BBC **FROM THE BIG BANG TO TODAY: A COSMIC ERAS TOUR**

#239 APRIL 2025

Sky at Night

THE UK'S BEST-SELLING ASTRONOMY MAGAZINE

GALAXY SEASON

Explore the treasure trove of star systems that lie in spring skies

PLUS
Where black holes come from and how we see them

NEW WAYS TO VIEW THE SUN AT PEAK ACTIVITY

MANUFACTURING IN SPACE: MAKING THE FUTURE NOW

DWARF 3 SMART SCOPE: NEW FEATURES TESTED

HIDDEN OCEANS, ALIEN LIFE: INSIDE THE ICY MOONS

WATCH THE CRESCENT MOON JOIN THE SEVEN SISTERS

Space factories

from science fiction to reality

Not too long ago, the space economy was a government endeavour. But, as **Ben Evans** reports, commercial players are rapidly changing what the future looks like for industry in space – with far-reaching consequences

One October day in 1969, Soviet cosmonauts Georgi Shonin and Valeri Kubasov attempted in-space manufacturing for the first time. They closed the hatch to the orbital module of their Soyuz 6 spacecraft, retreated to the descent module and activated a vacuum-welding furnace for a series of autonomous tests. What happened next could have killed them both.

Three months after Neil Armstrong and Buzz Aldrin walked on the Moon, a dispirited yet resurgent Soviet Union realigned its efforts to building Earth-circling space stations. Cosmonauts would no longer simply visit space, but live there. And that meant assembling huge off-world structures, fixing or strengthening components weakened by long-term exposure to the low-gravity, high-vacuum and high-radiation environment in Earth orbit.

Aboard Soyuz 6 was a squat green cylinder the size of a small household refrigerator. Weighing 110lb (50kg), the 'Vulcan' furnace included a low-pressure compressed plasma arc, a consumable electrode and an electron beam. It would weld pieces of aluminium alloy, titanium and stainless steel on a tiny turntable.

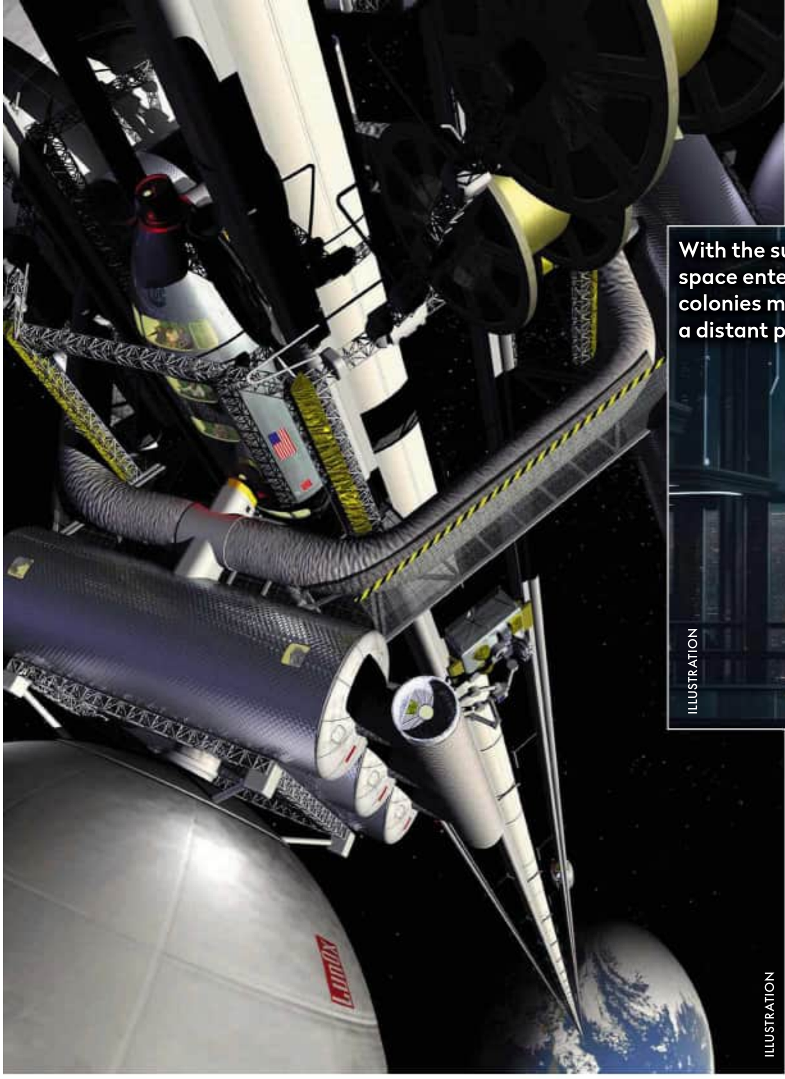
The experiment took place six hours before Soyuz 6 landed. After an automated trial run, Kubasov reopened the descent module's hatch for a manual test – and was shocked by what he saw. Vulcan had melted the metal samples… and the turntable… and part of the orbital module's floor… and then started firing its electron beam directly onto the spacecraft's hull.

Fearing an imminent decompression, the horrified cosmonauts gathered their samples, shut the hatch and returned to Earth. Not until 1990 and improved détente with the West did the full story emerge. But in the secretive days of the Cold War, the Soviets remained stonily silent, Kubasov noting darkly that Vulcan might prove useful "in emergencies" – ironic words, for Soyuz 6's 'emergency' was caused by the furnace itself.

Manufacturing beyond Earth

Today, the concept of in-space manufacturing (ISM) has expanded to entail fabricating, assembling and integrating tangible goods beyond Earth. It involves transforming raw or recycled materials into components, products or infrastructure by human or robotic manufacturing. There are three ▶

Factories built from space dirt on an asteroid being mined for its multi-trillion-dollar bounty – just one of the visions spurring on a raft of new private space companies



▲ **Space elevators or star ladders have long been a sci-fi trope for overcoming the sticky – and expensive – problem of leaving Earth**

With the surge in commercial space enterprises, off-world colonies may not be such a distant prospect

▶ types: ISM-for-Earth (goods with improved properties made in space to benefit people on Earth), ISM-for-space (goods made for use in space) and ISM-for-surface (goods produced on the surfaces of other celestial bodies).

Assembling huge space structures has been the stuff of science fiction for decades. Think vast space colonies housing millions of people in near Earth-like conditions; supertall space elevators hoisting cargo out of our planet's strong gravitational well into orbit at a mere fraction of current costs; mining precious minerals from asteroids or gigantic solar array 'farms' gathering sunlight, then beaming down energy via microwaves to satisfy our insatiable power needs.

Manufacturing in space, rather than prefabricating hardware on Earth to assemble it in orbit, allows for greater design flexibility, empowering engineers to think big, unencumbered by the need to squeeze hardware inside narrow rocket payload fairings or meet strict weight limits. But escaping Earth's gravity is notoriously difficult and prohibitively costly – so much so that until recently, ISM advances were impossible to 'scale' commercially.

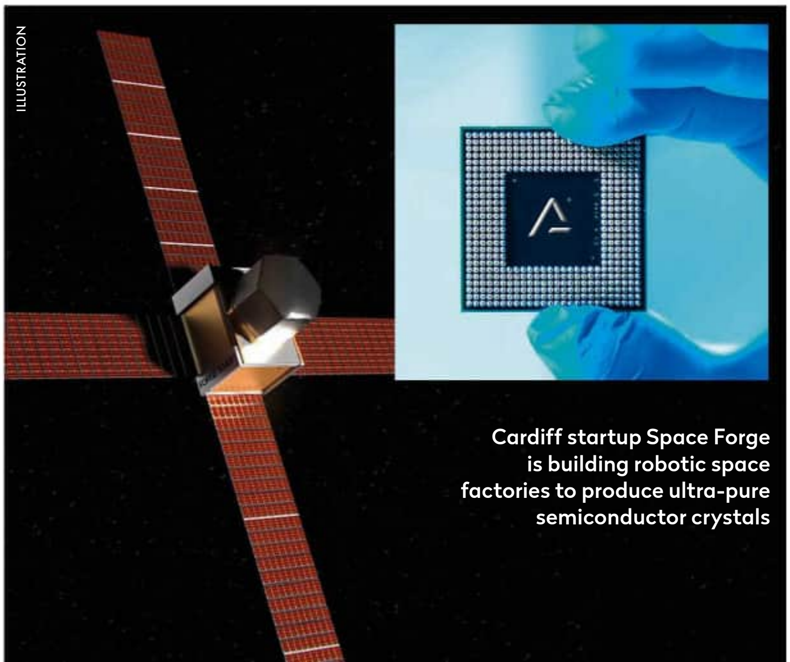
For decades, ISM occurred solely at the research level. Microgravity allows the production of high-quality semiconductors, pharmaceuticals and super-strong alloys with fewer of the terrestrial defects induced by gravity-driven buoyancy, convection and sedimentation. Materials can be melted, mixed and resolidified for a raft of Earthly benefits, including high-efficiency solar cells, superfast computer chips, microwave circuits, artificial human retinas, infrared sensors and improved medications.

The levels of perfection attainable in space's near-total vacuum may also produce better industrial practices and new alloys for making tinfoil or jet engines, aiding metal casting and welding. 'Containerless' processing – in which fluids and solids are manipulated at atomic levels, with acoustic or electromagnetic forces, to mitigate contamination caused by the walls of their containers – has yielded heightened levels of purity.

Commercial growth

But the space-launch landscape has now shifted, with the arrival of commercial players like Elon Musk's SpaceX and Jeff Bezos's Blue Origin. Today, there are more streamlined regulatory frameworks too, and more flexible, low-cost spacecraft platforms, including Rocket Lab's Pioneer, D-Orbit's ION Satellite Carrier and Momentus Space's Vigoride.

All that has spurred the growth of several startup firms keen to capitalise on emerging ISM commerce. Cardiff-headquartered Space Forge Ltd and its US subsidiary, Space Forge Inc, are developing free-flying facilities to make ultra-pure semiconductors in bulk for advanced computer chips, hopeful of snaring a niche in an industry projected to be worth $1 trillion in the next decade.



Cardiff startup Space Forge is building robotic space factories to produce ultra-pure semiconductor crystals

SCIENCE HISTORY IMAGES/ALAMY STOCK PHOTO, W.S. CODA/ALAMY STOCK PHOTO, SPACE FORGE X 2, BLUE ORIGIN, VARDA X 2

A planet for life alone?

The billionaire founder of Amazon and Blue Origin has a vision of the space economy's benefits to Earth

Despite Blue Origin founder Jeff Bezos's hope that all polluting industries will someday transition into space, where they'll be unable to damage Earth's biosphere, even he acquiesces the process will take many decades, if not centuries to achieve.

"In at least a few hundred years... all of our heavy industry will be moved off-planet," Bezos has said. "Earth will be zoned residential and light industrial. You shouldn't be doing any heavy energy on Earth."

Bezos envisages a future where computer chips are fabricated in colossal orbital factories and solar array farms produce energy 24/7, beaming it down to Earth; where the hugely polluting exploitation of raw materials – including precious minerals and metals of high-value worth – is moved to places where there is no ecosystem to destroy, like the Moon.

▲ Earth could be shielded from heavy industry, says Jeff Bezos

Blue Origin has taken steps to drive down the cost of reaching space with its passenger-carrying New Shepard suborbital booster, which has flown 28 times since 2015. And its gigantic New Glenn rocket, first launched in January 2025, features cleaner-burning propellants of liquified methane and can be reused for at least 25 missions.

The steps taken today by Blue Origin and others remain baby steps, and Bezos's vision of industry in deep space will doubtless not occur in our lifetimes. But reusability is a step in the right direction for making space more accessible for innovation to thrive.

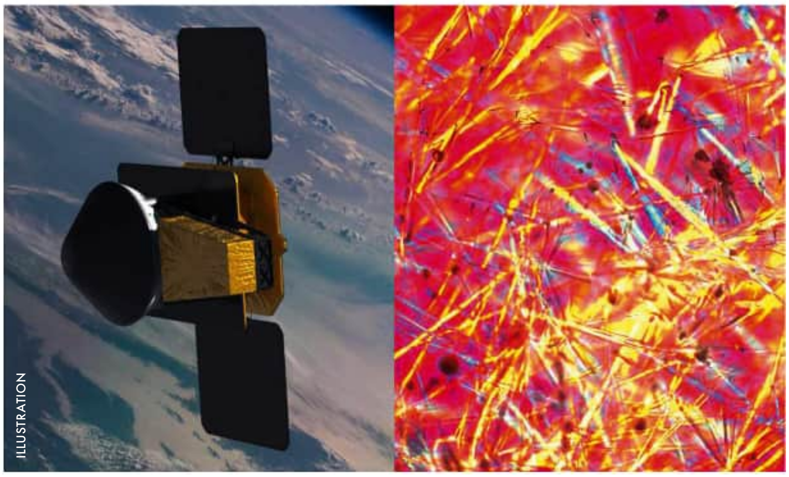
New Glenn, reusable and using cleaner propellant, is key to Bezos's vision

And California-based Varda Space is tapping into high-value pharmaceutical, fibre-optic and semiconductor markets. Its first mission – W-1, which Varda called a 'space factory' – launched in June 2023, growing crystals of the antiretroviral drug ritonavir and returning them to Earth in February 2024. Rocket Lab has built four Pioneer spacecraft for Varda's missions, the second of which launched in January 2025.

Future ISM applications include extracting precious minerals from other celestial bodies, lessening the impact of mining and better safeguarding our planet's finite natural resources. Current environmental constraints (including carbon-emission limits) could accelerate the transition of highly polluting heavy industries to destinations far beyond Earth. And that might facilitate sustained growth and offset social and environmental costs as those industries move elsewhere.

Lunar mining potential

The Moon is one such destination which could see more ISM in future decades. It is close enough to Earth to be reachable in a few days, but its low gravity, absence of an atmosphere and lack of an ecosystem leave it ripe for industrial exploitation. Viable enterprises in the future could include mining water-ice and hydrated minerals for life-support and propulsion systems, as well as extracting



▲ **Varda Space crystallised the antiviral drug ritonavir in its W-1 space factory**

anorthosite from the lunar highlands to smelt for aluminium, silica to make glass and iron for stronger, more lightweight alloys.

There are also plentiful reserves of helium-3 on the Moon, which creates a potential pathway to efficient nuclear fusion. With possibly 50 parts per billion of helium-3 in its permanently shadowed lunar craters, compared to 7.2 parts per trillion in Earth's atmosphere, the Moon may have enough to satiate our planet's energy needs for thousands of years. But extracting it will be laborious – 150 tonnes of lunar soil would need to be excavated to retrieve a single gram of helium-3. ▶

Cement, water and Moon soil could be combined to build habitats and launch pads on the lunar surface

▶ Despite these potential difficulties, in March 2024 the US startup firm Interlune unveiled its plans to commercially mine lunar helium-3 and return it to Earth for use in national security, quantum computing, medical energy and nuclear fusion markets.

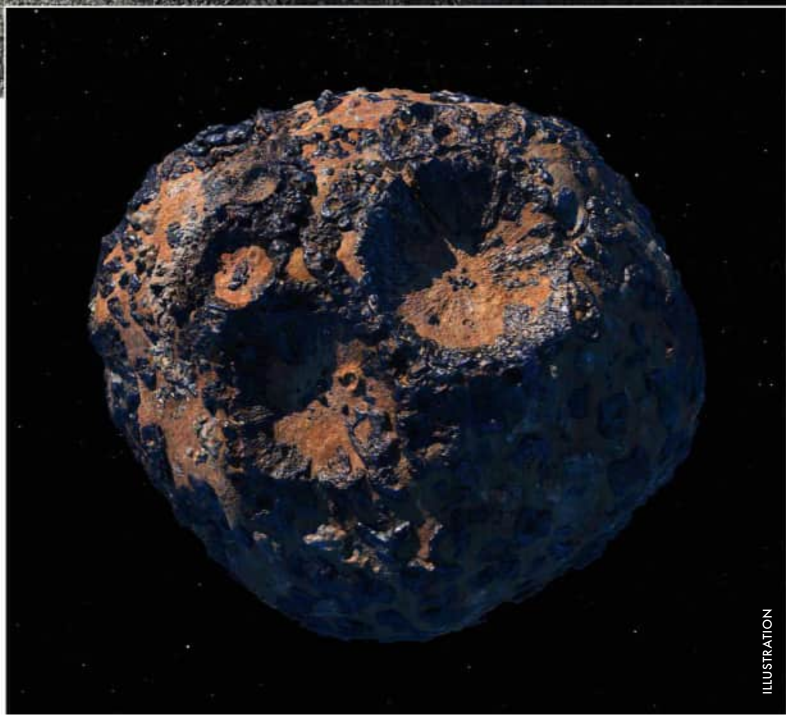
Rich pickings are also afforded by carbonaceous asteroids. Asteroid 511 Davida, for example, is estimated to possess $27 quadrillion in precious minerals, while the metal-rich 16 Psyche might have enough nickel-iron to supply industrial demands for several million years. And the Earth-crossing asteroid 3554 Amun could contain 30 times more metal than has ever been mined in human existence, with a purported 'value' in excess of $20 trillion.

In addition to valuable metals such as nickel, cobalt, gold and platinum, asteroids also provide a wealth of other volatile materials, useful for manufacturing fuels, fertilisers, water and oxygen for sustainable deep-space exploration. But capitalising on this seemingly limitless extraterrestrial bounty could prove its own showstopper – possibly producing a post-scarcity economy for many previously 'precious' minerals, but also flooding Earth's commodity markets so rapidly as to quickly make itself hideously unprofitable.

Living off the land

With an expectation that humans will soon return to the Moon, what's termed In-Situ Resource Utilisation (ISRU) – 'living off the land' – is imperative if future spacefaring communities are to attain self-sufficiency and independence from Earth. Lunar soil (regolith) is corrosive, highly abrasive and harmful to mechanical parts, but could be put to use as a general building material for foundations, habitats, hangars, roads and launch pads.

It can be employed to make 'concrete' (with normal cement and water, plus regolith as the aggregate) and its properties include high durability, resistance both to harmful gamma rays and to prolonged



▲ **The metal-rich 220km-wide (140-mile) asteroid Psyche is prime drilling territory**

exposure to near-total vacuum, and an ability to withstand sweeping temperature extremes on the Moon's radiation-drenched surface from 120°C (250°F) in direct sunlight to –150°C (–240°F) during the frigid lunar night.

In 2023, Blue Origin and Florida-based Redwire Corp began prototyping ISM technologies for NASA to build lunar infrastructure with materials from the Moon. Redwire will heat and solidify regolith using microwave emitters, while Blue Origin's Blue Alchemist process will make solar cells and transmission wires directly from regolith – extracting iron, silicon and aluminium at temperatures of 1,600°C (2,900°F) to attain purities better than 99.999 per cent, then depositing metallic contacts to fabricate high-efficiency power-generating arrays.

Redwire launched a 3D-printed lunar regolith 'simulant' to the International Space Station (ISS) in August 2021. Last year, astronauts

ESA/FOSTER + PARTNERS, NASA/JPL-CALTECH/ASU, NASA X 2, ESA/NASA

NASA's Butch Wilmore with a 3D-printed wrench created on board the International Space Station

More esoterically, the 3D-printed artwork capturing a human laugh

successfully mixed and cured the simulant to examine its behaviour, microstructure and mechanical strength.

The orbiting testbed

Indeed, 3D printing as an ISM tool is not new. In November 2014, Florida-based Made in Space Inc, trialled a 3D printer on the ISS for the first time, allowing astronaut Barry 'Butch' Wilmore to manufacture an 11.4cm (4.48-inch) ratchet wrench. Future 3D printing is expected to enhance mission success and improve safety, facilitate in-situ repairs, enhance astronauts' self-sufficiency and reduce the dependency on resupply missions from Earth.

Since then, other 3D printers have arrived at the ISS which have printed engineered plastics and successfully produced antenna parts and adaptors for air outlets. In 2017, the first piece of sculpted artwork, a 3D model of the soundwave of a human laugh, was printed on the ISS. And in January 2024, the European Space Agency (ESA) delivered a metal 3D printer to the station to print small metallic parts.

In 2023, Redwire's Pharmaceutical In-Space Laboratory Biocrystal Optimisation Experiment (PIL-BOX) launched to the ISS to manufacture pharmaceuticals for antiviral, antifungal and antiseizure uses. It grew high-purity insulin crystals and materials to combat rheumatoid arthritis, multiple myeloma and breast and prostate cancers.

Since 2019, the ISS's BioFabrication Facility (BFF) has used 'bioinks' – composed entirely of live human cells and nutrients – to print entire human organs. This included a partial human knee meniscus in 2023 for a US military research project and, last year, the first live human heart tissue sample, with bioprinting of human blood vessels expected to follow.

Made in Space Inc and Washington-headquartered Tethers Unlimited Inc have also provided recycling equipment to the ISS since 2018, repurposing used polymer materials into new filament for 3D-printing feedstock. In 2020, the printing of temperature-resistant reinforced ceramics was evaluated for the first time. Historically, 3,200kg (7,000lb) of spare parts are transported from Earth to the ISS annually – a process acceptable in low-Earth orbit but far less feasible for deep-space missions.

▲ **The ISS's new metal 3D printer is a step towards manufacturing tools and parts in space**

And when humans reach Mars, ISM will be critical to astronauts' self-sufficiency. NASA's Perseverance rover, which landed in Jezero Crater in February 2021, carried an experiment to extract carbon dioxide from the Red Planet's thin atmosphere and produce oxygen. The MOXIE experiment generated about 12g (0.4oz) of oxygen per hour at 98 per cent purity, considered higher than NASA's pre-flight predictions.

The costs, complexities and challenges of making ISM commonplace are immense. But it is difficult not to see the potential a century or two from now, and to let the mind drift for a moment to visualise the possibilities: bustling colonies built entirely in space, mining on the Moon and elsewhere, a post-scarcity economy – and most importantly, our own Earth, restored to the green and bountiful planet as it should be.

Ben Evans is a science writer and the author of several books on spaceflight