. In the coming decades, new efforts will be launched to test the hypothesis that life exists on present-day Mars.

Robotic exploration by default

Space exploration has many hazards for humans, the most extreme of which have become tragically evident through a number of high-profile disasters. In the early days of space exploration, computer control and automation capabilities were in their infancy. There was much that astronauts could do that could not be done any other way. As computational power, remote control systems, robotics and automation have become more sophisticated, the uniqueness of human capabilities has reduced in scope, changing the rationale and increasing the threshold for decisions on the value of exposing humans to the hazards of space.

Given the risks involved in human space exploration there are arguments that crewed craft should be limited to missions where human presence is essential and that robotic exploration should be the default. Future improvements in remote and autonomous systems may create debate on the value of humans in space at all. If machines could accomplish all that humans could accomplish in space and more, with no risk to health and to life; less cost in terms of protections required for humans; and greater capability with respect to acceleration, deceleration and manoeuvre, might there be an end to the era of the astronaut?

There are of course individual ambitions and geopolitical motives which drive the desire to send crewed missions into space for the pride and prestige associated with such a technical accomplishment[111]. For planned crewed missions, robots are likely to provide complementary roles by conducting more detailed reconnaissance missions in new locations to establish areas safer for human exploration with useful resources to support human life, eg water and shelter from extreme environmental conditions.

Robotics will also come to play a substantial role in both the construction and operation of space stations on the Moon and Mars, although the development of fully autonomous robots remains in its infancy. Nonetheless, Japan's space agency (JAXA) is working with industry and academia to create an autonomous robotic system that could build a Moon base. Similarly, companies such as space robotics start-up GITAI have demonstrated how a lunar base can be assembled robotically.

However, these systems are still at low technology readiness levels and a long way from realistic deployment – especially with respect to resilience to harsh physical and radiation environments. Nevertheless, there are opportunities for construction companies (eg Jacobs) who have shown interest in developing the necessary robotic construction tool and machinery, especially as they may create spinoffs, such as systems helping to improve efficiency and safety of the construction industry back on Earth. Until autonomous robots can be designed to conduct the full range of tasks required in more space missions, it is likely that robots will work alongside human explorers for the foreseeable future of such missions.

Leading stakeholders in the space sector speculate on exploring and establishing a sustained human presence in places other than Earth, sometimes citing existing and future human induced damage to Earth's environment as a rationale for creating an option for human existence elsewhere, including options for terraforming currently inhospitable environments. Given that human existence has been finely optimised over millennia for Earth, the challenges of terraforming to optimise for human existence elsewhere will obviously be considerably greater than the already substantial changes needed on Earth to limit climate change and exist sustainably on the planet for which our species has evolved. From a scientific perspective, policies to address climate change and biodiversity loss are as yet demonstrably inadequate on Earth, which implies that international policies to effectively amend planetary parameters in much more challenging circumstances elsewhere may be very difficult to agree and implement.

Conversely should greater political consensus improve to the extent that policies for environmental stability and sustainability on Earth succeed, this bodes well for such efforts elsewhere. Therefore even if human settlement elsewhere were deemed useful, desirable and feasible, success at living within our environmental means at home first would appear to be a prerequisite and logical priority, indeed it is the only practical option even for the long foreseeable future. In short if this cannot be achieved on Earth then it cannot be achieved on the Moon or on Mars.

Understanding the conditions

Whilst the immediate priority is likely to be to send robotic missions to space, more human spaceflight is inevitably on the horizon and it will be critical to be prepared to ensure that any humans sent on missions to the Moon and Mars are adequately supported.

To survive on the Moon and Mars for extended durations, human life will need to be supported by closed loop systems which reduce dependency on materials that are transported from Earth. This will involve adapting the environment to make it safer for sustained human presence and better understanding the impacts of such environments on human health. There are significant differences between conditions on Earth and the environments that would be experienced on the Moon and Mars. Table 1 provides some clues as to the challenges that humanity faces in establishing bases in these unforgiving locations. The Moon and Mars make Earth look idyllic by contrast, even factoring in the increasing array of damages caused by anthropogenic climate change.

TABLE 1

	Earth	Moon	Mars
Diameter	12,756 km	3,476 km	6,787 km
Gravity compared to Earth	100% (gravity regime humans evolved in, highest escape velocity)	16.6% (potential human health impacts, relatively low escape velocity for onward journeys)	37.7% (potential human health impacts, relatively low escape velocity for onward journeys)
Temperature range	-89°C – 56°C	-246°C – 121°C	-153°C – 24°C
Atmospheric components	78% nitrogen 21% oxygen 1% argon 0.035% carbon dioxide (breathable air)	Negligible (no breathable air)	95% carbon dioxide 3% nitrogen 1.6% argon 0.13% oxygen (no breathable air)
Atmospheric pressure	101.3 kPa	0.0 kPa (no atmosphere, aerobraking not possible)	0.7 kPa (very low, aerobraking not possible)
Magnetic field	Yes (offers protection from some forms of dangerous radiation)	No (no protection from radiation)	No (no protection from radiation)

Gravity

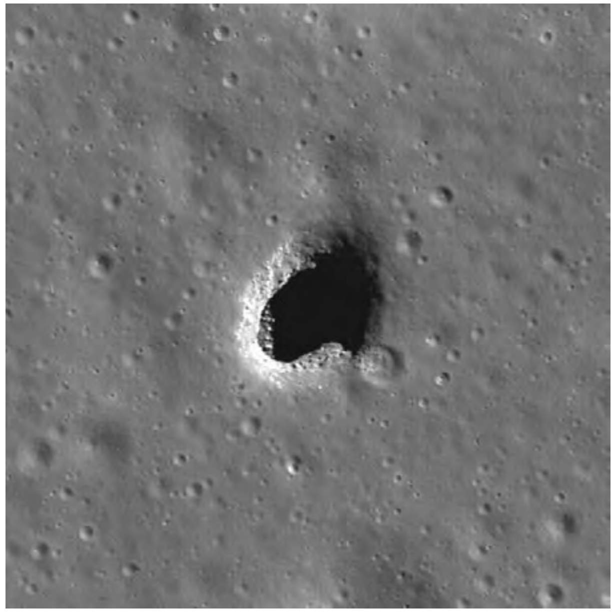
The Moon's gravity is six times less than Earth's and that of Mars' is three time less. Lower gravity does mean that less energy is required to launch materials from the surface of these celestial bodies, especially the Moon. Conversely, the low gravity of the Moon creates some challenges regarding the amount of Moon dust kicked up during landings and take-off is potentially hazardous for human health if not excluded from human habitation areas[112]. With less gravity holding it down, the lunar dust takes much longer to settle back on the surface, with some of it even reaching orbital altitudes. This could also create problems for particularly sensitive scientific instruments[113, 114].

Magnetic field

Earth's magnetic field protects terrestrial electronic systems and orbiting satellites from the effects of energetic particles (electrons and protons) carried by the solar winds. Neither the Moon nor Mars have a magnetic field today and charged particles from solar winds could damage unprotected electronic equipment which would therefore need to be designed to be resilient to these potentially damaging effects.

Atmosphere

Earth's atmosphere provides breathable oxygen that is essential for survival as well as protection from UV solar radiation. Sources of breathable oxygen will be critical for human survival on both the Moon and Mars. The lack of atmosphere on the Moon and the thinner atmosphere on Mars also means that the Moon and Mars experience greater extremes of temperature. Protection in sub-surface habitats, such as natural lava tubes, is considered a way to mitigate this challenge[115]. This may generate competition for promising sites for human habitation where temperature fluctuations are less extreme.



Above
Image of a 130 m wide hole in the surface of the moon in Mare Ingenii. The hole is believed to have been formed by the collapse of the roof of a lava tube. The image was taken by the Lunar Reconaissance Orbiter. © NASA.

Technical requirements for human bases

Power generation

A diverse range of power sources would be required if a higher level of human activity on the Moon and on Mars is to be supported.

Solar power

Solar cell manufacturing

Lunar regolith contains iron, silicon and aluminium which are key elements for the construction of solar cells. An autonomous rover which harvests these elements and creates solar cells in-situ has been proposed[116]. Commercial companies such as Blue Origin and Lunar Resources, claim to have been able to make solar cells from simulated lunar regolith on Earth[117]. They have achieved this by processing regolith in reactors which heat it to temperatures over 1,500C and then using an electrical current to extract the key elements. Finding ways to achieve this on the lunar surface will be a significant technical challenge to overcome, and will be an important step in reducing reliance on bringing such solar cells from Earth.

Space-based and surface solar power

Providing continuous power for lunar bases through the long two-week lunar night is a particular challenge for lunar exploration and operations. Solar panels on the surface can operate during the two-week daytime. Advances in energy density of battery storage will allow operations through the night. At the Moon's poles, there are crater rims which are almost permanently in sunlight ('peaks of eternal light')[118] providing scope for continuous access to solar generated electrical power in these regions.

Space-based solar power, with a small constellation of 100kW scale solar power satellites, could provide continuous power to lunar bases at all latitudes. NASA is studying space-based solar power for the Artemis programme.

Nuclear power

Other forms of energy will be required for regions of the moon which are in permanent shadow. Developing nuclear power facilities is therefore an attractive option.

Fission

Heat generated by the decay of radioactive Plutonium-238 was used as early as 1969 in the first Moon landing to maintain stable working temperatures for scientific instruments exposed to the cold lunar conditions. In Apollo 12, a similar system was used to power an electricity generator marking the first use of fission power on the Moon. Similar power systems are under consideration for future missions with the UK Space Agency funding work at the National Nuclear Laboratory in Cumbria to produce batteries powered by Americium-241[119]. This is a natural product of fission reactors such as Sellafield in Cumbria and is in more plentiful supply than Plutonium-238, which is only produced in the USA and Russia.

Of course, more ambitious plans over the next 50 years will require larger scale power production. Rolls Royce and a selection of UK Universities are developing a microreactor for use on the lunar surface[120]. It is the size of a small car and could deliver 50-100kW of energy using TRi-structural ISOtropic particle fuel (TRISO fuel)[121]. TRISO fuel, which was first developed in the 1960s, consists of poppy seed sized particles that contain oxygen, uranium and carbon, bound in ceramic to more safely contain materials required for fission reactions. While generally a more secure way of storing nuclear fuel, TRISO fuel particles would still pose a radiation risk in the event of an accident and so ensuring that appropriate protocols are in place to manage such a scenario would be critical.

NASA has commissioned Westinghouse and Astrobotic to develop the eVinci™ microreactor system for use on the Moon. Whilst a decade's worth of testing on Earth would be required before deployment in space, the microreactor could provide up to 5 megawatts of power. This is sufficient power for more than 1,000 homes on Earth, and its fuel would last for eight years[122]. Russia and China have announced plans to construct a nuclear reactor to power a joint space station on the Moon by 2035.

Fusion

Whilst fusion has great theoretical promise, particularly as a future low carbon low pollution energy source, as yet there are no practical sources of fusion power. Indeed 'net gain' (energy outputs that exceed energy inputs) has only recently been demonstrated in an experimental setting[123]. Nevertheless fusion technology is attracting large investments and making progress, so fusion power by 2075 is not inconceivable. The lack of a magnetic field on the Moon has caused accumulation of the isotope, Helium-3 (He-3), in lunar soil. He-3 is used in neutron detectors for determining the enrichment of nuclear fission material and the amount of oil in wells as they are being drilled, but it could also theoretically be used as a fuel for nuclear fusion reactions[124], a potential sustainable source of power. The reduction of neutron production makes He-3 fusion a safer prospect and would reduce the need for heavy shielding and frequent maintenance of reactor components. Additionally, the charged particles produced could in principle be directly converted into electricity.

GOVERNANCE CHALLENGE

Risks of nuclear fission power

Fission power produces harmful radioactive byproducts which would need to be disposed of securely to avoid harming humans living in bases on planetary bodies.

There are of course risks associated with transporting nuclear materials in space before it arrives at its ultimate destination. In 1964, a Thor-Ablestar rocket carrying the Transit 5BN-3 satellite failed to reach orbit, which resulted in 13 kilocuries of radioactive material being released into the stratosphere. To put it in perspective, while not without its risks, the level of radiation risk is significantly less than that deposited by nuclear weapons testing.

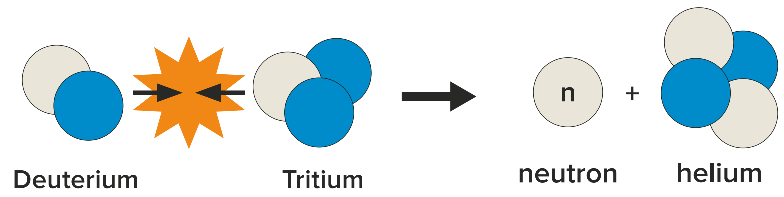
Accidents involving nuclear debris can also have financial consequences. In 1977, the Soviet Union satellite Kosmos 954, powered by 45kg of enriched uranium, experienced an uncontrolled descent scattering radioactive debris over Canada. This required a costly clean up job dubbed Operation Morning Light. Under the terms of the 1972 Space Liability Convention, a state responsible for launching an object into space is liable for damages caused. The Soviet Union eventually paid $3m Canadian in compensation.

If an accident were to happen on the Moon or Mars which damaged another state or commercial entity's property, the same legislation would doubtless be invoked and it will be important to consider how this might apply in other settings, especially if it is harder to demonstrate responsibility. Agreeing appropriate safety measures and sites for disposal of nuclear waste on the Moon and Mars will also be a key consideration.

FIGURE 19

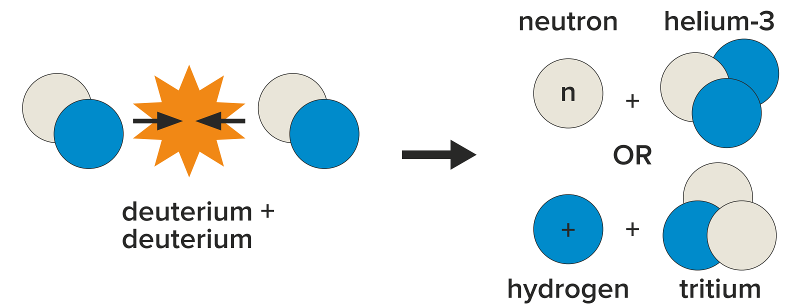
The building blocks of fusion

Deuterium-Tritium (D-T) Fusion
Requires temperatures around 100 million degrees Celsius (10 keV) to overcome the Coulomb barrier and initiate fusion.



Produces 17.6 MeV of energy per reaction, with 80% of the energy carried by neutrons.

Deuterium-Deuterium (D-D) Fusion
Requires temperatures around 500 – 1,000 million degrees Celsius (50 – 100 keV) due to the higher Coulomb barrier compared to D-T fusion.

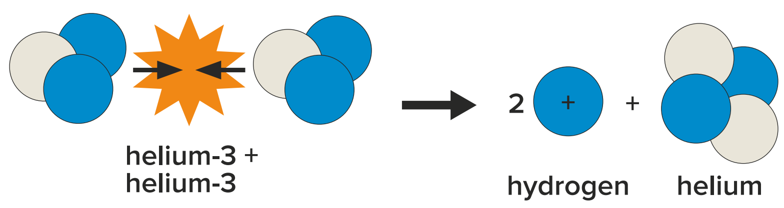


Produces 4.03 MeV or 3.27 MeV of energy per reaction, depending on the specific reaction pathway.

Deuterium fuel abundant on Earth in seawater.

Requires the lowest energy input of any fuel regime.

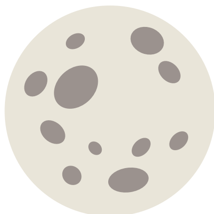
Helium-3-Helium-3 (He-3-He-3) Fusion
Requires extremely high temperatures, around 10 billion degrees Celsius (1 MeV), to overcome the Coulomb barrier and initiate fusion.



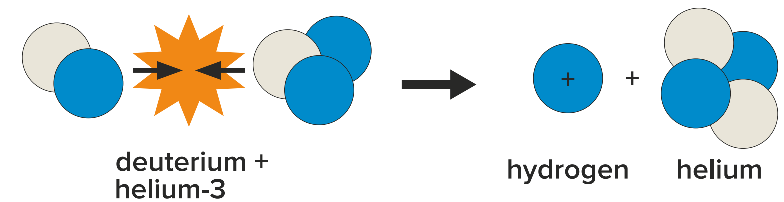
Produces 18.3 MeV of energy per reaction as charged particles.

Helium-3 fuel abundant on the Moon.

Products are all charged particles and can be used for rocket trust.



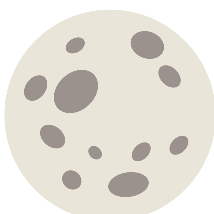
Deuterium-Helium-3 (D-He3) Fusion
Requires temperatures around 400 million degrees Celsius (400 keV) to achieve the necessary reaction rates.



The fusion of two Helium-3 nuclei produces Helium-4 and two protons, releasing about 12.86 MeV of energy per reaction. This reaction is aneutronic, meaning it produces no neutrons, which significantly reduces radiation hazards and material activation.

Helium-3 fuel abundanton the Moon.

Highest energy yield per reaction.



There are enormous technological challenges to address with use of He-3 in fusion reactors given that sustained fusion reactions have yet to be achieved on Earth. The 10bn degrees Celsius requirement to start a He-3-He3 reaction is also significantly higher than Deuterium-Tritium reactions which are the type that has been studied most extensively. However, this has not deterred commercial interest in developing extraction techniques for He-3. A startup company called Interlune has raised $15m to explore the possibility of mining He-3 on the moon commercially[125]. This is driven by estimates that He-3-He3 reactions from He-3 extracted from the Moon could meet the world's energy requirements for 500 years (based on figures for energy consumption published in 2021)[126]. However, this reaction is considered almost impossible given the extremely high temperature requirements as the reactor would cool faster by radiation than any reaction could reheat to sustain itself. The Deuterium- Helium 3 reaction is the only one considered possible, but even this is roughly 50 times more difficult to achieve than the better studied Deuterium-Tritium reaction. On Mars, there is five to eight times the amount of deuterium observed in the Martian atmosphere compared to water on Earth which could in theory be used for some of the lower energy fusion reactions, but finding a way to extract it economically would still be a significant challenge[127, 128].

Extracting either of these materials would likely only be of any use in-situ and would be very disruptive. Some estimates suggest that producing a single gram of He-3 would necessitate digging up 150 tons of lunar regolith because He-3 it is so diffusely distributed on the lunar surface. Despite relative higher abundance of He-3 and deuterium on the Moon and Mars respectively, it is also unclear if it would be economical to bring harvested materials back to Earth, where reliable local sources would be prioritised instead.

Launch and landing sites

There will be locations on the Moon and Mars that are better positioned for launch and landing activities. These might be the subject of competition unless agreements can be reached to ensure cooperation and fair access to important sites for different nations and commercial purposes. The lower gravity on the Moon makes the body an attractive launch site for future missions out into the Solar System, especially onwards to Mars. This is because much less energy is required to reach the escape velocity. If fuel and other resources for such missions can be generated in-situ on the Moon, this would make it a more attractive staging platform for missions to Mars.

The low atmospheric pressure on Mars coupled with the higher gravity compared to the Moon presents challenges. On Earth, it is possible to use the denser atmosphere to control landing of craft via aerobraking, which is much harder to achieve on Mars. Under the Moon's lower gravity, thrusters are sufficient to control descent of landers (despite having no atmosphere to aerobrake) to limit the disruption of the lunar surface, but on Mars, technology will need to be developed to safely control landing under stronger gravity.

Oxygen and water supplies

Lunar rock and soil are made up of 45% oxygen by weight in the form of oxide compounds. A variety of methods have been proposed to use energy to extract the oxygen from these compounds so it can be used for the production of breathable air as well as rocket propellant. It should be noted that using the oxygen for propellant, would mean that it is lost forever if burned in space compared to other uses such as manufacturing breathable air or drinking water from which it could be recycled for further use on the lunar surface. On Mars, the Perseverance rover has demonstrated that carbon dioxide in the thin Martin atmosphere can be converted to oxygen in a proof-of-concept study, using an instrument called the Mars In-situ Resource Utilization Experiment (MOXIE) which is about the size of a toaster[129]. Similarly, ice deposits on both the Moon and Mars could be used to produce drinking water and extract hydrogen as a fuel source[130].

Resources from Space Mining

By the end of this century, space-specific industries are likely to be joined by sectors that operate on Earth expanding their operations with the opportunities offered by developing in space. Central to these sectors will be space mining, or the extraction of resources from asteroids, the Moon, Mars, and other celestial bodies, in many cases by robotic systems. Although the economic arguments for space mining are still in their infancy, and it is unclear what elements or minerals would represent a viable business case for return to Earth, if permanent human bases are eventually established, it may be feasible and economically desirable to locate and extract local resources to support such bases. The next 50 years are likely to see developments in the technical means for space mining and processing capabilities. Such resources could include platinum-group elements, lithium, nickel and cobalt which are needed for batteries and other low-carbon technologies[131]. The market for mineral demand is not static though. A high price for any resource drives innovation to replace them, and recycling would affect the market and decrease dependency on mining for new sources of key elements. Plans to exploit extra-terrestrial resources would need to be robust against changes in terrestrial market conditions.

Left
MOXIE (Mars Oxygen In-Situ Resource Utilization Experiment) was launched aboard NASA's Perseverance rover to test a technology for extracting oxygen from the Red Planet's carbon dioxide-rich atmosphere. © NASA/JPL-Caltech/CNES/IRAP.

In terms of developing plans for longer duration stays on the Moon, mining operations could target processing of silica for solar panels, mining rocks for water and other low abundance volatiles and metals (eg, copper). Mining equipment could also be produced on the Moon, with its comparatively low gravity. Mars' history of high volcanic activity and cratering from asteroid impacts means it is potentially host to a range of metal ores which have been substantially depleted in Earth-based reserves for their valuable properties, although the location and abundance of such concentrations of economically useful elements and minerals on Mars is not yet known.

On Earth, expanding mining activity might involve digging deeper than before or setting up facilities on deep sea ocean beds[132], both of which may involve extremely high costs and may have significant environmental implications[133, 134]. Exploiting lunar and asteroid resources could therefore help to protect precious mineral resources of the Earth and the environments in which they exist (including their biotic communities). Space resource use will support space-based manufacturing by reducing the need to expend the huge quantities of energy needed to lift construction materials out of Earth's gravity well. It would be important to manage such exploitation fairly and sustainably, ideally through guidelines and standards developed at an early stage.

Asteroids could also be mined, an idea that has featured in science fiction for decades. Although the economic case is still unclear, scientists have identified asteroids that contain precious resources, from gold to platinum, on a scale unparalleled in Earth-based mines. Moreover, near Earth asteroids potentially offer huge mineral resources without the need to travel beyond Mars to the asteroid belt. Among the most likely targets are Easily Retrievable Objects (EROs)[135], a class of asteroids which would require only a small change in their velocity to bring them into a safe orbit either around the Earth or the Moon. This could feasibly be done with current rocket propulsion technology or in the longer term, using solar sail technology[136]. Plainly control of such objects would need to be carefully monitored due to potential defence implications.

Although some of the required capabilities for space mining are ready, space mining is not currently technologically or economically feasible as the converging technological domains involved, including robotics, artificial intelligence, and space transportation, still require substantial advances. By 2075, asteroid mining and processing operations could be well established, creating the materials and products for large in-space structures.

Right
This artist's concept depicts the 140-mile-wide (226-kilometer-wide) asteroid Psyche, which lies in the main asteroid belt between Mars and Jupiter. Psyche is the focal point of NASA's mission of the same name. © NASA/JPL-Caltech/ASU/Peter Rubin.

Several national space agencies and private companies are currently investing in space mining, conducting preliminary studies, and developing enabling technologies and regulatory frameworks (US in 2015, Luxembourg 2017, UAE 2020 and Japan 2021). Japan's national space agency successfully completed an asteroid sample return mission in 2020 with its Hayabusa2 spacecraft, first launched in 2014[137]. This mission has been extended and will continue to fly to new targets. Similarly, NASA's OSIRIS-Rex, returned 120g of material in September 2023[138]. NASA is also looking to study the asteroid 16 Psyche (which is believed to have enormous estimated material value) with an orbiter which launched in October 2023[139].

Space mining is one area that draws on many different science and engineering disciplines. For example, microorganisms can be used in the process of 'biomining' to extract useful elements from rocks. This process is routinely used on Earth to extract elements such as copper and gold from sulphidic ores. Microorganisms obviate the need to use chemicals such as cyanides which can be environmentally damaging and instead employ the capabilities of microorganisms evolved over billions of years to leach elements from rocks. Experiments from the UK have demonstrated the extraction of rare Earth elements from basaltic (lunar and Mars analogue) rock in microgravity and simulated Martian gravity on board the International Space Station. Thus, biological and physical sciences have numerous interfaces where collaborations and new technologies could be fruitfully developed. The recycling of elements and their extraction from local resources to support human infrastructure on other planetary bodies being one example[140, 141].

GOVERNANCE CHALLENGE

Space mining

It is unclear whether Article II of the Outer Space Treaty explicitly bans the ownership of resources extracted from planetary bodies such as the Moon and asteroids. Whilst this would indicate that the territory itself cannot be claimed by a nation and must be free to be explored and investigated by all states, it is less clear what "national appropriation" includes and whether In-Situ Resource Utilisation such as mining would be covered; not least as commercial companies, under some interpretations of the OST, could fall outside of the scope of "national appropriation". This interpretation has been taken forward by the Artemis Accords, signed by a significant number of space-faring nations, carving a path for future space mining. Luxembourg also passed a law in 2017 to declare space mining legal and set itself up as the European home for space mining business with various other funding initiatives to attract inward investment. This was followed by similar regulations in the UAE (2020) and Japan (2021).

Given the huge estimated value of some of the asteroids, this could cause huge disruption to Earth-based economies and widen inequalities if more space-capable nations are able to exploit these resources before others.

There are also conflicting aims in terms of scientific interest in studying asteroids for the purpose of discovery of life, planetary formation (Psyche is thought to be the core of an aborted planet) and understanding how humanity can protect itself from asteroids that could impact planet Earth.

Human Habitats

In preparation for the higher levels of human activity across the Solar System by 2075, research efforts can be expected in areas related to sustaining human life for extended periods of time on planetary bodies beyond Earth. On the Moon, this will include studies on building and operating habitats and their life-support systems in subsurface lava tubes[142] or in surface locations. On Mars, similar innovations will include exploring the potential for exploitation of in-situ resources, such as learning how to process regolith and clean it of compounds such as perchlorates[143]. This would enable the potential for plant and microbial growth for food and oxygen production to be tested. In both locations, and anywhere else in space for that matter, crucial technologies to be developed will include recycling technologies for water and other essential volatiles (especially the biologically important CHNOPS elements – see Box 1 in Chapter 1) to allow for extended human habitation. In essence, over the next 50 years, all the facets required for humans to live and operate in a healthy environment must be developed for these different environments. Some of the challenges, such as recycling water, will apply to all locations and a Solar System 'standardisation' in some of the approaches might naturally follow. However, some challenges will be specific to particular locations, such as removing perchlorates from soils, which will likely only be relevant on Mars.

Engineering Biology

Engineering biology, which draws on principles from engineering and biology to construct biological systems that do not exist in nature, as well as improving understanding of those that do, will both aid space activity and become part of it[144]. Applications include creating cells to produce useful items in space, such as pharmaceuticals and plastics, that support human and robot exploration[145, 146]. By enabling studies on cellular architecture and biomolecules, engineering biology and astrobiology will combine to enable new advances that support human endurance in space as well as detection of life.

Engineered microbes are already being used on Earth to imbue concrete with adaptive self-healing properties, while other cells have been engineered to produce high-performance water-resistant adhesives. Engineering biology could also be used to create or adapt organisms for similar uses in space. They could assist in extracting minerals and chemicals from celestial bodies and extract water from rocks and ice, a key step in providing resources to explore other planets and moons.

Synthetic organisms could be used to create and improve closed-loop systems – particularly habitation and life support systems which circulate almost all waste back into use, turning the by-products into food, oxygen, and many other essential resources for space missions and habitation. New organisms can be used for water treatment systems, on-demand drug production, food production and extremophiles could provide a portfolio of genes that could be used to incorporate extreme physical and chemical tolerances into a wide range of other organisms.

Organisms could be designed to perform specific tasks, such as sensing and monitoring the environment, or providing maintenance and repairs for spacecraft or bases. Microgravity-tolerant plants, radiation-resistant cells, material-producing microbes tolerant to desiccation and extreme cold, and many other organisms, could all combine to make it much more cost-effective to explore and settle other planets and moons.

By 2075, abilities to custom engineer microbes using engineering biology are likely to provide a vast set of different organisms that convert all sorts of matter into higher-value products. Already harmless microbes used in food production, like household yeast, have been genetically reprogrammed in a range of projects to make fuels, fragrances, and flavours, as well medicines such as painkillers, vaccines, antibodies, and vitamins. Similar bioengineering techniques could be a key part of making ingredients for meat-replacement foods and could also make the building blocks for bioplastic-based materials and fibres like spider silk. The ability for a set of easily grown microbes to make so many different products makes such an organism an attractive asset for space exploration, as a kit of thousands of such microbes weighs just a few grams. The various microbes in this kit could be engineered in advance and used to make a wide range of products from different resources as and when they are needed, effectively acting as a tiny, portable factory. AI techniques such as the huge expansion on protein sequences elucidated by Alphafold 3 are rapidly accelerating developments in this field by revealing and interpreting the code for useful compounds which could support missions[147].

Such studies will have great synergy with scientific efforts to resolve challenges on Earth, for example in finding ways to make replicating lifeforms that can operate in environments where humans cannot. This could provide new ways to remediate areas of Earth which have become, or are already inhospitable, like deserts[148] and polluted environments.

Terraforming

In the distant future, it may be possible to modify the regolith and climate of Mars to create conditions which are much more Earth-like. Planetary scale transformation of substrate and climate will have a huge number of technical hurdles involving a multidisciplinary effort and would likely happen in small stages over hundreds of years. Towards 2075 the first examples may appear, of testing combinations of engineering biology and atmospheric modification in a contained system on the surface of Mars to create conditions which are more hospitable to human habitation.
One of the greatest challenges would be maintaining warmth to enable liquid water to be maintained. A range of means to achieve this have been considered. Recently, the prospect of using artificial aerosols comprising nanoparticles made from materials on Mars was raised. They could be scattered in the atmosphere to increase temperatures on a global scale by more than 30 Kelvin at a much faster rate than other methods[149]. The science of solar radiation modification however is highly uncertain, and policy applications controversial.

There are also potential ethical dilemmas of how to handle any native lifeforms which may yet be shown to exist on Mars. Such planetary scale transformation of the Martian surface could cause substantial disruption to any extant indigenous life that may be discovered. Careful consideration would need to be given to the roles and responsibilities in conserving such life.

GOVERNANCE CHALLENGE

Planetary protection

Forward contamination

The United Nations (UN) Outer Space Treaty of 1967[150] empowers the Committee on Space Research (COSPAR) to set out non-binding guidelines[151], for how missions to different planetary bodies in the Solar System ought to be handled. COSPAR has five categories of mission, four of which refer to the risk of contaminating space environments with microorganisms from Earth. Categories I and II cover missions on planetary bodies which are not of interest or of limited interest in terms of potential for discovery of life. Category III concerns orbiter or flyby missions around planetary bodies which are of interest to the discovery of life (but not coming into contact with the surface). Category IV covers the most strict requirements where instruments are landed on the surface of a planetary body where there is an interest for the discovery of life. In this case, requirements include that "Sterilization of the entire spacecraft may be required for landers and rovers with life-detection experiments, and for those landing in or moving to a region where terrestrial microorganisms may survive and grow, or where indigenous life may be present. For other landers and rovers, the requirements would be for decontamination and partial sterilization of the landed hardware."

It is essential that protocols are carefully followed as there is likely to be scientific debate over the validity of new discoveries if concerns arise over contamination with microorganisms from Earth. Distinguishing between contaminated and pristine samples will be particularly important for future Mars missions.

The impact of engineered microbes or cells on planetary protection

A supplementary consideration is the planetary protection issues that might arise from eg the creation of artificial lifeforms engineered to withstand the extreme conditions of Mars. Such organisms could be so successful in this harsh environment that they could rapidly outcompete native organisms yet to be discovered. It will be important therefore to bring together the communities working on ethical and policy concerns of engineering biology and planetary protection to better understand the risks of releasing such organisms on planetary bodies and how they might be mitigated by careful engineering of the microbes. Extensions to COSPAR's guidelines would need to be prepared to govern this sort of activity, along with appropriate standards.

Back contamination

Although generally perceived to be very low risk, there is some concern that sample return missions could result in the introduction of materials which could be harmful to Earth's biosphere. Category V covers sample return missions which are further subdivided into Restricted and Unrestricted:

- Unrestricted Category V: "Earth-return missions from bodies deemed by scientific opinion to have no indigenous life forms." eg the Moon, Venus
- Restricted Category V: "Earth-return missions from bodies deemed by scientific opinion to be of significant interest to the process of chemical evolution or the origin of life." eg Enceladus, Europa and Mars

Restricted Category V missions require careful preparation to ensure samples are secured appropriately. It has been proposed for NASA's Mars sample return, that a second container that has not touched the Martian surface could be used to secure samples in the vacuum of space. This container would require reliable seals and strong construction to withstand any damage from debris on the return to Earth which could compromise its containment and cause unintended release on descent to Earth's surface. Samples would be received on Earth in specialised Biosafety Level 4 (BSL-4) facilities which are designed with features to contain the most hazardous pathogens.

The Outer Space Treaty places liability for any damage resulting from contamination with the party (nation) who is responsible for launching and operating the spacecraft carrying it. That said there is no provision to hold to account those parties who may adopt less strict safety procedures and the commitment and capability of different nations and commercial entities to comply with COSPAR planetary protection guidelines will therefore vary.

Left
Planetary protection engineers at NASA's Jet Propulsion Laboratory in Southern California swab engineering models of the tubes that will store Martian rock and sediment samples as part of NASA's Mars 2020 Perseverance mission. Team members wanted to understand the transport of biological particles when the rover is taking rock cores. These measurements helped the rover team design hardware and sampling methods that meet stringent biological contamination control requirements. © NASA/JPL-Caltech.

Taking care of human health, safety and wellbeing in space

Until recently, astronauts have been chosen through highly selective programmes and they needed to demonstrate a high level of health and fitness. In the next 50 years more specialised roles will appear (eg in science and construction) that involve people with a greater range of health statuses travelling to space. Clarifying the rule of law with respect to people in extra-terrestrial locations will be essential to determine what their rights and responsibilities are and who is responsible for their welfare.

Human health in space

Current understanding of how space affects the human body is limited, as is the capacity to deliver medical care beyond Earth. By 2075, enormously improved understanding of human physiology and space medicine will be required if much greater numbers of people who are likely to travel to space are to enjoy a state of health that meets the World Health Organisation's definition as a "state of complete physical, mental and social well-being".

Long-duration space exploration missions beyond low Earth orbit, such as multi-year missions to Mars, will bring new challenges for professional astronauts – who are extremely fit and well trained – given that the longest continuous human exposure to microgravity to date is 438days. However, it is unknown how the effects of gravity on the Moon and Mars, 16% and 38% of Earth's gravity respectively, will impact the human condition over the long term. The long trips made to travel between these destinations and Earth will still be undertaken on board ships with effectively zero gravity. Meanwhile, shorter tourist trips to space are likely to be made by people with different physiological makeups who have not had astronaut training and who may have conditions that trigger new issues in the unfamiliar environment. A 3-day mission containing ordinary civilians on SpaceX's Inspiration4 mission enabled data to be collected on the impacts of space travel on a broad range of physiological and stress responses, some of which match those of long-term spaceflight[152]. SpaceX followed this with another privately funded mission, Polaris Dawn. This saw a group of astronauts complete the first privately funded spacewalk at 700km above the Earth's surface. The mission ascended to 1400km at its highest altitude, within the inner Van Allen radiation belt which contains high levels of highly energetic protons, a risk to human health as well as scientific equipment. This will yield insights into the short-term effects of radiation exposure and the suitability of protective measures. Such studies will need to be expanded to understand the impact of longer durations.

The human body changes in microgravity in ways that are only starting to be understood. The cardiovascular system alters even during short-term space flights of up to two weeks because the body ceases to perform tasks that gravity demands[153]. The body is no longer required to work against gravity which leads to less muscle activity and loss of bone and muscle, which requires significant exercise load to counteract.

In space, the lower body no longer needs to physically work to support a person in an upright position, which reduces loading of the musculoskeletal system, impairs the blood pressure response normally seen when a person is standing and affects the balance system. These factors combine to make it hard for returning astronauts to stand up easily. Muscle wasting and other effects of space travel such as glucose intolerance, fat reallocation and bone depletion, have been compared by clinicians to early vascular aging on Earth although more accurately it is an accelerated model of degradation due to inactivity rather than ageing per se. Understanding of these effects is at a very early stage. Advances are required in areas such as vision, immunology, and the cardiovascular system, to respond to the way they are affected by radiation and altered gravity.

Research is required to address the health impacts of space travel and priorities for space therapies across the whole population spectrum of human physiology. Currently, progress is slow due to limited opportunities to fly experiments and the low number of people who have flown in space. There are many other calls on limited funding but the case for space medicines is strengthened by the fact that space exploration can be a motor for driving substantial advances in understanding of human physiology and psychology with relevance to terrestrial practice. It is now possible to apply detailed molecular biology techniques such as transcriptome sequencing to understand how genes are expressed differently in space for example, which will reveal the precise impacts of space travel on the human body for a range of demographics[154]. This will enable the discovery of spaceflight biomarkers and mitigation measures to protect human health.

Space related scientific advances have already contributed significantly to improving medicine on Earth, such as via the use of digital image processing techniques (in CT and MRI scans) developed by NASA. As in other sectors, such as energy and computing, the quest for new space-based medical breakthroughs will have terrestrial spillovers.

If medical research is stepped up to fill the gaps in understanding, then benefits could arise in personal bespoke medicine; medical screening and intervention technology; and predictive models of human physiology and psychology. The advance of human physiology studies in space itself can also lead to many ancillary developments, including drug discovery and 'organ on a chip' technology for enhanced studies of cancers[155, 156].

Little is known about the degree to which medicines that are effective on Earth can be applied in space, with very few rigorous studies considering the differences in their action in microgravity conditions. Another barrier to space pharmaceuticals is the lack of knowledge regarding the environment's impact on drug stability, altered pharmacokinetics (what the body does to the drugs) and pharmacodynamics (what the drug does to the body). For long duration missions there are questions regarding what drugs could be taken from Earth and what may need to be synthesised in-situ.

Further challenges are presented by the potential for emergency situations requiring immediate medical attention, like managing heart attacks or strokes or those requiring medical procedures like surgery, because of limited research and the absence of tried and tested techniques and treatments. Further ahead it may be possible for certain procedures to be completed by robotic surgical instruments controlled remotely from Earth.

As access to space travel widens, not only to people with different health profiles, but different genders and ethnicities, health-related studies should cater for the diversity of the human population. For example, female astronauts experience a greater reduction in plasma volume during spaceflight[157]. They also tend to respond to reductions in blood pressure by increasing heart rate, whereas men experience an increase in vascular resistance. There have also been no spaceflight studies on drug response focused on inter-ethnic difference.

If different genders or ethnic groups are not properly represented in the base of participants from the outset as space activity expands, then those populations may miss out on the potential benefits, or worse, come to harm by being treated as though they were the same as another group.

Space medicine will also need to take advantage of progress made in personalised healthcare that customises treatments to the individual genome. However, the field is in its infancy and although it is progressing through its early stages, better understanding and more sophisticated tools to tailor diagnoses and treatment to individuals will be required as more people venture into space.

Much was also learned in early space travel by using mammal models to study the impacts of space in risky environments. The earliest example was the Soviet Union sending Laika the dog into orbit on Sputnik 2 in 1957. This may continue to be considered as human presence expands in the Solar System, though plainly ethical concerns would need to be carefully factored in and the essential use of animals justified robustly as is the case with any scientific experiment involving animals.

BOX 8

A new wave of astronauts?

ESA concluded its Fly! Feasibility Programme in January 2025. The aim was to assess whether British surgeon and former Paralympian, John McFall would be able to meet the criteria to become an ESA astronaut. John McFall, who has a one-sided lower-limb amputation following a motorcycle accident, was assessed using the following criteria:

- **Training:** Compliance with ESA Astronaut Basic Training requirements, including sea and winter survival, as well as any specific training John might need if selected for a flight.
- **Spacecraft operations:** Analysis of each phase of the flight – pre-launch, ascent, free flight, and landing – to ensure John could meet emergency procedure requirements both on Earth and in microgravity.
- **Space Station operations:** Emergency and safety protocols on the station, along with John's ability to navigate and stabilise himself effectively in microgravity.
- **Medical:** Assessment of John's capability to carry out exercise countermeasures in orbit and manage changes in his stump volume that could affect prosthetic fit and comfort.
- **Crew support:** Needs such as quarantine facilities or mission-specific clothing. This systematic review analysed around 80 specific considerations, forming the foundation of the Feasibility Study.

The conclusion was that John's disability did not interfere in the process of long duration space travel in a way that could not be solved with a range of small adjustments. One such example was the change in pressure in space affecting the join of his prosthetic leg, which could be easily adapted. John is now an astronaut in reserve waiting for a mission and could become the first astronaut with a disability to fly. A lesson here is that adjustments can be made to enable a more diverse pool of astronauts to fly, which will be essential as certain skills will be required in space in the years to come and limiting the selection pool to able-bodied candidates could prove restrictive. Reviewing the selection criteria for astronauts will naturally follow.

This also provides exciting opportunities to better understand the role of the space environment on the human body and to develop new solutions to make space travel accessible. These opportunities could also improve life on Earth by illustrating the difference between impairment and disability (ie the interaction between the individual's impairment and the environment).

The psychological impacts of long duration space travel will also need to be assessed. Especially considering that real-time communication with mental health professionals on Earth would not be possible for astronauts on a multi-year round trip to Mars.

Human enhancement

Humans may use various enhancements to protect themselves and expand their physical capabilities[158]. Force augmentation exoskeletons may be used to magnify human strength, building on those already used in healthcare among patients suffering weakness due to injury or diseases. Exoskeletons could enable astronauts to be more productive as well as to work effectively following journeys that could take years in zero gravity, reducing bone density and strength[159]. They will also enable visits to space by experts who do not have the same physical fitness as a professional astronaut. Neural interfaces that link human nervous systems to external devices might also be applied in various ways in space, including human control of remote robotics such as the ESA robotic arm.

Human wellbeing in space

The prospect of sustained human presence in space, especially for those who are not from a military background, raises the question of participants' wider well-being. A holistic healthcare and well-being concept needs to be built into policies and models developed for future occupants of space stations on the Moon and Mars.

Whilst attempts to populate planetary bodies with citizens would be premature for the type of bases that will appear over the next 50 years, human pregnancy may well arise as a consequence of prolonged human presence in space environments. As such it will be necessary to prepare protocols ahead of such potential occurrences. The extent to which space impacts pregnancy is yet to be understood. No attempt has been made to study this field in full. Provisions should be made to establish clear rules for such eventualities.

Health and Safety at work in space

As human activity expands on the Moon and on Mars, there will also be the need for a large human workforce to support this activity. Questions arise on how these individuals would be protected during this employment and under which Earth-based jurisdictions. The states which are party to the International Space Station (ISS) Intergovernmental Agreement retain criminal jurisdiction over their nationals while they are on the ISS. Therefore if the activities of one of their nationals adversely affects the life or health of a national of another state or damages the property of another state, the responsible national could be subject to criminal prosecution by that other state. This might be something that could be reflected in treatment of citizens in other space environments.

FIGURE 20

Force Augmentation Exoskeleton

Above
Force augmentation skeletons. © NASA.

GOVERNANCE CHALLENGE

Space workers' rights

The number of individuals living and working in space, most likely concentrated on the Moon and Mars, could grow substantially over the coming decade. Space workers will require legal safeguards in the long-term, providing individuals with measures to protect their health and wellbeing as well as the possibility of more specific rights for things like returning to Earth. The question of what responsibilities and duties commercial space companies have towards their space-based workforce is still an open question. Ideally, the process to design a set of space workers' rights should be international and inclusive. If space workers' rights are not achieved through international consensus and adopted by most spacefaring nations, then the lack of a level-playing field could create an undesirable race to the bottom in relation to such desirable rights.

Making matters more complex is that adverse effects of space may not be known for many years after exposure. Comparisons can be made with effects such as the long term exposure of 'matchgirls' to white phosphorus in Victorian England and for workers handling asbestos between 1950s-1990s leading to respiratory health issues and ultimately a ban on use in the UK in 1999. Establishing causal links for health concerns will be important and space workers' health should be monitored closely.

Currently, the UN's Outer Space Treaty 1967 and The Rescue Agreement[160] which followed it determine that any astronaut from any nation is an "envoy of mankind," and signatory states should support any astronaut in distress, regardless of nationality, indicating they "shall immediately take all possible steps to rescue them and render them all necessary assistance". Otherwise individual space agencies have policies in place around protections for astronauts for example exposure to radiation levels[161]. In the US in 2017, the National Aeronautics and Space Administration (NASA) Transition Authorization Act of 2017 (Public Law 115-10) was signed into law[162]. Also referred to as the TREAT Act ("To Research, Evaluate, Assess, and Treat Astronauts Act,") it expands NASA's existing role to monitor, diagnose, and treat medical and psychological conditions of former astronauts associated with spaceflight. Expanded legal protections will be necessary to cover a wider range of activities for individuals from all nations.

Interstellar space travel (travel between stars)

Crewed missions to the Moon and Mars are one thing, but what about the potential for voyages further afield to other locations in the Solar System and beyond? Only a handful of human-made objects have travelled beyond the Solar System, the most famous of which are the Voyager probes.

One of the limitations of travelling such extreme distances is the speeds which can be reached using existing in-space propulsion technologies. To travel interstellar distances in reasonable time frames for human life spans, craft would need to be developed which are capable of travelling at speeds approaching the speed of light. The record for the fastest man-made object is held by the Parker Solar Probe, which reached a staggering speed of 635,266 km per hour[163]. However, this is still only approximately 0.06% of the speed of light. At this speed, it would still take 7,378 years to travel from Earth to Alpha Centauri, the nearest neighbouring star system.

Advanced propulsion systems such as nuclear propulsion and solar sails may help to shorten the travel time between such great distances. However, there are risks involved with travelling through space approaching lightspeed even if such velocities can be achieved. Collision with something as small as an interstellar dust grain at high speed could cause significant if not catastrophic damage[164] and designing craft with adequate shielding would be a considerable engineering challenge.

Even if crewed interstellar travel were desirable, it is extremely unlikely that this will occur in the next 50 years, and there are significant questions about the value of human missions in such high-risk environments given that robotic craft are becoming increasingly capable. Even so there have been a variety of competitions and research initiatives to develop credible proposals for large crewed interstellar starships based on existing and hypothetical technologies. NASA previously operated a Breakthrough Propulsion Physics Program which was closed in 2003 after more than $1m of investment due to no breakthroughs being imminent. Advances in technology may revive interest in this area of research over the next 50 years.

There have also been proposals to send robotic craft to Alpha Centauri, 4.34 lightyears away. If speeds of 15 – 20% of the speed of light can be reached, then a journey would take 20 – 30 years to complete. Breakthrough Starshot[165] backed by private investors, is a programme intending to develop and send a swarm of 1000 centimetre scale nanocraft powered by solar sail technology called StarChips, to Alpha Centauri. The small size of design of these craft also reduces the risk of impact with anything that could cause damage in interstellar space. Reporting messages back to Earth using current communications technology would take 4 years to travel that distance ie based on lightspeed communication. Though there are challenges with transmitting signals over such distances. The big problem with communicating over interstellar distances is power. It is possible to transmit information by laser over a few Astronomical Units (AU, the distance between the Sun and Earth's orbit), but over a few light years is a completely different matter. Activity on the Breakthrough Starshot project has gone quiet in recent years, though it demonstrates the types of initiatives that may emerge in due course to send craft beyond the Solar System.

Conclusions

- Exploration of the Moon, and later Mars, is growing rapidly with competition primarily between the USA and China but with India and the UAE following. Two geopolitical camps are developing - Artemis and the International Lunar Research Station, but there are likely to emerge many opportunities for robotic and human lunar activity through other state and non-state actors over the coming decades.
- The Moon is a key stepping-stone to Mars, especially as water is present in the dark craters for life support and fuel. Both, however, represent hazardous environments for both humans and robots/machines.
- The construction of substantial human bases on the Moon or Mars will rely on extensive autonomous robotics. The power requirements to support a human base on Mars will require nuclear energy.
- Some commercial activity will appear with space mining, a priority for several nations and commercial companies, which has the potential to be hugely valuable economically and disrupt markets for metals, for example, as well as easing pressure on Earth-based resources.
- Human activities on the Moon, for example through the Artemis Lunar Gateway and the International Lunar Research Station, offer huge opportunities for science and medicine – hosting radio astronomy on the far side of the Moon could extend knowledge of the Universe dramatically.
- The management and ethics of human physical and mental health for sustained stay on the Moon and long duration space travel, including procreation, will be an important concern for society.
- There will be questions to resolve concerning the governance of and jurisdiction over distant human activity on the Moon and Mars.
- Human missions to the outer reaches of the Solar System and beyond remain highly unlikely because there are high risks and many technological challenges to solve. Advances in remote control, robotics and automation, may call into question the rationale for humans in space.

Companion pieces

Public dialogue on Space

The Royal Society commissioned Ipsos to conduct a series of public dialogues about using space safely and sustainably for the long-term benefit of humanity. A total of 96 members of the public took part, across four locations in Great Britain (Wrexham, Glasgow, Leicester, and Cornwall). The participants attended two full day workshops, aided by informative stimulus in the form of introductory text, explanations, and access to space specialists.

The Royal Society identified four policy themes to engage the public on: Discovery of Life, Governance in Space, Industry in Space, and Sustainability. These key themes formed the basis of four future scenarios and framed the workshop discussions. Ipsos drew together principles from what participants felt about the future of space. These principles are displayed in dedicated sections in this report alongside relevant quotes from participants.

Prior knowledge of the challenges, opportunities, and future of space exploration and settlement was variable amongst participants and often quite limited. This work demonstrates a clear need to raise awareness amongst the general public of the ways space can benefit humanity as well as the risks that it poses. When informed as part of the process of the public dialogue, participants were nonetheless very interested and thoughtful on the subjects discussed. The Royal Society would therefore encourage further public engagement and consultation on space. As taxpayers and beneficiaries of these future initiatives and technologies, the public deserves a say in how they are rolled out, governed and the benefits distributed.

The Public Dialogue on Space has been published in full and can be found at **royalsociety.org/space2075**

Generations by Stephen Baxter: a sci-fi story

The Society commissioned a short story by award-winning sci-fi author, Stephen Baxter, to bring the content of this Perspective to an extended audience. This story captures some of the social and philosophical questions and challenges that might be raised by the scientific and technological developments envisaged over the next 50 years.

Generations follows the journey of a pioneering family of space explorers as they venture out from Earth over the next 50 years. This trailblazing family is faced with many novel challenges such as giving birth in orbit, the perils of handling life discovered on other planets, power struggles on the Moon and finally a journey into deepest space.

Text and audiobook versions of *Generations* by Stephen Baxter will be pubished in due course.

A pack of teaching resources with the science behind the story is under development in coordination with the European Space Education Resource Office (ESERO) and STEM Learning which will be published alongside the story itself.

"The Messenger was to be the first crewed starship built by humans. It was a solar-sail ship, like most of humanity's most adventurous vessels. It had been assembled in Earth orbit – but, once completed, it did not head straight out. First, before leaving forever, it would make a final momentum-grabbing slingshot around the Sun, then it would pass back through the inner Solar System in just hours – passing through the orbits of Mercury, Venus, Earth, then leave forever.

And its close encounter with Earth would be the last time Svetlana would be able to speak to her family, save for time-delayed message scraps. Even so, she wouldn't have been that surprised if it turned into a family row.

There had always been tension in the family that Svetlana – herself born in the middle of a lunar revolution – had grown up being aware of. That was what you got in a family of heroes."

Excerpt from *Generations* by Stephen Baxter.

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Working group

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Co-Chairs
Sir Martin Sweeting FRS, Distinguished Professor of Space Engineering and Executive Chairman, University of Surrey and Surrey Satellite Technology Ltd.
Professor Suzie Imber, Professor of Planetary Science, University of Leicester
Professor Charles Cockell, Professor of Astrobiology, The University of Edinburgh

Members
Martin Soltau, CEO, Space Solar
Hira Virdee, Founder and CEO, Lumi Space
Elizabeth Seward, Head of Strategy, Space CTO, BAE Systems
Joanne Wheeler, Managing Partner, Chair Satellite Finance Network, Alden
Professor John Zarnecki, Emeritus Professor of Space Science, Open University
Professor Michele Dougherty FRS, Professor of Space Physics, Imperial College London
Kate Robson-Brown, Chair of UKSpaceLABs – UK space life science and biomedical science, University of Bristol
Pete Hodkinson, Head of Aerospace Medicine, Kings College London
Li Shean Toh, Assistant Professor, Division of Pharmacy Practice and Policy, University of Nottingham
Kevin Fong, National Clinical Adviser, NHS England
Samia Nefti-Meziani, Founder and Head, Autonomous Systems and Advances Robotics Research Centre (ASAR) and the North of England Robotics Innovation Centre
Yang Gao, Professor of Space Autonomous Systems, University of Surrey
Carsten Maple, Professor of Cyber Systems Engineering, University of Warwick
Mark Sephton, Professor of Organic Geochemistry, Imperial College London
Thomas Cheney, Lecturer in Space Governance and Astrobiology, Open University
Tom Ellis, Professor in Synthetic Genome Engineering, Imperial College London

Reviewers

This report has been reviewed by expert readers and by an independent Panel of experts, before being approved by Officers of the Royal Society. The Review Panel members were not asked to endorse the conclusions or recommendations of the report, but to act as independent referees of its technical content and presentation. Panel members acted in a personal and not a representative capacity. The Royal Society gratefully acknowledges the contribution of the reviewers.

Reviewers and advisers
Professor Brian Cox FRS, Professor of Particle Physics at the University of Manchester and The Royal Society Professor for Public Engagement in Science
Professor Carlos Frenk FRS, Director of the Institute for Computational Cosmology, Durham University
Chris Lee, Space Sector Strategic Adviser, AstroSpace Solutions and Visiting Professor, University of Leicester
Professor Chris Johnson, Chief Scientific Adviser in the Department for Science, Innovation and Technology (DSIT)
Professor David Parker, Visiting Professor in Space Systems and Policy, University of Southampton
Rt Hon Lord Willetts FRS, Chair of the UK Space Agency, Resolution Foundation, UK Space Agency
David Wade, Space Underwriter, Atrium Space Insurance Consortium (ASIC)
Dr Erika de Benedictis, Computational physicist and molecular biologist, The Crick Institute
Professor Francis Nimmo FRS, Professor, Department of Earth and Planetary Sciences, University of California, Santa Cruz
Professor Gerry Gilmore FRS, Emeritus Professor of Experimental Philosophy, Institute of Astronomy, at the University of Cambridge
Professor Henry Hertzfeld, Research Professor of Space Policy and International Affairs, George Washington University
Professor Hugh Lewis, Professor of Astronautics, University of Southampton
Dr Irene di Giulio, Senior Lecturer, Anatomy and Biomechanics, Kings College London
Professor James Osborn, Founding Director, Durham University Space Research Centre (SPARC)
Professor Jenny Nelson FRS, Professor of Physics, Imperial College London

Reviewers and advisers (continued)
Professor Jian-Wei Pan ForMemRS, Professor, Department of Modern Physics and Executive Vice President, University of Science and Technology of China
Professor John Burrows FRS, Director of the Institutes of Environmental Physics and Remote Sensing, University of Bremen
Jonathan Farrow, Deputy Director of Strategy, Futures, Partnerships and Requirements, US Space Force
Dr Kelly Weinersmith, Author of *A City on Mars* – Royal Society Science Book Prize winner, Rice University
Mark Bacon, Deputy Director of Programmes, Direct Investments & Sector Policy, DSIT
Mark Sims, Director of Space Research Centre, Space Academic Network (SPAN), University of Leicester
Professor Martin Green FRS, University of New South Wales
Sir Martin Rees FRS, Astronomer Royal, University of Cambridge
Neil Bowles, Professor of Planetary Science, Space Academic Network (SPAN), University of Oxford
Paul Bate, Chief Executive Officer, UKSA
Major General Paul Tedman, Commander of UK Space Force
Professor Ravi Silva FREng, Director, Advanced Technology Institute (ATI), University of Surrey
Professor Richard Horne FRS, Head of Space Weather, British Antarctic Survey
Richard Varvill, Chief Technology Officer, Reaction Engines
Professor Sheila Rowan FRS, Physical Secretary of the Royal Society and Professor of Physics and Astronomy, University of Glasgow
Sir Steve Cowley FRS, Director of the United States Department of Energy (DOE) Princeton Plasma Physics Laboratory (PPPL), Princeton University
Dame Sue Ion FRS, Hon President of the UK National Skills Academy for Nuclear and member of the UK Nuclear Regulator's Independent Advisory Panel

Royal Society Staff

Many staff at the Royal Society contributed to the production of this report. The project team is listed below.

Project team
Dr Matthew Barnbrook, Senior Policy Adviser
Leyton Wells, Policy Adviser
Jack Pilkington, Former Senior Policy Adviser
Dr Rupert Lewis, Former Chief Science Policy Officer
Elizabeth Surkovic, Former Head of Policy (Resilient Futures)
Thomas Frostick, Head of Policy (Research and Innovation)

Additional support
Karen Newman, Design and Brand Manager
Dame Julie Maxton, Executive Director
Archie Herrick, Policy Adviser
Kelly Smith, Senior Policy Adviser
Mia Kett, Senior Policy Adviser
Marcos Rodriguez, Senior Research Analyst
Bill Hartnett, Director of Communications
Molly Lowe, Press Officer
Katie Osborne, Former Press Officer
Jamie Upton, Senior Public Engagement Officer
Kimberley Freeman, Head of Public Engagement

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For further information
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6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
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