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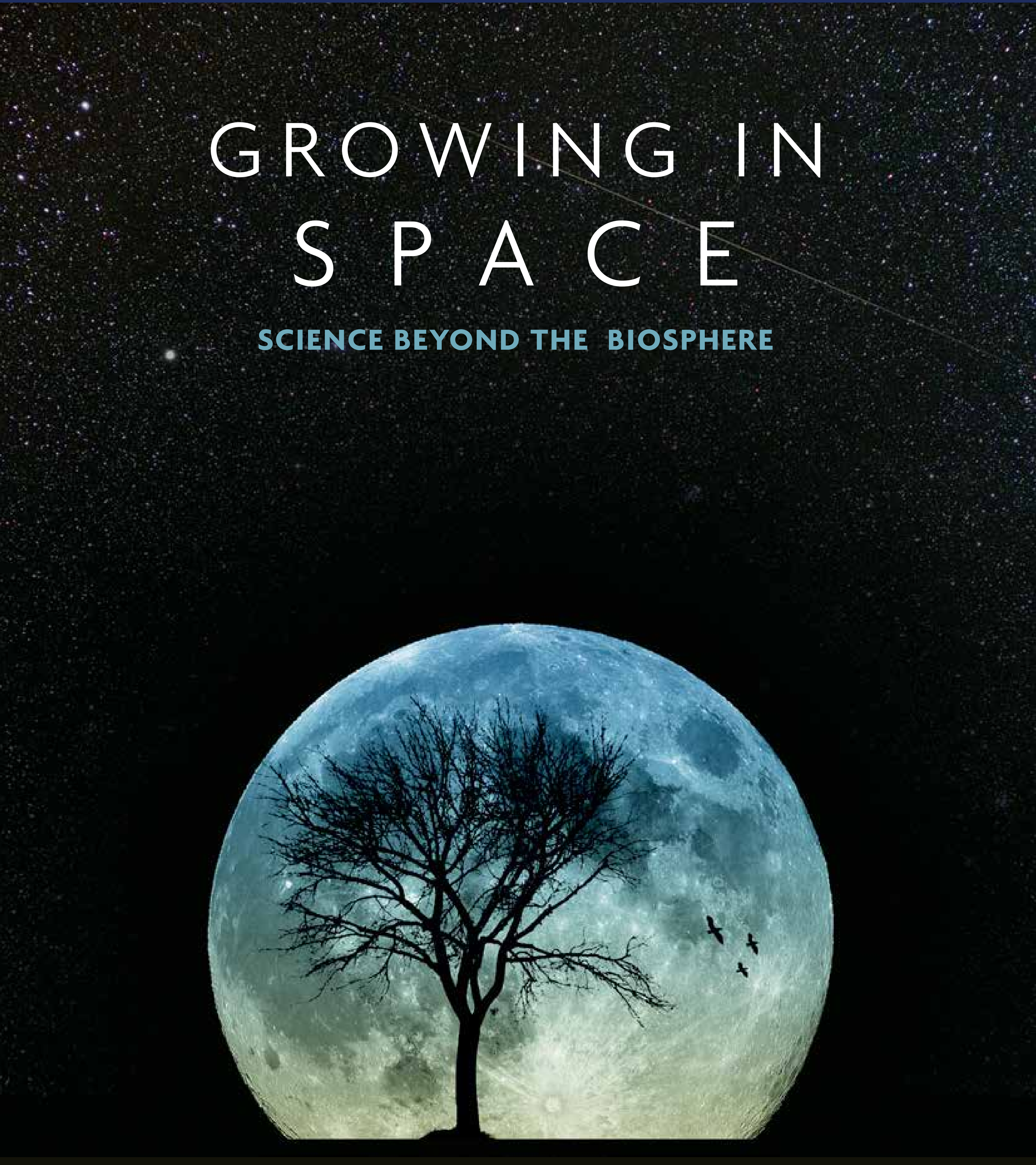

GROWING IN SPACE

SCIENCE BEYOND THE BIOSPHERE

EDITORIAL

What on Earth is Space science useful for?

From the moment humans began launching into Space, we have been turning our tools of exploration back towards the Earth itself. The first images taken by near-Space rockets in the 1940s were grainy black-and-white slivers, showing the curve of our planet's limb but little else. In the years since, these fleeting glimpses have been outshone by myriad modern images: full-colour Earths glittering in ever-higher relief against the black velvet of Space.

By now most of us are so familiar with the image of our world as a planet that it seems hard to believe that the release of the first pictures of Earth as a whole took years (and a lobbying campaign by Stewart Brand, complete with slogan badges). Certainly, the primary motivations for observing Earth from Space have been scientific – the careful study and monitoring of our planet have taught us a great deal about the processes that make our home world tick. More than anything, though, these iconic pictures of Earth serve the central cultural role of reminding us that we are a tiny, hospitable island, adrift in the grandeur of Space. Like the dizzying vistas of our deep universe captured by the Hubble Space Telescope, these images are fundamentally someone's data— and yet, they are also something more.

Today, we face the emerging truth that we are but one of billions of terrestrial planets in our Galaxy. Over just the past few years, NASA's *Kepler* spacecraft has found over a thousand new planets orbiting other stars, revealing that our skies teem with as-yet undiscovered worlds. We do not yet know whether any of these planets provide alternate oases for life beyond our own planet, but new telescopes coming online will begin to provide clues within the coming decade. Some existing projects even dovetail directly with Earth observations: the EPOXI mission, designed to study planets around other stars, looked back at the Earth–Moon system as a means of providing a direct comparison with these more distant worlds. In capturing the glint of sunshine off the oceans of our own home planet, EPOXI also caught a glimmer of a future where we are can compare these new planets with our Earth.

With these discoveries, a far less grand picture of Earth comes to mind: the "pale blue dot" image taken in 1990 by the *Voyager* spacecraft as it sped out of our Solar System. On this single pixel, as Carl Sagan eloquently stated, "everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives". In our Space-faring future, it is imperative that we preserve the home world that has fostered the developments that led us this far – the habitable gem that will always be our best platform for exploring the cosmos.

Dr. Lucianne Walkowicz is an Astronomer at the Adler Planetarium in Chicago, where she studies stellar magnetic activity and how stars influence a planet's suitability as a host for alien life. She is also an artist and works in a variety of media, from oil paint to sound. http://tangledfields.com

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CONTENTS

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Is it time for a new perspective in environmental science?

Environmental scientists have helped to shape people's relationship with nature. **Adam Donnan** wonders whether we have a further role in determining our relationship with the cosmos.

NASA on the Commons

Environmental scientists and space enthusiasts may seem like uneasy bedfellows. Given the ongoing destruction of the atmosphere by relatively energy-light forms of transport, environmentalists may view with horror the ever-closer attempts to extended affordable Space travel from the domain of states and corporations to ordinary citizens. Others may see Space exploration as a waste of resources that should be spent on more pressing environmental challenges at home.

However, the birth of the environmental movement can arguably be traced back to the pictures, brought back by *Apollo 8*, of Earth set against the void in all its colourful fragility. Nature photographer Galen Rowell declared the 1968 picture of Earthrise as "the most influential environmental photograph ever taken"[1]. The picture had a profound effect on the collective human psyche, sparking a realisation of the delicateness of our living environment and its finite nature. This is called the 'overview effect', a term coined in 1987 by Frank White[2], although the sentiment has a much longer history, with Socrates allegedly saying, "Humanity must rise above the earth, to the top of the atmosphere and beyond. For only then will we understand the world in which we live"[3].

Subsequent endeavours in Space have established an extensive satellite network used to observe the Earth's surface, atmosphere and vegetation, providing vast amounts of data about our planet. This has radically transformed environmental science by greatly increasing the amount of data available for analysis and, in many cases, reducing the financial cost of its collection.

> **"I've often heard people say: 'I wonder what it would feel like to be on board a spaceship,' and the answer is very simple. What does it feel like? That's all we have ever experienced. We are all astronauts on a little spaceship called Earth."**
> *Buckminster Fuller (2008)*[4]

The difficulties of Space travel focus human endeavour on minimising resource use, recycling, and maintaining the balance of atmospheric gases, air quality and water supply. Scarcity in Space provides a far greater discipline than the plenitude on Earth. The sandbox of the spacecraft may one day become the planetary ethos of Buckminster Fuller's Spaceship Earth.

▲ **Figure 1. Nile river delta at night, seen from space (NASA, Creative Commons[8])**

> **“The sandbox of the spacecraft may one day become the planetary ethos of Buckminster Fuller’s Spaceship Earth.”**

Studying the more extreme Earth environments, such as underwater volcanoes, may also assist us in studying other planets. Charles Cockell, Professor of Astrobiology in at the University of Edinburgh, has even called for the merger of environmental and Space disciplines, as he believes each shares the same objective: “creating sustainable communities in the cosmos – whether they are on Earth or on any other planet”[5].

BOX 1: JAMES LOVELOCK

In 1961, Lovelock, whilst employed as a consultant with NASA to analyse alien atmospheres, began thinking about the Earth from the perspective of an extra-terrestrial. He noted that Earth is “a planet with apparently the strange property of keeping itself always a fit and comfortable place for living things to inhabit. I had an idea that somehow this property was not an accident of its position in the Solar System but was a consequence of life on its surface”[6]. This led him to formulate an explanation of an Earth that had been transfigured and transformed by a self-evolving and self-regulating living system. As Lovelock explains, the idea of Gaia came to him when he shared the view of the Earth of the *Apollo* astronauts: “Suddenly, as a revelation, I saw the Earth as a living planet”[7].

Lovelock notes the powerful effect that Space had on his environmental thinking, pointing out that he differed from his scientific colleagues because “the view from Space let me see the Earth from the top down, not in the usual reductionist way from the bottom up”[6].

SPACE’S EFFECT ON ENVIRONMENTAL SCIENCE

A number of the most influential voices within environmental science were profoundly affected by their work connected to Space observation. Most notably, James Lovelock (see **Box 1**), who developed the Gaia theory as a direct result of the observation of the gas compositions of the atmosphere of other planets, and James Hansen (see **Box 2**) – considered the father of global awareness of climate change – who spent a large part of his career at NASA.

BOX 2: JAMES HANSEN

James Hansen is a world-renowned climate scientist, and currently an adjunct professor at Columbia University in the USA. He is best known for his research in climatology and his role in spreading awareness of global warming and its adverse effects.

Hansen began his career studying Venus, but as concern arose in the 1970s about the effects of human emissions of greenhouse gases, he began looking at the Earth’s sensitivity to them, fearing that Earth might suffer a similar fate to Venus. Hansen was the head of the NASA Goddard Institute for Space Studies for over 30 years. Its main role has been to make predictions about climate change in the 21st century, based on a historical analysis of the Earth’s paleoclimate as well as sea level, carbon dioxide and temperature records. After 46 years as NASA’s chief climatologist, Hansen left to pursue climate activism.

ENVIRONMENTALISM MUST FOLLOW US TO THE STARS

The unimaginably vast and inhospitable nature of Space and the unsuitability of other planets to harbour life may make humanity value our fragile oasis more. Charles Cockell imagines a future “Space-faring environmental ethic” that has fed back to “the people of the Earth [so we will] walk through a forest or park and see everything around us as a unique form of life in the universe”[5]. The stories told by astronauts support this idea: they often focus more on the experience of gazing in wonder back at life-bearing Earth rather than out to the unexplored stars.

Our relationship with Space is not only about seeing the Earth from Space, but also seeing it *in* Space. Much as environmental science helped us to recognise that humans are part of, and not separate from, a wider ecosystem, a new self-awareness is needed to recognise that we are in Space, whether we leave the planet or not. As our physical frontiers expand, our ethics may also need to adapt and evolve. For example, will the vast expanses of lifeless vacuum will lead to the adoption of a new interstellar environmental ethic where it is forgivable to dump waste in these zones?

Charles Cockell paints a picture of a day when “organisations dedicated solely to Space exploration or environmentalism will seem quite anachronistic in a civilisation that has transformed itself into the Space-faring guardians of a planetary oasis in Space”[5], food for thought for the next IES 50-year strategy! I hope this issue will convince readers that there is no need to reset environmental progress when we leave the Earth’s atmosphere. Environmental scientists have helped our progress on one planet in determining our relationship with nature – the challenge for the next century will be in helping to determine our relationship with the universe. **ES**

Adam Donnan has worked at the IES since 2006. In 2013 he was appointed as the organisation’s first CEO.

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Monitoring nature from space: what is so exciting about it?

Nathalie Pettorelli explains how satellite remote sensing can complement *in-situ* data collection.

Every day, conservation biologists around the world try to address the same daunting question: how do you reconcile human needs and the maintenance of biological diversity? With our planet gaining over 50 million people every year, human demands for natural resources and space are constantly growing. These demands have translated into increased habitat loss and degradation, pollution, overexploitation, greenhouse gas emissions and the spread of invasive species. Unsurprisingly, many species have struggled, and are still struggling, to adapt to these rapid environmental changes. The consequence is that we are in the process of losing what makes our world unique and so wonderful, namely the diversity of organisms that share it.

◀ **Figure 1. The Richat Structure (in Mauritania) from space. This image is a false-colour composite combining *Sentinel-1A* c-band radar and *Landsat 8* infrared bands. (Credit: Harry Owen)**

But do we need to care about diversity? Decades of scientific investigations have come to the same conclusion: diversity matters, a lot. Interestingly, whether we look at businesses or ecological systems, the statement holds – diversity is what makes us perform well, it is what makes us future proof:

- Diverse companies are more likely to have financial returns above their national industry medians;
- The richer the diversity of life, the greater the opportunity for medical discoveries, economic development and adaptive responses to new challenges, such as climate change; and
- Diversity is also what underpins evolution, in ecological and societal systems.

Put simply, diversity is a competitive advantage, whether we look at businesses, populations or ecosystems. So we cannot afford to lose more of the diversity of life on Earth, which means that we have to find solutions that allow us to meet human development goals while simultaneously ensuring that biodiversity is conserved.

CONSERVATION NEEDS DATA

Our ability to monitor the state of our planet and the impacts of human activity on its inhabitants and resources is fundamental to designing appropriate and optimised environmental management strategies. Biodiversity is yet far from being the easiest thing to monitor: the concept is defined by the Convention on Biological Diversity as "the variability among living organisms from all sources including diversity within species, between species and of ecosystems"[1]. This refers to different components (genetic, population/species, community/ecosystem) that each possess compositional, structural and functional attributes. These attributes can be considered as the three dimensions of biodiversity.

Aside from biodiversity being complex to monitor, the type of information needed is also not particularly easy to access. To rise to the challenges posed by global environmental change, the scientific community needs to be able to access global, long-term, reliable

▲ **Figure 2. Europe by night, as viewed by the NOAA *Suomi NPP* VIIRS (visible infrared imaging radiometer suite). (Credit: Harry Owen)**

information on spatio-temporal changes in the distribution of threats to biological diversity, and in the distribution, structure, composition, and functioning of ecosystems. Scientists also need evidence of the effectiveness of management actions.

THE ROLE OF SATELLITES

One way to address this huge data need relies on making use of all the information collected by satellites orbiting around our Earth. Not the ones that help with weather forecasts and mobile phones, but the ones that are continuously monitoring the global environment, and have done so for decades. Their diversity is ironically quite spectacular: some collect information about just how 'green' our world is on a fortnightly basis; some allow people to spot whales from space; some can help to map the distribution of particular tree species; some gather information about deforestation and forest regrowth. What these data can do is directly linked to the type of sensors on board those satellites: for example, sensors such as radar and lidar help us paint three-dimensional pictures of what is happening on the ground, and hyperspectral sensors can detect the biochemical fingerprint of certain plant species.

Satellite data offer many advantages to those ecologists who aim to understand how natural ecosystems work on a very limited budget: the information is repeatable, standardised, verifiable, and sometimes free. These data permit one to address questions on scales simply inaccessible to ground-based methods alone: detecting the greening of the Sahel in Africa, monitoring fire occurrence around the world, tracking the rate of coastal retreat in the Sundarbans in Bangladesh would simply be impossible without the help of this technology. Importantly, satellite data allow you in some cases to go back in time, as many of them started to collect information in the seventies and eighties: this makes it possible to quantify what we have lost where over the past decades, and potentially to identify why.

A real benefit of satellite data also lies in the variety of information about the distribution of biodiversity that can be accessed:

- The distribution of certain species can be mapped from space;
- Taxonomic diversity and community composition can be inferred from satellite information; and
- Changes in ecosystem structure (e.g., vegetation height) and function (e.g., photosynthetically active radiation) can be detected using satellite imagery.

In short, this technology facilitates the development of an integrated, multi-dimensional monitoring framework for biodiversity, whereby changes in the attributes of each component of biological diversity can be tracked for a single area at a given time.

UNDERSTANDING BIODIVERSITY LOSS

Satellites also capture information that helps us to understand why, and predict where, biological diversity is declining. For example, measurements taken on the ground can be integrated with satellite data to track the current distributions of certain invasive species to predict their projected advance. High-resolution images can be used to map problems associated with oil exploration and exploitation. The response of animals to shifts in temperatures or availability in food and resources can be analysed and predicted from satellite-based information. Land degradation and the fragmentation of ecosystems as well as the expansion of urban areas have all been successfully monitored using the unique viewpoint of satellites. There are some great examples of how satellites can support marine conservation – spotting and monitoring oil spills, and making it easier to detect illegal, undeclared or unreported fishing using satellite data together with the data from vessels' monitoring systems.

▲ **Figure 3. Mnazi Bay, Mozambique, as viewed by *Landsat 8*. (Credit: Clare Duncan)**

GAPS AND COSTS

Like all things in life, satellite data are not perfect, however: depending on their nature, data acquisition and manipulation can incur large costs, sometimes to the point of being prohibitive. Also, satellite data cannot match the accuracy, precision and thematic richness of *in-situ* measurement and monitoring. For them to fulfil their potential in environmental management, they need to be used in combination with local, ground-based information. Yet the integration of *in-situ* data, expert knowledge provided by local ecologists and the technical expertise of remote sensing analysts remains limited. Opportunities to overcome these challenges have never been greater though, and collaborative work that brings together these is starting to become more common.

These are exciting times for anyone interested in large-scale biodiversity monitoring and environmental management: from camera traps and microphone arrays to guided drones and Doppler radar, new technological developments are constantly expanding opportunities to learn about our planet, and to make more-informed decisions about how to manage it. Yet these opportunities require from us to engage with new people, outside our field of expertise, and to develop a common language and coordinated agenda. They force us to interact with new concepts, new software, new data formats. They push us outside our comfort zone. This is not easy, and may not be immediately rewarding to the individuals who embark on this adventure.

At the same time, such a step is critical to broadening the scope for remote sensing technology to support wildlife and environmental management. Resources to smooth the journey are increasingly being made available, and the number of platforms supporting interdisciplinary collaboration is on the rise. Efforts are also being made to facilitate the use of satellite data by managers: initiatives such as the Digital Observatory for Protected Areas (DOPA) demonstrate that the implementation of a global, satellite-based biodiversity monitoring framework aiming to assess, monitor and forecast the state of, and pressures on, protected areas is within reach.

Dr Nathalie Pettorelli is a Fellow at the Institute of Zoology, Zoological Society of London. Her research is about assessing and predicting the impacts of global environmental change on biodiversity and ecosystem services.

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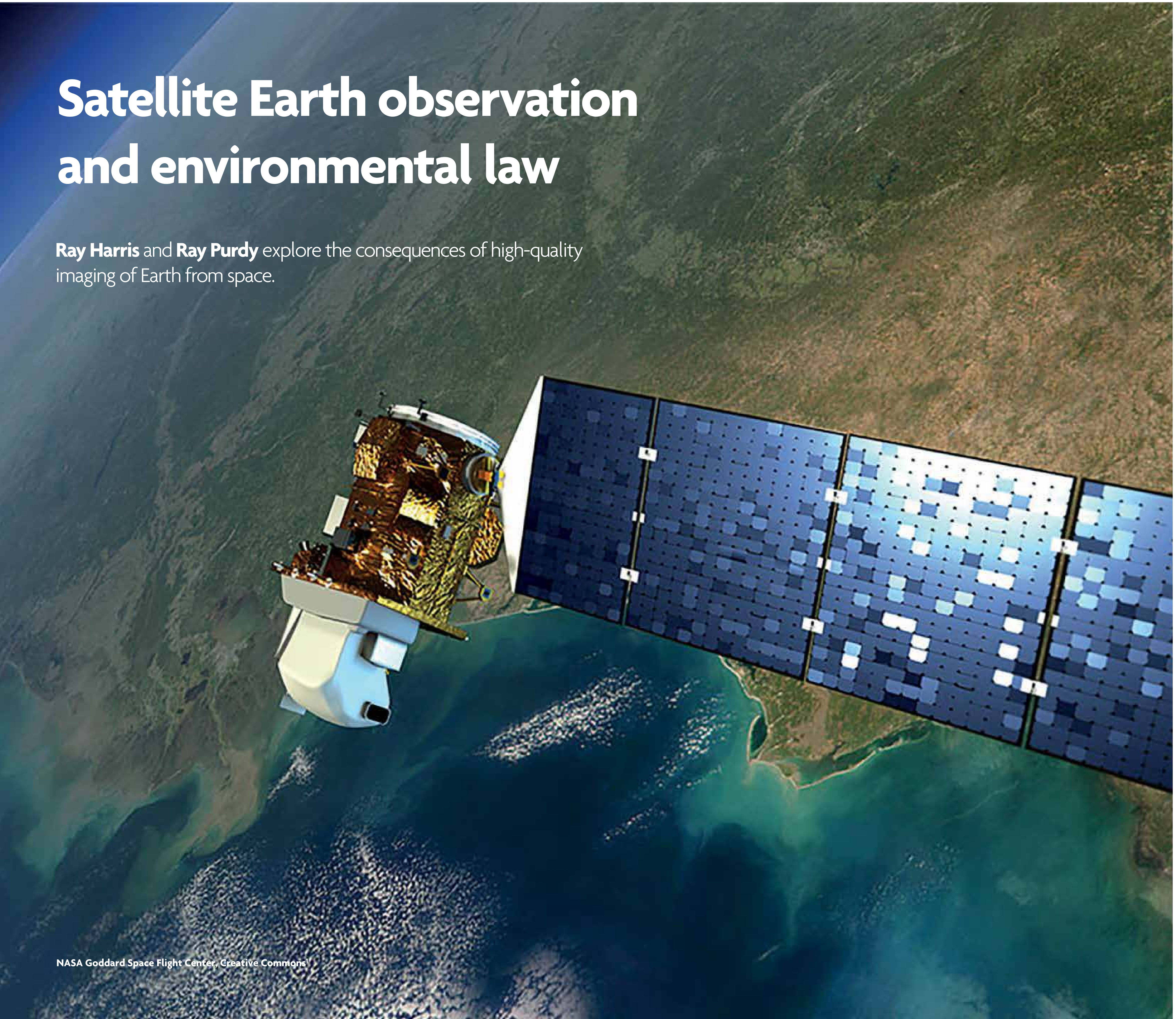
Satellite Earth observation and environmental law

Ray Harris and **Ray Purdy** explore the consequences of high-quality imaging of Earth from space.



NASA Goddard Space Flight Center, Creative Commons[1]

The first satellite dedicated to observing the Earth's environment was launched in the USA in April 1960. It was called *Tiros-1* and it was a weather satellite dedicated to imaging the cloud patterns of the globe as a contribution to improved analyses in meteorology. The decade of the 1960s saw improvements in the capabilities of a series of weather satellites launched by the USA and by the (then) USSR. In 1972, the USA launched the first satellite dedicated to imaging the land surface of the Earth. The satellite was called *Landsat-1*, and it was the start of the massive growth in the number of Earth observation (EO) satellites and in our capability to image and therefore to monitor all parts of our planet from space.[1] Immediately after the launch of *Landsat-1*, many environmental applications were developed that explored the use of the image data in (amongst other topics) deforestation, agricultural change, coastal pollution and urban growth assessments.

Many countries now have their own EO satellites in orbit, for example France, Canada, Japan, Argentina, Brazil, Nigeria and China. The Committee on Earth Observation Satellites (CEOS) lists over 150 EO satellites currently in orbit[2]. Many countries have collaborated on the development of environmental applications of EO data, and the most prominent collaboration organisation is the Group on Earth Observations (GEO), which has 100 country and institutional members. GEO concentrates its work on deriving benefits to society from the many and diverse investments in satellite EO, with a focus on the following nine subject areas.

- Agriculture
- Climate
- Ecosystems
- Health
- Weather
- Biodiversity
- Disasters
- Energy
- Water

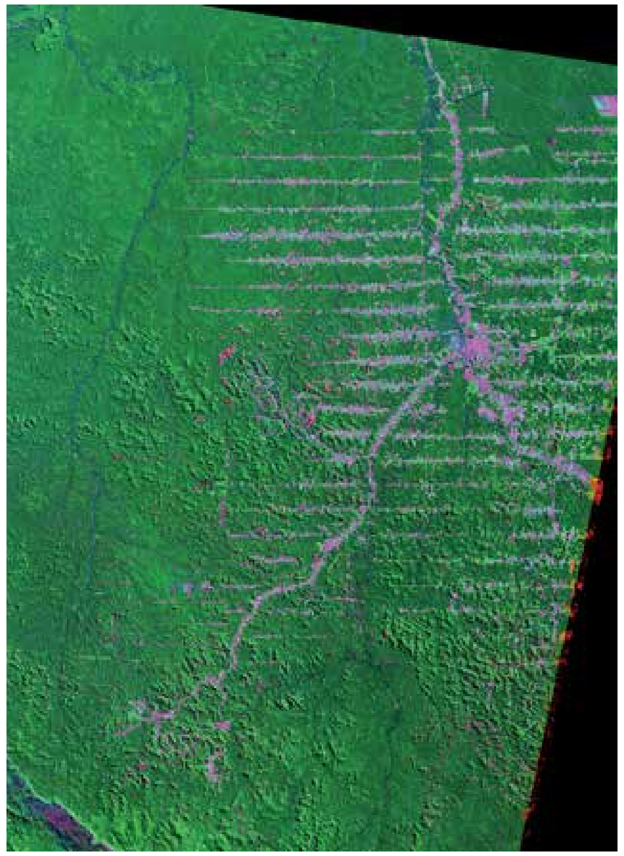
One key requirement of GEO is that its members, which are mainly national governments, commit to accepting the GEO data policy, which requires full and open exchange of data at the lowest possible cost[3].

EO APPLICATIONS

Satellite EO data have mainly been used in environmental science or related subjects such as disaster management. Several application areas have been able to become more operational in nature, for example agriculture monitoring. But fewer applications have been formalised to apply in legal situations. This article briefly presents some case studies and examples of where EO data have been used in the monitoring or enforcement of compliance with environmental law, and explores the potential for improving the enforcement of environmental legislation. The major change in satellite EO that has improved the use of the image data for environmental law enforcement has been in the improvements in spatial resolution – the size of the pixels in an image as represented as a ground

▼ Table 1. The reduction in the smallest pixel size offered by Earth observation (EO) satellites since the 1970s.

Years	Pixel size (metres)
1970s	79
1980s	30
1990s	10
2000	1
2001	0.6
2007	0.5
2015	0.3



▲ Figure 1. *Landsat 5* image of the Rondonia region of Brazil, 16 July 1986. The horizontal pattern in the right of the image has been created by the systematic, linear deforestation of part of the Amazon rainforest.

measurement. *Landsat-1* had a pixel size of 79 m, which is useful for monitoring large areas such as tropical rainforests. Brazil, for example, has used *Landsat* data for many years to identify illegal logging in the Amazon rainforest (see **Figure 1**). Since 1972 the smallest pixel size offered by EO satellites has reduced, and **Table 1** shows the change in pixel size from the 79 m of *Landsat-1* to the present day with a smallest pixel size of 0.3 m from the DigitalGlobe *WorldView-3* satellite. **Figure 2** shows an example of *WorldView-3* imagery to illustrate the level of detail that is now possible from space.

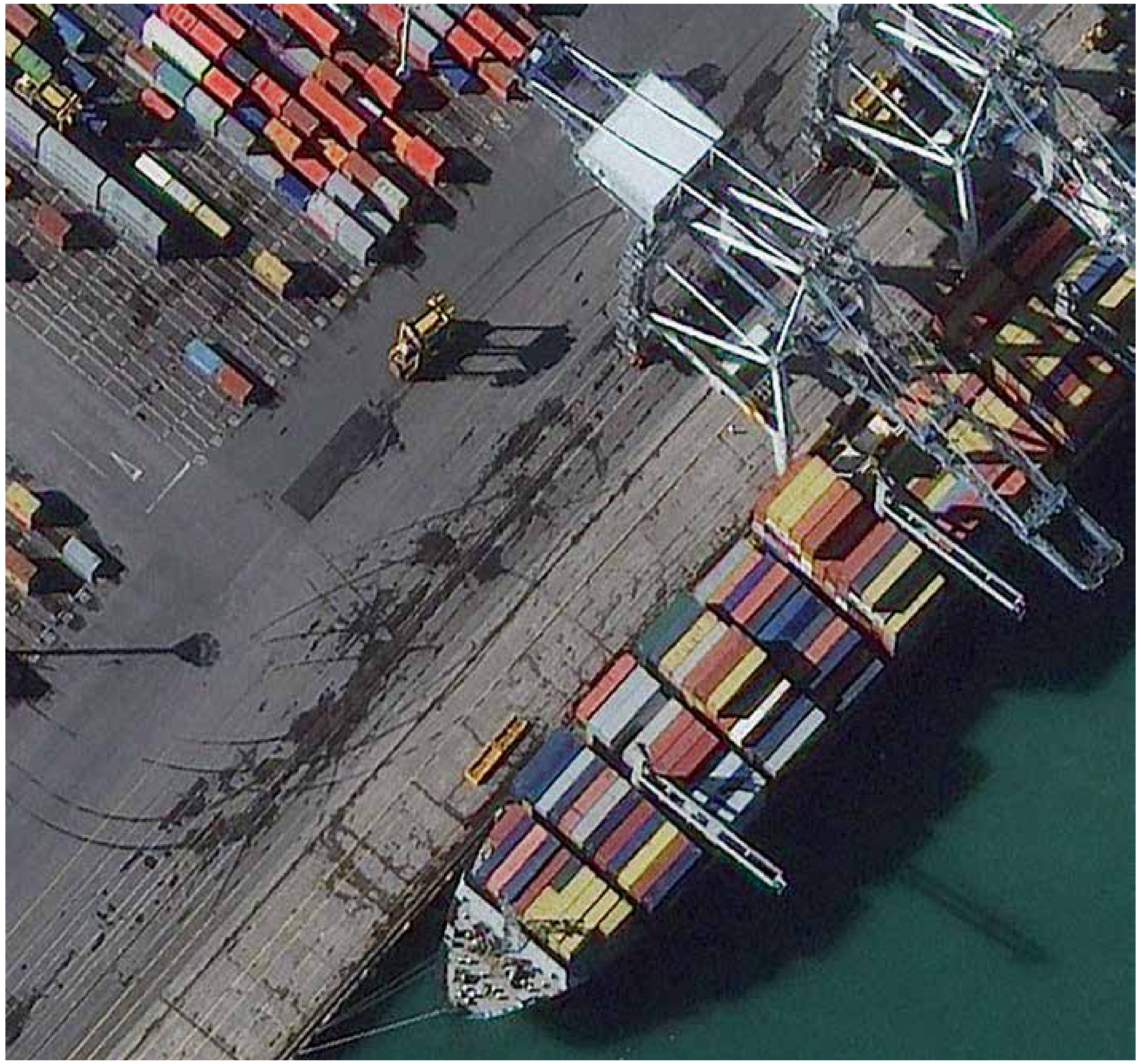
With a pixel size of 0.3 m, satellite EO images are now comparable to aerial photography. The difference is that while aerial photography coverage is constrained by the air law in each country, there is no legal restriction on the locations on the planet where satellite images can be collected from. The closest we have to legislation controlling imaging from space are the United Nations Principles on Remote Sensing agreed in 1986[3]. These principles are guidelines for access to EO data and are not legally binding.

As well as improvements to spatial resolution, other technical improvements in satellite EO have included the use of radar (which enables image data of the surface to be collected during both day and night and even in the presence of cloud), and the use of thermal infrared sensors (that show temperature changes at the surface of the Earth). These and other technical developments plus example applications are summarised in literature such as *The SAGE Handbook of Remote Sensing*[5] and the *Encyclopaedia of Remote Sensing*[6].

There has been growing recognition across the world that satellite EO successfully provides information for evidence-based policy decisions concerning environmental conditions. For example, satellite studies have demonstrated the rate of melting ice caps and the impact these are having on rising sea levels. However, this has more relevance to general environmental monitoring rather than legal enforcement strategies. There is a broad range of opportunities in the field of environmental law that satellite EO can potentially offer, and two specific uses will be discussed below.

TARGETED ENFORCEMENT

One application is that satellite EO can be used by regulators as part of a targeted enforcement strategy to monitor specific environmental laws. For example, in Australia, EO images have been used by several states over many years in an attempt to curb illegal deforestation associated with farming activities. Targeted satellite EO allows regulatory bodies to measure and compare the rates and extent of land clearance over time, alerting them to any suspicious behaviour that is taking place before conducting targeted ground inspections[7].



▲ Figure 2. A *WorldView-3* image of the commercial port in Auckland, New Zealand, showing containers being loaded on and off a container ship. (© 2015 DigitalGlobe, Inc.)

A similar form of targeted regulatory monitoring also exists in the agriculture sector in the European Union, where member states use satellites to monitor farm subsidy payments under agricultural cross compliance schemes. Satellite EO is successfully used to identify crops, determine correct areas of agricultural parcels, and check if claimants are complying with certain environmental conditions attached to subsidies. Both of these have been incorporated into the policing strategies of the relevant legislation, and satellite images have been directly used as evidence in courts. The deforestation and agricultural applications have probably been developed more quickly than other applications because satellite EO is a very cost-effective way of obtaining land cover information for large areas. Regulators have also used satellite EO to monitor legal compliance at smaller, high-risk sites. In a test case at UCL, we examined a real-life successful prosecution for operating an illegal scrapyard without a waste management licence. The offender was given a set period of time in which to comply with a court order to remove illegal vehicles from the scrapyard. We examined a satellite image taken after the date for compliance with the court order and not only did this show that the court order had not been complied with, but that the illegal activity might have actually intensified, as it appeared there were now more cars on the site[8].

▲ **Figure 3. An illegal landfill site. EO imagery archives can be of use to prosecutors demonstrating illegal activity in court. (© Volodymyr Shevchuk | Dreamstime)**

HISTORICAL EVIDENCE

A second important application for satellite EO is in providing historical evidence. A major benefit of satellite EO, and one that is unique in its scale and timing, is the fact that many images are saved to archives. Imagery collected by most commercial satellites can be archived in data banks and purchased from image suppliers by anyone. Systematic archiving of satellite images could in theory provide regulators or a court with a relatively impartial snapshot of a location in the past, providing accurate evidence that would often be otherwise unavailable.

In another test case, we examined a prosecution of an illegal landfill (a major criminal operation). At trial, the regulator stated that this offence had taken place over an eight-month period. An examination of archived imagery showed that the illegal landfill appeared to be ongoing for a much longer period of time – at least 20 months. This highlights the practical function of imagery archives for prosecuting authorities. If they had access to such imagery, then they might have used this in court to press for a harsher sentence.

The involvement of non-governmental organisations (NGOs) in environmental issues has dramatically increased in recent years. Aided by new methods of information gathering, they have become increasingly sophisticated in their methods of collecting evidence of wrongdoing to assist them in communicating their message. NGOs widely use satellite technologies to show evidence of human rights abuses in places such as Burma, Darfur and Zimbabwe. In the environmental domain there is growing interest in the use of archived satellite EO. For example, the Environmental Law Alliance Worldwide became aware of plans for the construction of a waste landfill site in the Philippines. The Alliance considered the site to be in an environmentally sensitive location because it was in a low-lying coastal area that was extensively covered with mangroves. The environmental examination report of the company that was proposing to create the landfill site made no mention of the loss of mangroves, so the Alliance used satellite images to provide evidence that an extensive canopy of mangroves would be illegally cleared if the landfill were constructed.

Insurance investigators charged a couple in New Orleans with insurance fraud after satellite images taken immediately after Hurricane Katrina revealed that the damage to their house actually occurred after the hurricane. Images were purchased after investigators considered that the damage did not look like other hurricane damage and appeared to be human-made. Evidence from satellite imagery was also used to prosecute the operators of an oil tanker that discharged 1,604,738 litres of slop oil in the Singapore Strait, after satellite radar images showed the origin and track of the oil pollution in the sea.

The general role of EO images in a legal context is to contribute to building the evidence base for prosecutions, ultimately for use in a court of law. The images are typically used to show environmental information such as vegetation quality and extent, ice extent, land surface height or deformation and the extent of water bodies. An important aspect of the view from space is that this information can be collected anywhere on the planet in pursuit of an environmental goal. Archive data are available and so it is possible to explore any one site over several years to examine whether environmental laws have been broken.

EO PROBLEMS

However, there are problems with using satellite EO data in practice. Much EO data are free of charge, such as all *Landsat* imagery and all data from the European Space Agency *Sentinel* missions. These data have a medium spatial resolution, with pixel sizes of 10–20 m. The best spatial resolution is, however, offered by companies in the commercial sector, such as DigitalGlobe. The pricing structure of these very-high-resolution data is confusing, but in general an image of a target area of 5 x 5 km costs around £400. The high-resolution satellites can also be tasked to acquire specific imagery, although this is at an added cost. Where there is extensive cloud cover then image data in the optical part of the electromagnetic spectrum cannot be collected; an alternative is the use of radar, which can penetrate cloud but which is difficult to interpret.

Satellite EO data is still immature as evidence, with different sensors and processing methodologies available for the same task. Since EO data is by nature digital/electronic, there might be concerns about authenticity and reliability in a court context. There could be questions, for example, as to whether an image could have been altered, in either a deliberately misleading or an accidental way. There are no developed national or international rules or standards in place as to the specific use of satellite imagery as evidence. Anyone wishing to introduce EO satellite data as evidence in court is required to anticipate evidential challenges and adopt procedures in advance; this includes audit trails and security.

Satellite images are different from other forms of surveillance because those being monitored in this way cannot tell when they are being watched. Knowledge of potential or actual surveillance from space appears to have had a strong influence on the compliance behaviour of those subject to regulation. Regulatory bodies could create the impression of a substantial capability and threat of enforcement with in reality only a very limited regulatory resource commitment. Our research has shown that a majority of those already subject to satellite monitoring checks thought that the checks were acting as a deterrent. When asked in surveys, some of those regulated in this way also massively over-estimated the true extent of the satellite monitoring programmes. For example, nearly half of British farmers thought that satellite checks were made of their land annually, when the true monitoring figure was closer to every twenty-three years[8].

EO DATA IN THE FUTURE

The use of satellite EO data in environmental law clearly has potential, both as an evidential tool and also as a deterrent tool, but its use is still at an early stage. Those working in the environmental law sector have had little or no awareness of what these new EO technologies can do. Generally, the success of introducing new forms of technology relies upon establishing a confidence base amongst those who might use it. Precedents will be needed as further evidence of effectiveness, reliability and cost. Once there are proven, cost-effective demonstration studies, it might not be too long before we see a more widespread adoption of EO technologies into legal and regulatory strategies in the environmental sector.

In the context of reduced budgets and questions over the adequacy of resources and public acceptability of new risk-based enforcement methods, there is a compelling argument that satellite EO could become an important tool in the future application of modern environmental laws. Its potential contribution in this area is likely to be increasingly recognised, especially if recent step-changes in the technology continue at such breathtaking pace and we see data prices fall to attractive levels. ES

Ray Harris is a Director of Air and Space Evidence Ltd and Emeritus Professor of Geography at University College London. He was Professor of Remote Sensing at UCL from 1995 to 2008. ray.harris@ucl.ac.uk.

Ray Purdy is a Director of Air and Space Evidence Ltd, Director of Ecocentric Consulting, and an Honorary Visiting Senior Research Fellow in Environmental Law at University College London. raymond.purdy@ucl.ac.uk.

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The ethics of space exploration

Jai Galliott argues that our environmental responsibilities extend into outer space.

The dream of space travel has long held an allure for humankind, but it wasn't until the 20th century that people took their first gravity-defying flights. When Neil Armstrong and Buzz Aldrin stepped onto the moon, describing its magnificent desolation, they fulfilled the dreams of millions. However, space travel is no longer limited to an elite group of highly trained and well-disciplined military officers and test pilots. The possibility of commercial space travel is already on our horizon, raising a number of significant practical and moral challenges relating to the environment.

PRIVATE INITIATIVES

As we have seen with other transport industries, competition and new markets reduce costs and encourage innovation. In much the same way, they seem bound to make it easier to get to space. Unwilling to wait for governments to lead the way, private enterprise has been quite aggressive in its efforts to introduce private individuals to space. In 1996, a wealthy entrepreneur offered a US$10 million dollar bounty to the first privately financed team that could fly a passenger vehicle into space, fuelling unprecedented competition and

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> **"The possibility of commercial space travel is already on our horizon, raising a number of significant practical and moral challenges relating to the environment."**

investment. Sir Richard Branson's company, Virgin Galactic, has already built and tested an orbital vehicle capable of lifting aspiring astronauts into near space, with several hundred people from around the globe now having paid a substantial deposit to secure their place in space. SpaceX, founded by Paypal and Tesla Motors co-founder Elon Musk, also made history when it became the first private company to secure a contract from the US government and successfully send cargo to the International Space Station. More recently, the company furthered this history in securing contracts for private manned launches to the Station, provisionally scheduled to take place towards the end of 2017. In a more futuristic but equally plausible effort, a company called Planetary Resources also plans to mine asteroids for rare and valuable minerals. While all of these efforts are likely to gradually contribute to an improved understanding of the space environment, all stand to endanger it in the process.

Of course, there may come a day when space exploration and colonisation become a necessity rather than a commercial choice. Some scoff at this idea, but the meteor that struck Chelyabinsk in Russia in February 2015 served to highlight that we live in a cosmic shooting gallery. A small chunk of rock – estimated to be 15 m wide – hit the atmosphere in spectacular fashion, causing significant damage and numerous injuries. The fact is that we live in the midst of large falling rocks and rising seas and the next falling object may be of cataclysmic size and effect. There may come a day when we need to extend all aspects of living into space, meaning that we would need to work, study, play, have sex, fight, die, worship, raise children, age, pay taxes, vote and so on, in space. The mere thought of this possible future, and the stresses that this would place on the space environment, should cause us to think rather differently about space exploration. The need to evacuate Earth may not happen in our lifetime, but the knowledge we gain from investigating the possibility will indicate the need to preserve space and potentially shed light on a range of other practical problems here on Earth.

Whatever the reasons for going to the 'final frontier' and whatever we do once we get there, we must take the time to think about our responsibilities as space pioneers. Our level of scientific development, and ability to influence international affairs and policy, confers upon us an obligation to study the ethical and environmental considerations associated with space exploration. When we compare space exploration to our conquering of other frontiers, we learn that understanding the potential consequences from the very beginning is critical. When Britain colonised the countries that formed its empire, it had no plan to deal with the indigenous populations, the introduction of disease or the management of resources. Likewise, when the USA began to embrace personal computing and the internet, there was no policy to deal with intellectual property, the introduction of computer viruses or e-waste. In both cases, we are still recovering from the absence of a good plan, but we now have the benefit of hindsight that we can apply in the case of space. The relevant enabling technologies are maturing rapidly and if we are to fulfil our obligations to present and future generations, we must begin to think more seriously about the issues associated with creating a private space industry and possibly sending people to live on far-away planets.

UNDERSTANDING OUR RESPONSIBILITIES

To some extent, this is already happening. Back in 2006, NASA solicited feedback from the public about the plans for the now-defunct Constellation Program, which aimed for the completion of the International Space Station and a return to the moon by 2020. They were looking for environmental issues and concerns that people might have, and soon after released a report addressing them. In June 2014, NASA also requested that interested organisations and members of the public review and comment on the Draft Environmental Impact Statement prepared for the agency's much more ambitious Mars 2020 mission, aimed at gathering information and demonstrating technologies that might one day facilitate a manned mission to Mars.

In compliance with the US National Environmental Policy Act, the Federal Aviation Administration Office of Commercial Space Transportation also generates reports to evaluate the potential environmental impacts that may result from launch licenses and experimental permits to non-government commercial space launch and exploration companies. These reports typically deal only with the ways in which space exploration can affect us here on Earth:

> **"When it comes to the extraction of water and volatiles for fuels on a planet such as Mars and drilling of asteroids with potential terrestrial impacts, there is simply no telling what might happen, and this supports the provisional case for planetary and space protection."**

- Noise impacts;
- Risks to the public concerning launch failures and atmospheric reentry;
- The use of solid rocket fuels and the depletion of the ozone layer; and
- Impacts on local animal and plant species associated with the construction of new launch facilities and activities.

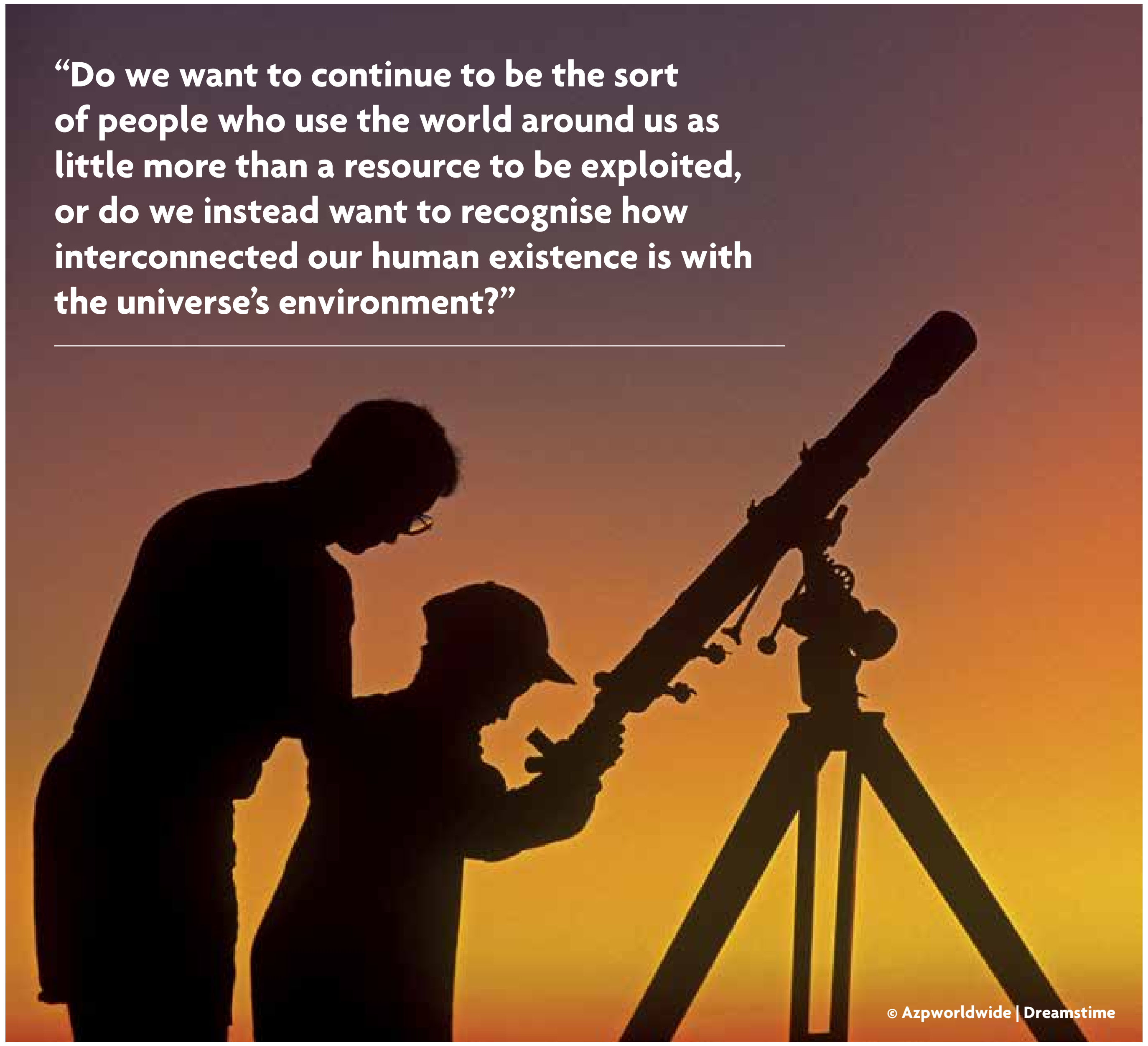
While these environmental impacts are no doubt important and require immediate counter measures, upon close consideration, there is a plethora of questions that demand serious attention, but are not covered in the existing reports: those affecting the outer space environment. These deserve a good deal of attention because if we fail to treat the relevant space and planetary environments with the respect that they deserve, we effectively compromise their intrinsic and extrinsic value.

SOME QUESTIONS TO RAISE

The necessary dialogue can be conducted at various levels of abstraction. For instance, we can raise further practical questions about something like space junk, how this junk affects operational satellites and other spacecraft, and whether it is possible to remove any of it or mitigate its impact into the future. However, when we start thinking about the realm of outer space and add in the complexity and uncertainty that accompanies any reasoning about the future of commercial space exploration, many of the most pertinent questions are best posed in philosophical terms.

First, we need to ask ourselves whether and to what degree resource depletion is in conflict with the demands of justice. We must recognise that the precious planetary and asteroidal resources that we use will not be available for others, notably including other less technologically advanced nations and future generations of our own people. It is not enough to suggest that the number of asteroids or amount of water or land on Mars is sufficient to meet the needs of all because, while this may be true in technical terms, resource depletion is as much about the accessibility of environmental resources as their availability.

Second, we must think about the collective identity that we are continually shaping and consider its relation to the environment. Do we want to continue to be the sort of people who use the world around us as little more than a resource to be exploited, or do we instead want to recognise how interconnected our human existence is with the universe's environment? There is an increasing willingness to assimilate into the local environment rather than be at war with it, but when the question turns to the space environment and its ability to bolster our own biosphere, everything points to more work and education being required.



> **"Do we want to continue to be the sort of people who use the world around us as little more than a resource to be exploited, or do we instead want to recognise how interconnected our human existence is with the universe's environment?"**

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Third, and finally, we need to consider the extent to which extraction and use ought to come at the price of destruction, if at all. As we have already seen on Earth with fracking and oil drilling, there can be significant unintended consequences of invasive exploration, and when it comes to the extraction of water and volatiles for fuels on a planet such as Mars and drilling of asteroids with potential terrestrial impacts, there is simply no telling what might happen, and this supports the provisional case for planetary and space protection. **ES**

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Dr Jai Galliott is Research Fellow in Indo-Pacific Defence at the University of New South Wales in Sydney, Australia. He is an expert on ethical, legal and strategic implications of emerging technologies. www.jaigalliott.com

Tackling space debris in the orbital environment

Hugh Lewis explains the problem and a surprising source for its solution.


NASA on the Commons, Creative Commons[1]

Nearly 40 years ago, two scientists from the NASA Johnson Space Center in Houston predicted the formation of a belt of debris around the Earth arising from future collisions between artificial satellites. The name of one of those scientists, Donald Kessler, a former head of the Orbital Debris Program Office at NASA, has since provided a commonly used expression to describe the collision cascading process that results in such a debris belt: the Kessler Syndrome.

Based on the work described in their 1978 paper, Donald Kessler and Burton Cour-Palais concluded that satellite collisions could become an important source of debris before the year 2000, and that the number of collisions would likely increase exponentially, even if no new satellites were launched, unless some debris-control measures were adopted[2]. Kessler and Cour-Palais identified a critical population density of objects beyond which collision fragments would be produced at a rate that would exceed the rate at which they are removed by atmospheric drag. Some people, including Kessler himself, have referred to this process as a “collision cascade”.

In 2001, Kessler and his colleague Phillip Anz-Meador used a simple model of the orbital debris population to show that the critical density had likely been reached and exceeded at some key altitudes in low Earth orbit (LEO)[3]. The altitudes affected are amongst the most widely used for Earth observation and communications purposes. The stark warning from Kessler and Anz-Meador, that “the fragment population would become too hazardous to continue space operations in low Earth orbit”, came ahead of the adoption of debris mitigation guidelines by the United Nations aimed at preventing this troubling future. In part, these guidelines focused on limiting the long-term presence of objects in important regions of Earth's orbit, including LEO, and over time their importance has become widely recognised[4].

A GROWING PROBLEM

Nevertheless, work conducted a decade ago by the current head of NASA’s Orbital Debris Program Office, J.-C. Liou, with Nicholas Johnson (his predecessor), using a complex predictive debris model called LEGEND, suggested that even the widespread adoption of these mitigation guidelines would not prevent the increase in the amount of orbital debris[5]. Their result has since been confirmed using a range of different predictive models employed by the space agency members of the Inter-Agency Space Debris Coordination Committee (IADC)[6], the inter-governmental forum for the discussion of technical issues relating to space debris.

These technical results have provided fuel for commentators arguing that access to space will be jeopardised by the growing population of space debris. Indeed, the spectre of a collision cascade prompted by the Kessler Syndrome is commonly raised in the wake of any fragmentation event in Earth orbit. The film *Gravity* relied on the apparent legitimacy of these concerns, focusing its plot on the consequences of a single act of disregard for debris mitigation guidelines. The real-life event upon which the plot is drawn – the deliberate destruction by the Chinese government of a defunct weather satellite in January 2007 – has undeniably raised awareness of the space debris problem amongst operators, who must regularly manoeuvre their satellites to avoid fragments generated by this event. To make matters worse, an accidental collision involving an operational *Iridium* satellite and a defunct Russian *Kosmos* satellite in February 2009 further demonstrated the hazard to satellites operating in LEO. Yet even in the aftermath of arguably the space age’s largest and most significant fragmentation events, there has been no emergence of the collision cascade that has so worried the space commentators. So, is the situation as bad as we thought?

In an interview given in 2012 for the *Space Safety Magazine*, Kessler attempted to provide some clarity on the issue. He said, “The cascade process can be more accurately thought of as continuous and as already started, where each collision or explosion in orbit slowly results in an increase in the frequency of future collisions”[7]. Previously, his paper with Phillip Anz-Meador, presented at the European Conference on Space Debris in 2001, identified critical densities for both “unstable” and “runaway” conditions. The authors argued that several altitude regions had passed the “unstable” threshold but few contained a population sufficient to exceed the density required for a “runaway” population[3]. Indeed, the IADC results[6] show that the widespread implementation of debris mitigation measures – to prevent explosions and to limit the lifetime of objects in the LEO region – can be sufficient to prevent the number of collisions increasing exponentially, a hallmark of the collision cascade feared by Kessler.

AN INSOLUBLE PROBLEM?

Nonetheless, it is highly likely that the population of space debris will increase beyond our capability to constrain it. Even an inordinately expensive and technically demanding campaign of remediation, where new space missions are used to remove large derelict objects from LEO or to perform derelict-on-derelict collision avoidance, may not diminish the potential for the Kessler Syndrome to establish itself. This is in spite of countless technology ideas for debris removal being proposed and missions to demonstrate them being planned. The reason for the pessimism is not because a debris remediation effort will be pointless or detrimental – in fact, the opposite is true. Instead, the challenge lies with respect to the prevailing behaviour of some satellite operators. They are aware of the space debris hazard, and its potential to jeopardise not just their missions but all access to space, yet for whatever reason do not conform to the debris mitigation guidelines or best practices being promoted by the IADC and the United

Nations. Whilst this assessment may appear to be overly harsh, results published by the European Space Agency (ESA) and the French space agency, CNES, show that fewer than 20 per cent of eligible satellites and upper stages in LEO have successfully carried out a post-mission disposal action. In contrast, about 70 per cent of satellites in geostationary Earth orbit (GEO) reaching the end of their life carry out such an action regularly. Without an increase in the success rates for LEO, remediation efforts will be fruitless: many more objects will be added to and persist in the LEO environment through regular launch activities than can be removed via remediation actions.

> **“New space users will need to be supported to facilitate their economic aspirations whilst at the same time enabling them to become responsible custodians of the orbital environment”**

According to James Beck of Belstead Research in the UK, there is lag in the space debris environment due to mass storage in large intact objects[8]. As a result, we will not see the negative impacts of a failure to address the space debris hazard until decades into the future. This distance in time is likely to be one of a number of reasons why we find the problem difficult to address. These reasons are arguably the same as those associated with the global issues posed by climate change. George Marshall, the author of *Don’t Even Think About It: Why Our Brains Are Wired to Ignore Climate Change*, identifies five key factors that influence our inability to address this type of challenge:

- It is distant in time;
- It is distant in place;
- It is uncertain;
- It is costly to address; and
- It is unprecedented[9].

Until the threat is more certain and tangible, we are unlikely to act.

USING SPACE RESPONSIBLY

The preservation and the responsible use of the space environment is a fundamental aim of the first UK National Space Policy, published in December 2015, which recognises global space assets as “part of our critical national infrastructure”[10]. Through its roles in the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) and the IADC, the UK is supporting the development of measures and best practices aimed at ensuring the sustainable use of the orbital environment. However, perhaps the best chance for addressing the threat from space debris arises from an unlikely source, which is also a focus of the UK government and articulated in the National Space Policy: the commercial space sector. On the face of it, it seems patently absurd to expect a sector that is expecting to increase the number of space launches and the number of satellites in LEO far beyond what we have seen in the past to be the foundation of responsible and sustainable use of space. A mark of this new wave of commercial space activity, for example, can be seen in the proposals by the companies OneWeb and SpaceX to establish large constellations of satellites in LEO for the purpose of delivering high-speed internet services to regions of the world where this is lacking. The OneWeb proposal alone would double the number of active satellites in LEO. Given the somewhat patchy success rates for post-mission disposal we have seen in this orbital environment, surely more satellites would lead to the acceleration of the feared Kessler Syndrome?

To understand why the benefits of a growing commercial space sector might extend beyond the purely economic into the realms of space sustainability, we need only look at the orbital region where the post-mission disposal success rates are consistently high: geostationary orbit. There are many commercial operators with satellites in GEO. According to the Union of Concerned Scientists, which maintains a database of operational satellites, GEO contains just over one-third of all operational satellites (as of August 2015) and of those, nearly two-thirds are owned and operated by commercial entities. In contrast, LEO has typically been the domain of governments and currently half of all satellites there with a launch mass greater than 50 kg are government owned.

THE ECONOMIC INCENTIVE

There is another important factor to consider too: the geostationary ring itself is precisely defined – it occupies an altitude band of only a few kilometres and is a highly congested environment. In order for a new, more capable, satellite to occupy a particular location, the current occupant must be moved. So, in spite of the significant costs involved in conforming to best practices and debris mitigation guidelines in this region, there is a longer-term commercial incentive for compliance. With the key factors identified by George Marshall in mind, perhaps it is the economic threat that renders the space debris problem more tangible and close. Here, perhaps, is the incentive that has been lacking.

Accordingly, it might not be unreasonable to assume that in the face of increasing congestion from commercial satellites operating in LEO, the commercial space sector would be a good caretaker of the orbital environment. In fact, Michael Lindsay, the of Mission Systems Engineering and Analysis Lead at OneWeb, outlined constellation proposals at the International Astronautical Congress in October 2015 that demonstrate a clear awareness of space debris and a willingness to do more than is necessary to mitigate the hazards it poses[11]. The same is true of a number of new commercial operators.

▲ **Figure 1. A SpaceX *Falcon 9* rocket launching from Cape Canaveral in April 2015. SpaceX is one of several private companies now investing in the Space sector. (© Stephenallen | Dreamstime)**

In the coming decades, the successful growth, or otherwise, of the commercial space sector will be closely tied to how it responds to the space debris problem. As a result of this connection, the new space users will need to be supported to facilitate their economic aspirations whilst at the same time enabling them to become responsible custodians of the orbital environment. Perhaps then the spectre of the Kessler Syndrome, so spectacularly depicted in *Gravity*, may be set aside. **ES**

Hugh G. Lewis is a Senior Lecturer in Aerospace Engineering at the University of Southampton. He is a member of the UK delegations to the Inter-Agency Space Debris Coordination Committee and the United Nations Committee on the Peaceful Uses of Outer Space

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Ethics after the Space Act

Tony Milligan outlines the legislation that governs our use of Space and whether it is fit for purpose.

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In November 2015, President Obama signed the Space Act (Spurring Private Aerospace and Competitive Entrepreneurship Act) into law, granting private companies rights in abiological materials mined in space. The goal was to support the development of asteroid mining by US companies at some point in the not-too-distant future. The material wealth that asteroids offer is considerable. While helium-3 (^{3}He) from the Sun bounces off of the Earth's atmosphere, asteroids lack a comparable protective layer and so ^{3}He particles can be trapped in their regolith (powdered rock surface material). ^{3}He is one of the best candidates for use in fusion reactors, which may well be a coming technology, although there are conflicting narratives about their viability. As such, ^{3}He is extremely valuable as well as very rare. Relatively small quantities can fetch a high price.

Some (but not most) asteroids are also mineral rich: they contain a range of metals that might replace the Earth's dwindling stocks of everything ranging from copper to titanium if they could ever be returned from space. The main prizes, however, are the platinum group metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum), which would be worth a large fortune on the open market. However, the costs of extraction and the impracticalities and expense surrounding return suggest that, in the absence of futuristic technologies, most of what is mined in space is ultimately likely to stay there for use in the development of infrastructure. In which case, the iron contained in the metallic M-type asteroids will be extremely useful, as will the water ice in C-type asteroids, which are the likeliest candidates for early mining. Either way, with or without return, the dream of supplementing the Earth's finite resources, and acquiring wealth in the process, has already generated a sizeable lobby to press for property rights in extracted materials. Hence the Space Act.

IS THE SPACE ACT LEGAL?

The legal standing of the Space Act is, however, a matter of some debate. Under the Outer Space Treaty (1967), space is "the province of all mankind". That is to say, it is a commons in the formal sense of being a shared entitlement for all, a resource that cannot be partitioned into private interest claims. Restrictions against the lodging of property claims by states are also taken to apply to the private corporations answerable to some "launching state" defined in the terms of the UN Liability Convention (1972) as the state from whose territory or facility any objects are launched into space or the state which procures the launch of any space object, (Article I(c)). The Outer Space Treaty, which is regarded as the more important of the two because it deals with basic claims and entitlements, was framed during the Cold War and before the first Moon landing, and designed to allay mutual fears that one or other side might claim the high ground of space. In the absence of similar pressures, replacement treaties have been impossible to secure, with the actual players in space exploration refusing to ratify a later Moon Agreement (1979), which would have required robust forms of equal entitlement, e.g. mission samples to be made available to all countries. Nonetheless, in spite of non-ratification, the agreement helps to clarify what the idea of "common heritage" in space might involve.

NASA on the Commons

What has changed matters, and led to the USA's decision to try to go it alone without any further international agreement, is not simply lobbying but also the rapid growth of a near-Earth economy over the past decade. This has filled some of the roles played by the now-defunct Space Shuttle programme, based around:

- Satellite launch;
- Economical habitat design (led by Bigelow Aerospace);
- Private resupply of the International Space Station (by SpaceX);
- A technological race to put together the basics for space tourism (led by Virgin Galactic); and
- The direct prospect of asteroid mining (with several players such as SpaceX and Planetary Resources already in the field).

Asteroid mining is, as we might expect, going to be much harder than the private corporations have sometimes suggested in order to secure funding and political support, but we may be no great distance away from the first attempts. We have already witnessed the first landing on an asteroid and some limited sample return, and NASA have plans for the capture and orbital insertion of an asteroid fragment. A time frame of two decades may be long enough for the first experimental attempts to be made, and is probably long enough for more ambitious sample-return missions. By that time, the principle that corporations can claim ownership of materials that they remove from asteroids (but not the asteroids themselves) may be too well established in the USA to easily counteract even if, for some reason, it is deemed worthwhile to do so. Investment in the process may have gone too far to be held in check.

The decision to go it alone and unilaterally declare exploitation rights is, however, politically and ethically problematic for several reasons. Politically, it is problematic because while the USA may favour a less-constrained process of resource extraction than various European bodies such as the European Space Agency (ESA), they certainly do not favour the comprehensive absence of regulation in space. At some point, the USA will have to persuade countries that may well overtake them in terms of technology, China in particular, that a go-it-alone approach is counterproductive and that the observance of international space agreements is in everyone's interest. This applies also to mining corporations that will have a vested interest in the avoidance of the equivalent of claim jumping, i.e. the exploitation of identified resources by rivals after a mining corporation has done all of the basic and expensive identification and preparatory work. Even under the Space Act, asteroids cannot be owned and a monopoly of extraction rights is not upheld anywhere. This introduces the risk that initial financial outlays may end up benefitting others. (A situation that no major corporation will want.)

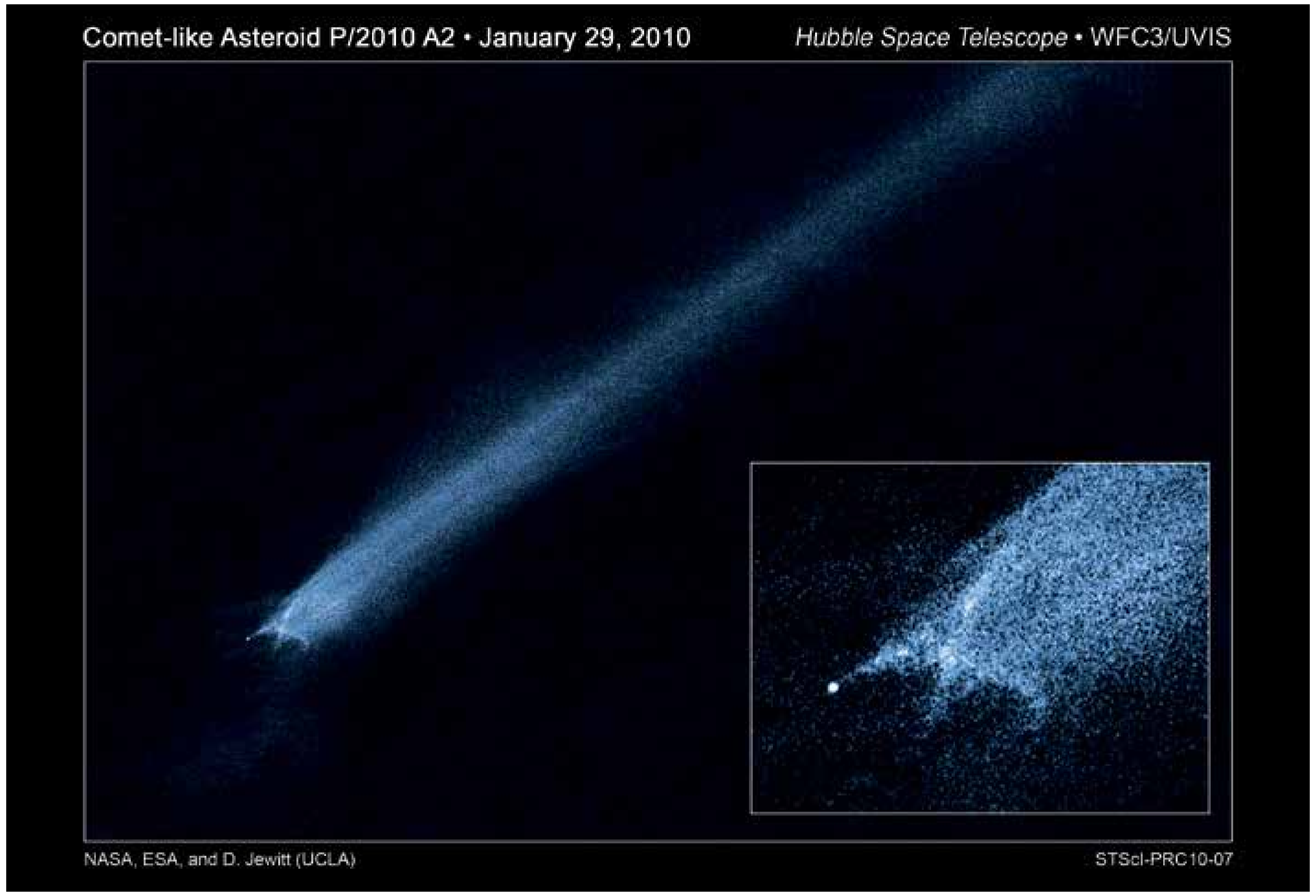
Ethically, such mining is problematic for reasons of sustainability, terrestrial impact, and the protection of larger bodies in space. However, a concern within the space community, and particularly within more libertarian sections of the latter in the USA, among whom there is a feeling that a move into space should be a move away from ethical constraints, is that (a) there is simply nothing to protect in space; and (b) bringing ethics into the discussion is likely to involve the familiar bureaucratic obstacles of economic activity on the Earth. In support of the first claim, it may be pointed out that asteroids and other bodies that will be within our reach any time soon are not (to the best of our knowledge) mature ecosystems. Environmental concern would therefore extend ethical considerations by including non-sentient microorganisms (if there are any) or things other than life forms. For the second claim, there are regular appeals to something approaching a duty to extend our human presence, the only or best way of doing which is sometimes taken to involve a freeing of the private sector to get on with its job.

SUSTAINABILITY AND FAIRNESS

The issues of sustainability and fairness seem unavoidable. While it is easy to imagine the supplementation of limited terrestrial resources with the infinite resources of space, the simple fact of the matter is that only a tiny fraction of the latter are ever likely to be accessible. In terms of asteroids we must either find a way of getting to the asteroid belt or else we must wait for them to come to us. The former option is a very long way off, and there are only a small number of mineral-rich asteroids with trajectories that intersect with the inner Solar System[1]. Identifying these targets and their pathways can take several years.

If the available targets are limited and require a good deal of time to identify, then it is likely that multiple agencies will end up competing for the same resource. And given that a body such as an asteroid cannot be owned without a more wide-sweeping change in international law, the difficulties of granting extraction rights become clear. Sustainability is in play because extraction that is unconnected to extending the human reach out to the asteroid belt will simply result in an intermittent exhaustion of the available resources. Distributive justice is in play because, while space is notionally the common province of all, only some can access the resources in question. And among those who can, only a few can do so at any given time.

Issues of this sort form part of a broader class of problems concerning resources that are either limited or of limited accessibility in space. Orbital niches for satellites are a limited resource; ^{3}He trapped in asteroid and lunar regoliths is a finite resource; the prime locations for establishing infrastructure on the Moon (so-called 'peaks of eternal light' on the rims of polar craters that might contain water ice) are extremely limited.How these common province items are shared out, or the compensation due to others for monopolised use, is far from clear. One way, suggested in several articles and a paper to the European Space Policy Institute in September 2015, has been put forward by James Schwartz at the University of Wichita in the USA: the adoption of a framework for just distribution that would require more regulation and compensatory mechanisms than the Space Act envisages[2]. In forthcoming researchElvis, Milligan and Krolikovski propose some possible measures to deal with the lunar case in the interests of protecting scientific activity and the avoidance of any use of the latter as a pretext for *de-facto* property claims[3]. Comprehensively unregulated extraction looks like a recipe for injustice, policy problems and legal headaches all round. And so, while the era of full-scale international treaties may be over, sooner or later at least some of the major players may well have to come to the table and thrash out a workable deal to guarantee security of resource use.



▲ **Figure 1. Image of comet-like asteroid P/2010 A2 taken by the Hubble Space Telescope. (Credit: NASA, ESA and D. Jewitt UCLA[6])**

PROTECTING ALL OBJECTS IN SPACE

'Protection' in space, in the sense involved in 'planetary protection' has historically meant the protection of science rather than the protection of what is other than human. It has had little to do with environmental protection as such. Contamination of landing sites on Mars by microbes carried from the Earth may corrupt scientific results and this is not only a rationale for its prevention but often *the* rationale for protection. Restriction of asteroid mining under the Space Act is guided by the same considerations. Any discovery of biological materials will effectively shut down an operation for further investigation. This is a constraint of a minimal sort which all but the most libertarian-minded agree to be necessary. But beyond some arguments in the space ethics and geoethics literature, and some occasional thoughts by the Committee on Space Research (COSPAR), the international body with a special role for the interpretation of space law, the presupposition has tended to be that bodies themselves simply do not warrant protection[4]. This still leaves open some possibilities for arguments about the Moon and Mars as culturally significant objects for us, but it will do little to generate reasons for constraint with regard to the mining of asteroids.

As noted above, one of the cautionary drivers against any move into value theory that might suggest that places and things have importance in their own right is a concern that this will lead to excessive regulation of the emerging space economy. But what may come as a surprise to those who are new to the arguments is that a case for the protection of at least celestial bodies in their own right will not necessarily line up against asteroid protection. Since the 1980s, the argument for such protection has been framed in terms that draw from the environmental ethicist Holmes Rolston, to the effect that certain celestial bodies (the Moon and Mars being obvious examples) have some manner of structured integrity that is worthy of respect. Mars contains the Vallis Marineris, vaster than the Grand Canyon. It has the Tharsis Bulge and Olympus Mons, the largest volcano in the Solar System, and some distinctive structural features that most humans would regard as impressive or sublime. Some objects we refer to by numbers (as in the case of most asteroids) and some we refer to by names. This act of naming is taken by Rolston to be a useful guide to which bodies might have integrity of the relevant sort and which probably do not.

At an intuitive level, there is a good deal to be said for this position. Would we really think it appropriate for Olympus Mons to be mined for driveway chips? Probably not. And would our objections here simply be in terms of protecting science or the aesthetic pleasure of viewers that might thereby be spoiled? Analogous arguments can be made for human artifacts: nobody gets to mine the inside of the Sphinx in order to make souvenirs for tourists; nobody get to mine the interior of the pyramids or the interior of Stonehenge, and here the point is not that it would change the appearance of these things (because it would not actually do so), nor that historic information would be lost (that might also be false). Extending this kind of argument from artifacts that have cultural significance to non-artifacts, such as asteroids and planets, may well be possible. Terrestrial analogues, such as Ayer's Rock may work in favour of this move.

Arguments of this sort will not generate reasons for a 'hands-off' policy, but they will show that we have reasons for regulation and for constraint about exactly how resource extraction and use takes place. And, somewhat at odds with the recent US legislation, such arguments will extend to a number of the larger asteroids such as Ceres and Vesta (which have relevant distinctive features) and to satellite bodies such as Phobos in orbit around Mars (because they form part of larger systems that have integrity). But they might also generate reasons to look favourably upon some instances of asteroid mining as an alternative to the mining of larger bodies such as the Moon or Mars, which warrant stronger integrity-based protection. Conveniently, it is the asteroids rather than the Moon or Mars that have turned out to be resource rich, in terms of the resources that are most valued terrestrially.

An exception to this convenient truth is again ^{3}He, which turns out to be present in greater densities on the Moon. By comparison to the Moon, asteroids have a smaller mass, exert less of a gravitational pull and retain less ejecta when subject to impacts; they therefore have a lower proportion of mature regolith with less ^{3}He in it. Given that the densities of ^{3}He anywhere are low (usually measured in parts per billion), from a sheer logistical and resource standpoint, lunar ^{3}He mining looks like a better option than mining asteroids. It might, of course, still not be a particularly good option because of various impracticalities (Ian Crawford of Birkbeck College has recently argued along these lines) or because of a further range of reasons that we have for lunar protection such as the extent of the mining required (especially given that density falls off with depth and so mining would have to be spread over a large area)[5]. But this is unlikely to deter governments that want to develop their fusion programmes. And in the aftermath of various disastrous failures in fission systems, most notably in Japan, the rationale for this can readily be understood.

What then seems to make sense is the proposal of regulated asteroid mining on some of the more uniform and less distinctive asteroids, as an alternative to mining on planetary or lunar surfaces. This does, however, introduce various dangers. How, for example, are we to contain the impact of a flooding of terrestrial markets with vast amounts of expensive raw materials if some economical method of return is ever discovered? And how are we to safeguard environments with integrity once an asteroid mining programme is up and running and the technology to extend ambitions elsewhere is within reach? But these are ethical problems of a different sort. They are containment issues rather than issues of whether or not asteroid mining itself can be environmentally defensible. On that particular matter the US legislation may be on reasonably solid ground.

Tony Milligan is a Teaching Fellow in Ethics and the Philosophy of Religion with the Department of Theology and Religious Studies at King's College London. His publications in this area include a book entitled *Nobody Owns the Moon: The Ethics of Space Exploitation* (2015, McFarland, North Carolina). Along with James Schwartz, he is the co-editor of a forthcoming volume on *The Ethics of Space Exploitation*, which is due out from Springer early in 2016.

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Space agriculture is bringing farming indoors

Gary Stutte analyses the impact of growing food for spaceflight.

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Imagine the pioneers of the future colonising Mars, growing their own food, recycling their waste and prospering in a hostile environment with limited resources. These explorers will rely on technology, biology and ingenuity to provide the fresh air, clean water and nutritious food essential for survival. Living space, energy and supplies will be at a premium. The solution to all these challenges will be based on the insights and understanding of living in closed environments that are being developed today.

The European Space Agency (ESA), NASA, China, Japan and Russia, along with private organisations in Europe and North America, have carried out research on growing food in spacecraft, space stations, the Moon, Mars and beyond. They have also built facilities for the large-scale testing of physical and biological means of keeping humans alive, and humans' ability to adapt. These experiments have been as short as few days to more than 500 days long, and they have provided key insights into the design of, and social interactions in, a closed-loop life-support system.

THE IMPORTANCE OF PLANTS

All the experiments have included agriculture as an integral part of the simulations. Why? The answer to that question lies in two fundamental biological processes: photosynthesis and transpiration. When exposed to light, green plants convert carbon dioxide (CO_2) into food and oxygen through the process of photosynthesis. The oxygen is converted back to CO_2 with each breath the crew takes. Transpiration is the process whereby plants lose water vapour through openings on the leaves, having taken it up through their roots. The process can be used to convert contaminated water into drinking water. With the proper selection of environmental conditions and plant species, these two processes will produce food and water. This is the basis for the development of a robust, sustainable and efficient biological life support system (BLSS) for long-duration space missions.

NASA scientists recognised very early that biological life support will be an essential component of future space colonies – they first tested photosynthetic algae for oxygen production in the late 1950s. However, it was not until the mid-1980s that a dedicated effort to determine the feasibility of using higher plants to maintain air quality, purify water and produce food was undertaken.

NASA sponsored a series of workshops in the 1980s that brought together agronomists, horticulturists, engineers, microbiologists, food scientists, space biologists and mission planners to identify the food production, nutrition, recycling and environmental control issues necessary to support a crew on a long-duration space mission. Following those meetings, NASA initiated the Controlled Ecological Life Support Systems (CELSS) programme to determine the feasibility of biologically stable life-support systems at a one-person scale. The CELLS programme (later renamed the Advance Life Support programme) involved government, industry and university scientists in a concerted effort to understand, solve and test solutions to the challenge of building a BLSS at a one-person scale.

A centrepiece of this testing was the Biomass Production Chamber (BPC; see **Figure 1**). The BPC was a two-story, 113 m^3 closed-loop plant growth chamber with four growing levels capable of supporting 5 m^2 of plants

▲ **Figure 1. The Biomass Production Chamber at NASA's John F. Kennedy Space Center. (Courtesy of NASA)**

▲ **Figure 2. Hydroponically grown potatoes were maintained for 105 days under electric lights in the Biomass Production Chamber at NASA's Kennedy Space Center. (Courtesy of NASA)**

per level, a recirculating hydroponic (soil-less) system for nutrient delivery, and 96 400 watt high-pressure sodium lamps for lighting. It allowed carbon dioxide removal, oxygen production and water purification to be continuously monitored from planting to harvest. Ultimately, biological processes for the recovery of nutrients from the inedible leaves of stems of plants to be extracted and reused. The BPC was used for testing for over a decade (1988–1999) to advance the concepts of sustainable food production in a closed environment.

Lettuces, potatoes, radishes, rice, soyabeans and wheat were all successfully grown in the BPC. By adapting a hydroponic production system, the nutrients could be optimised, water use drastically reduced, and the soil root environment managed. High-output lighting gave control over daylength and provided the energy necessary to drive photosynthesis. The closed system allowed the recycling of water and nutrients to the plants. The concentration of CO_2 could be controlled to maximise growth rate, and the amount of oxygen produced could be monitored.

The results were dramatic and had immediate terrestrial applications. Lettuce could be grown from seed to harvest in less than 28 days and produce yields that exceeded all the commercial production models of the day. World-record potato yields were obtained in two-thirds of the time of field production (see **Figure 2**). Wheat yields were twice that achieved in the field. These results were quickly identified by university and industry scientists and incorporated into greenhouse and controlled production environment protocols across the globe. Research from the Kennedy Space Center programme alone resulted in over 600 scientific papers, technical reports and books, and provided much of the baseline data necessary for the design of lunar and Mars colonies.

THE IMPACTS OF LEDs

While dramatic results can be obtained by growing plants in closed chambers on Earth, there are different challenges to growing plants in space. These include requirements for:

- Lightweight, durable materials for construction;
- Safe and efficient lighting sources; and
- Lightweight and robust environmental monitoring and control systems.

▲ **Figure 3. Adding LEDs to plant growth chambers allows different colours to be used to optimise the growth of plants. (Image used with permission)**

Concurrent with the development and testing of the BPC in the late 1980s, NASA began funding research on the use of light-emitting diodes (LEDs) as light sources for plant growth chambers in space, and in 1989, NASA-funded scientists reported that a number of horticultural crops could be successfully grown using LEDs. These results led to the first LED lights being used to grow plants in space in 1994. This pioneering work was the start of a transformation of greenhouse lighting. The transition to LEDs can reduce energy use in greenhouse by over a third, cutting the use of fossil fuels and the release of greenhouse gases into the atmosphere.

Arguably, the demonstration that plants could be grown under LEDs enabled the development of viable indoor plant production facilities for fruit, vegetables and ornamental and medical plants. The cool-running LEDs allow plants to be placed very close to the lights, and indoor farms with vertical layers can be constructed. These vertical plant factories can be established in urban environments, and by going up instead of sideways, increase the yield per acre by 60 to 100 fold over field-produced crops. Production close to the point of use minimises losses due to harvest, transport and shelf life.

▲ **Figure 4. Dwarf wheat plants grown on the International Space Station. (Courtesy of NASA)**

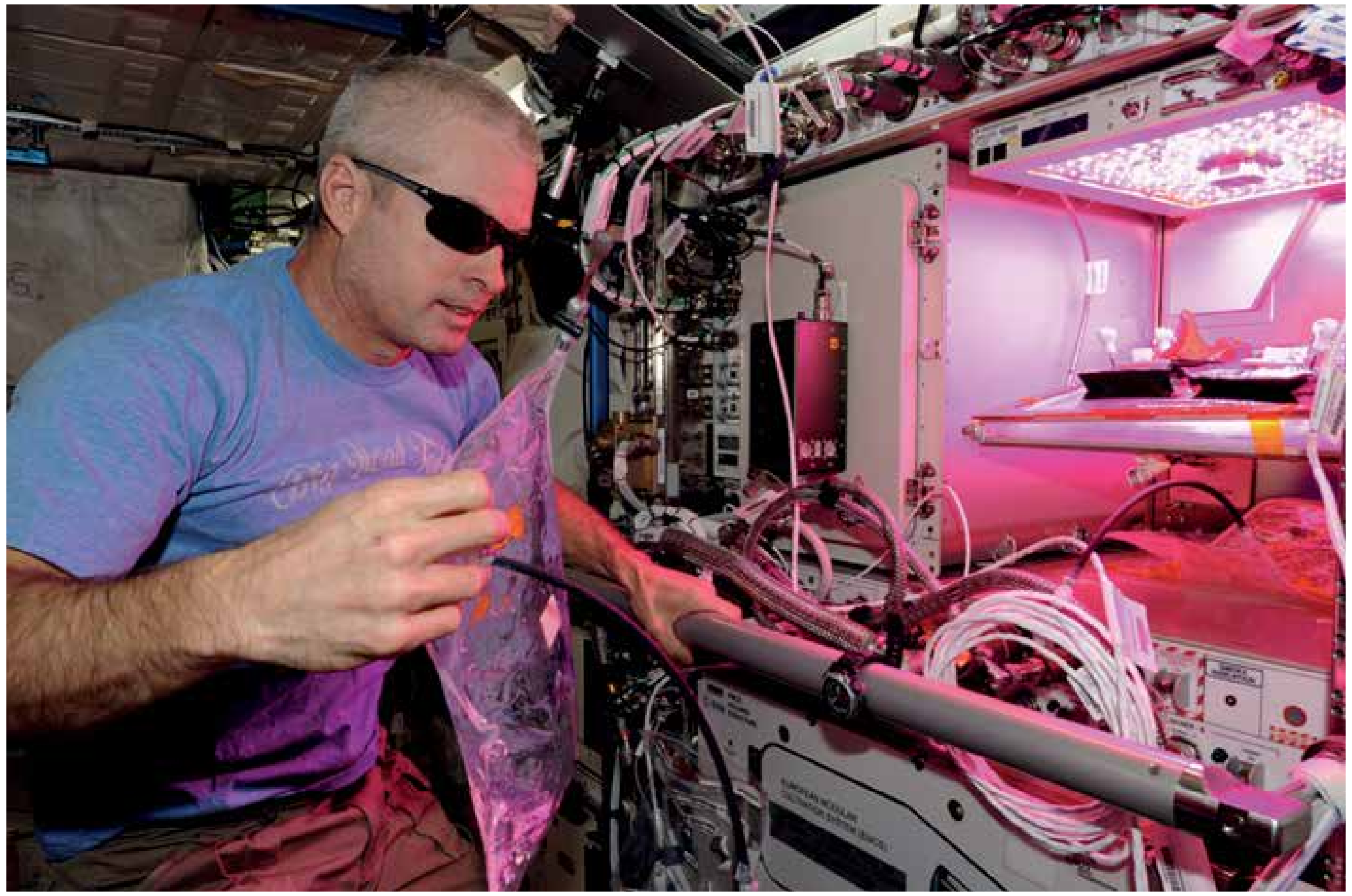
Plants respond to the different wavelengths of light in different ways, with some wavelengths affecting photosynthesis, others the shape of the leaves, and others determining flowering. The use of LEDs allows these wavelengths to be mixed and matched in various ways to optimise the response of a plant for a given purpose (see **Figure 3**). For example, it has been shown that the nutritional value of the lettuces is increased when the amount of blue in the spectrum is increased. Similarly, the production of antioxidants and beneficial phytochemicals can be increased by altering the spectrum at critical stages of development. These findings pave the way for using plants as biological countermeasures for the physical effects of space travel on human health.

PLANTS ON THE ISS

As the technical ability to push the limits of plant productivity in a closed environment was being established on Earth, the understanding of how to grow plants in space was being determined. Experiments on the *Space Shuttle* and International Space Station (ISS) have established that plants can complete all phases of development: germination, seedling emergence, vegetative growth, flowering, fruiting and ripening.

One of the earliest plant experiments on the ISS was to determine if wheat was able to grow, photosynthesise and transpire as well as on Earth (see **Figure 4**). This was critical to confirming the findings from the large-scale tests in the BPC, and to providing further evidence that biological life support was feasible in space. Results from that experiment were unambiguous, clearly demonstrating that critical life support functions could be sustained under spaceflight conditions. Many experiments in space have refined our understanding of how plants sense and respond to gravity, and current technology has advanced to the point that astronauts are growing salad crops to supplement their diets while on extended missions to ISS (see **Figure 5**).

NASA has also explored the psychological benefit of including plants as part of the living and working environment of future planetary explorers. In the Desert Research and Technology Studies (DRATs) tests conducted in the high desert of Arizona, NASA tests prototypes to determine how they will work in a simulated exploration environment. The crew lives and works in space-like habitats and goes through scientific, medical and exploration activities. For three years, small-scale plant production systems to grow salad crops



▲ Figure 5. Astronaut Dr Steve Swanson harvests lettuce plants grown on the International Space Station in the VEGGIE plant growth chamber. (Courtesy of NASA)

for the crew were incorporated into the design of the living and working habitat. NASA-sponsored research had also shown that the addition of many ornamental foliage plants were effective removing atmospheric contaminants from the air, and provided a focal point for crew social and recreational activities.

The development of BLSS for long-duration space missions is not without its challenges. Most significant are the constraints of mass, volume and power to build, operate and sustain it. There are breakthroughs needed in the design of lightweight materials that can provide protection from the temperature and vacuum extremes of space while allowing light into the plants.

INDOOR AGRICULTURE

The challenge of feeding the world population is huge, in part because so much food is wasted – about one-third of it every year.[2] Over 3.5 million of the world's population live in urban areas, which are dependent on remote production, transport and distribution of food. The food supply of millions of others is threatened by disease, pests, drought and flooding. Political unrest, sanctions and war disrupt the distribution of food to many millions more. As the population increases, the pressures on water, nutrient and land resources of the Earth will increase exponentially. Using the tools for feeding the planetary explorers of the future may provide a key to meeting the challenges of feeding the world today and tomorrow.

> "Incorporating energy-efficient LEDs into urban plant factories will reduce the acreage needed to grow food, reduce the use of pesticides, maximise water-use efficiency, reduce spoilage during transport and bring production closer to the consumer "

The space-based research to achieve sustainable production under a closed environment will enable the recovery and reuse of water, scrub CO_2 from the environment, and provide locally produced food. Incorporating energy-efficient LEDs into urban plant factories will reduce the acreage needed to grow food, reduce the use of pesticides, maximise water-use efficiency, reduce spoilage during transport and bring production closer to the consumer. The number of vertical plant factories around the world is relatively small, but their numbers are increasing rapidly. They are producing high-value, perishable horticultural crops and specialised plants for medicines (see **Figure 6**). As the costs of the technology decreases, and the demands increase, these facilities will become a prominent presence in urban environments.

▲ Figure 6. A vertical plant factory located in research hospital in Kwandong, South Korea produces over 20 different species of culinary and medicinal plants that provide both food and medicine for patients. (Image used with permission)

For families, small-scale, energy-efficient plant growth units will enable them to produce their own food in the urban environment. This will ensures that food is fresh, healthy and easily available. Modular, multilevel plant growth chambers are being designed for use in remote locations, including deserts, refugee camps and war zones. These units are equally suitable for converting vacant or under-used urban spaces into a year-round source of food.

Humanity is indeed looking to space agriculture designed for the future colonists of distant planets to solve the immediate problems of feeding the millions of humans on Earth today – and tomorrow. ES

Dr Gary Stutte is horticulturist and space biologist who has worked for over 20 years developing testing and designing plant growth systems to grow plants in space. He has lead multiple experiments on the International Space Station and published over related 150 articles. He is a founding member and Executive Director of the American Council of Medicinally Active Plants and President of SyNRGE, LLC, a company dedicated to translating the findings of space research into solutions for Earth. (Gary.Stutte@gmail.com)

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Trees in Space: no longer the forbidden fruit

Thomas Graham explains the advantages of carrying fruit on space missions and the advances that are making this possible.

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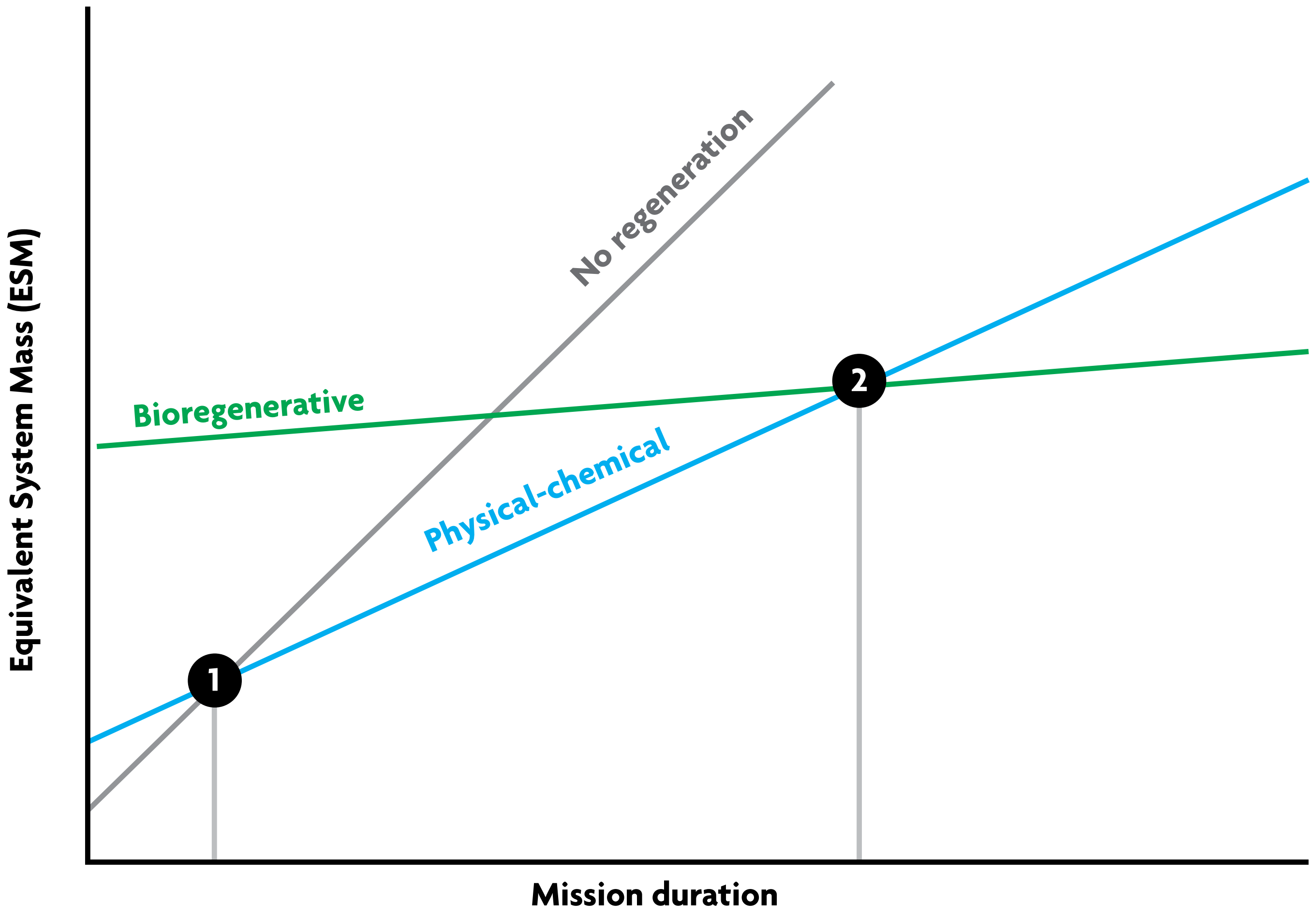
The flow of scientific and technological advances from spaceflight research and development to Earth-based applications is both varied and substantial[1]. Historically, NASA and other space agencies around the world have played critical roles in a wide range of fields, including agriculture, climate science, environmental monitoring, human health science, materials science and robotics. This flow of scientific knowledge and technology is not unidirectional: many scientific and technological advances designed to address terrestrial problems have proven to be critical advances for spaceflight as well.

> **“If humans are to exist outside the Earth’s biosphere for extended durations, there is an absolute requirement that plants and other biological systems make the journey as well.”**

BIOREGENERATIVE LIFE SUPPORT

If humans are to exist outside the Earth’s biosphere for extended durations, there is an absolute requirement that plants and other biological systems make the journey as well. Through photosynthesis and other metabolic pathways plants provide crew nutrition (food production), air revitalisation (carbon dioxide removal and oxygen production), and contribute to the recycling of drinking water from wastewater (through transpiration). All of these ecological services are required to keep humans healthy and productive in spaceflight environments[2], and importantly, plant-based life-support systems are *bioregenerative*; they do not require additional inputs from Earth once established (assuming ‘local’ energy input such as solar or nuclear). Plants also contribute to the psychological wellbeing of crew members – a largely intangible but highly significant contribution when considering the long periods of isolation and difficult living conditions associated with multi-year missions.

As humans venture further from Earth for longer periods of time and ultimately establish a permanent presence beyond Earth (on Mars, for example), it will become progressively more prohibitive and impractical in terms of mass and energy (and ultimately money) to supply those crews with air, food, water and other consumables from Earth. There will be a point at which complete (or nearly so) recycling of air, water, and food will become necessary, through some combination of physical–chemical and bioregenerative systems.



▲ **Figure 1. Comparison of the equivalent system mass* required for the three primary life-support system options. Breakeven point 1 illustrates the mission duration for which physical–chemical systems become more advantageous than non-regenerative systems from a system mass perspective. Breakeven point 2 illustrates the mission duration for which bioregenerative systems become more advantageous than strictly physical–chemical systems. (Courtesy Dr Matthew Bamsey) * ESM is a standardised parameter that incorporates not only mass requirements but volume, power, crew time etc., into a single comparable metric.**

Physical-chemical systems assume almost-closed air and water recycling, but with food brought from Earth, while bioregenerative life-support systems assume almost closed-air, water and food recycling; 'no regeneration' missions are those with no significant recovery of air, food and water (see **Figure 1**).

COUNTERING THE EFFECTS OF SPACE TRAVEL

There are many obstacles on the path leading to a human presence on the Moon, Mars, and beyond. Many of the obstacles involve the challenges of keeping humans healthy and productive in the extreme environments that they will face, both on the journey and once established at their destination. Radiation and reduced gravity conditions are two major issues for long-duration human space exploration, issues that will require a suite of countermeasures to ensure mission success.

The crew's diet will play a large role in dealing with the effects of the spaceflight environment on the human body. The provision of fresh food, as part of a bioregenerative life-support system, is critical, as many antioxidants and other phytochemicals may not be stable under spaceflight storage conditions. Further, the provision of fresh food has a very powerful psychological benefit for the crew, which is vital during long missions.

FRESH FRUIT IN SPACE

Tree fruits have long been deliberated on as potential menu components for the crews that will venture beyond low Earth orbit (LEO). A continuous supply of fresh fruit could provide unique nutritive contributions to the crew's diet and offer enhanced menu diversity to prevent menu fatigue[3]. Although highly desirable, tree crops are also highly incompatible with spaceflight crop production and bioregenerative life-support systems in general: they are large, take a long time to mature and, in the case of temperate species, require a cold dormancy period between fruiting cycles.

The space available for crop production in any current or foreseeable spaceflight plant production system is limited and certainly could not accommodate a typically sized fruit tree. Trees also take three to twenty years to mature enough to flower and fruit, timeframes that are incompatible with current mission scenarios. Temperate tree fruit species, such as plum or apple, only produce fruit once per year – they do not produce fruit continuously as would be required in a bioregenerative life-support system. Finally, there is also concern with tree crops regarding their harvest index (the ratio of edible biomass to total biomass), as trees tend to dedicate significant resources to the development of wood relative to fruit.

> **"Terrestrially focused scientific and technological advances can and do solve spaceflight problems, often unbeknownst to those making the advances."**

A TERRESTRIAL SOLUTION

As previously mentioned, terrestrially focused scientific and technological advances can and do solve spaceflight problems, often unbeknownst to those making the advances. One such advance that seems to have overcome the barriers to using tree fruit in bioregenerative life-support systems is the recent development, by United States Department of Agriculture (USDA) researchers, of plum trees *(Prunus domestica)* that over-express the flowering locus T1 (FT1) gene taken from *Populus trichocarpa*, a poplar species native to North America[4]. These FT1-plum trees were developed in the hope of accelerating the breeding cycle of plum trees (on Earth) in order to confront pathogens, such as the plum pox virus, that have devastating impacts on plum production globally. Through the over-expression of the FT1 gene, the USDA was successful in getting the trees to flower and produce fruit within one to ten months compared to three to seven years for typical plum trees[4]. The greatly accelerated breeding cycle has allowed those same researchers to develop disease-resistant cultivars in a fraction of the time it would normally take.[5]

In addition to a greatly accelerated flowering and fruiting cycle, the over-expression of the FT1 gene resulted in several other alterations in the typical growth and development patterns of the plum trees (see **Figures 2, 3 and 4**), which could allow these fruit trees to conform to the constraints of spaceflight agriculture[6].

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Figure 2

Figure 3

Figure 4

Many plants, particularly trees, exhibit apical dominance, which is the dominant growth of the central stem over the development of side branches. The over-expression of FT1 in plum trees seems to disrupt apical dominance, resulting in a more prostrate or bushy growth pattern (see **Figure 4**). The effect is sufficient, with moderate pruning, to allow the FT1 plum trees to be comparable in size to other herbaceous spaceflight candidate crops such as sweet peppers *(Capsicum annuum)* (see **Figure 3**). Further, this modified growth habit also seems to reduce the amount of wood production relative to fruit production. This could reduce the amount of inedible biomass that the overall life-support system would need to recycle, while improving the harvest index of the crop (see **Figure 2**).

Plant scientists and system engineers developing bioregenerative life-support systems strive to have consistent production of all the life-support services (air, food, water). In terms of food production this means that a candidate crop should either be easily staggered (i.e., planted at regular intervals to ensure continual production) or indeterminate (i.e., it grows and produces fruit continuously; e.g., vine tomatoes). Tree fruit species have not met either of these criteria until now. Under the influence of the FT1 over-expression, the plum trees developed by the USDA flower and fruit continuously, much like indeterminate tomatoes; they do not require a cold dormancy period for new flower buds to open.

Another note of interest is that, through sheer coincidence, there is a significant body of evidence to suggest that the phytochemical complement found in plums can prevent or even reverse bone density loss in terrestrial rodent and human models[7,8,9,10]. The ramifications of this are considerable, given that microgravity and ionizing radiation-induced bone density loss are major barriers to long-duration spaceflight. A recent NASA-led study has shown the intake of dried plums to be a very effective countermeasure against bone loss (in rodent models) resulting from exposure to ionizing radiation; exposure such as that which would be encountered during interplanetary exploration missions[10]. These findings once again demonstrate the bidirectional flow of scientific and technological developments between Earth and Space.

◀ Figure 2. Continuous fruit production results from FT1 over-expression, which not only allows for a continual plum supply, it also negates the need for a dormancy period in which the plant would no longer be contributing to air and water recycling.

◀ Figure 3. With moderate pruning the trees can be kept at a size compatible with spaceflight growth volume constraints. The FT1 plums are comparable to standard sweet peppers *(Capsicum annuum)* shown here.

◀ Figure 4. A further example of the morphological modifications associated with FT1 over-expression: the tall plant on the left does not over-express the FT1 gene, whereas the middle and right plants do.

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TERRESTRIAL APPLICATIONS

It is worth noting that the loss of chilling requirements due to FT1 over-expression can shed light on the mechanisms that govern fruit-tree dormancy. This information will be critical in efforts to adapt current food crops to climate change. As the range in which plums are currently grown warms, existing cultivars may no longer receive sufficient chilling to prompt flowering. The USDA's so-called FasTrack breeding system, combined with the knowledge gained from a better understanding of dormancy regulation through FT1 over-expression, may help to prevent the collapse of tree fruit crops, such as plums, in their current range.

The development of the FT1 plums was in no way motivated by spaceflight aspirations, rather it was firmly rooted in the need to address a very real threat to an important food crop on Earth. Regardless, the advances made by the USDA has helped NASA open the door to an entirely new class of candidate crops for bioregenerative life-support. In return NASA and the University of Guelph are developing the horticultural management protocols (such as vegetative propagation methods and controlled environment production) that will help the USDA further develop these plums for terrestrial applications, such as vertical agriculture and other high-density cropping systems. ES

Dr Thomas Graham is currently the Research & Development Manager at the University of Guelph's Controlled Environment Systems Research Facility, and former NASA Post-Doctoral Research Fellow at the Kennedy Space Center. He has been involved in controlled environment plant production research, including bioregenerative life-support, for nearly 20 years.

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Unlocking the lunar archive

Louise Alexander explains how the history of the Solar System is contained in lunar samples.

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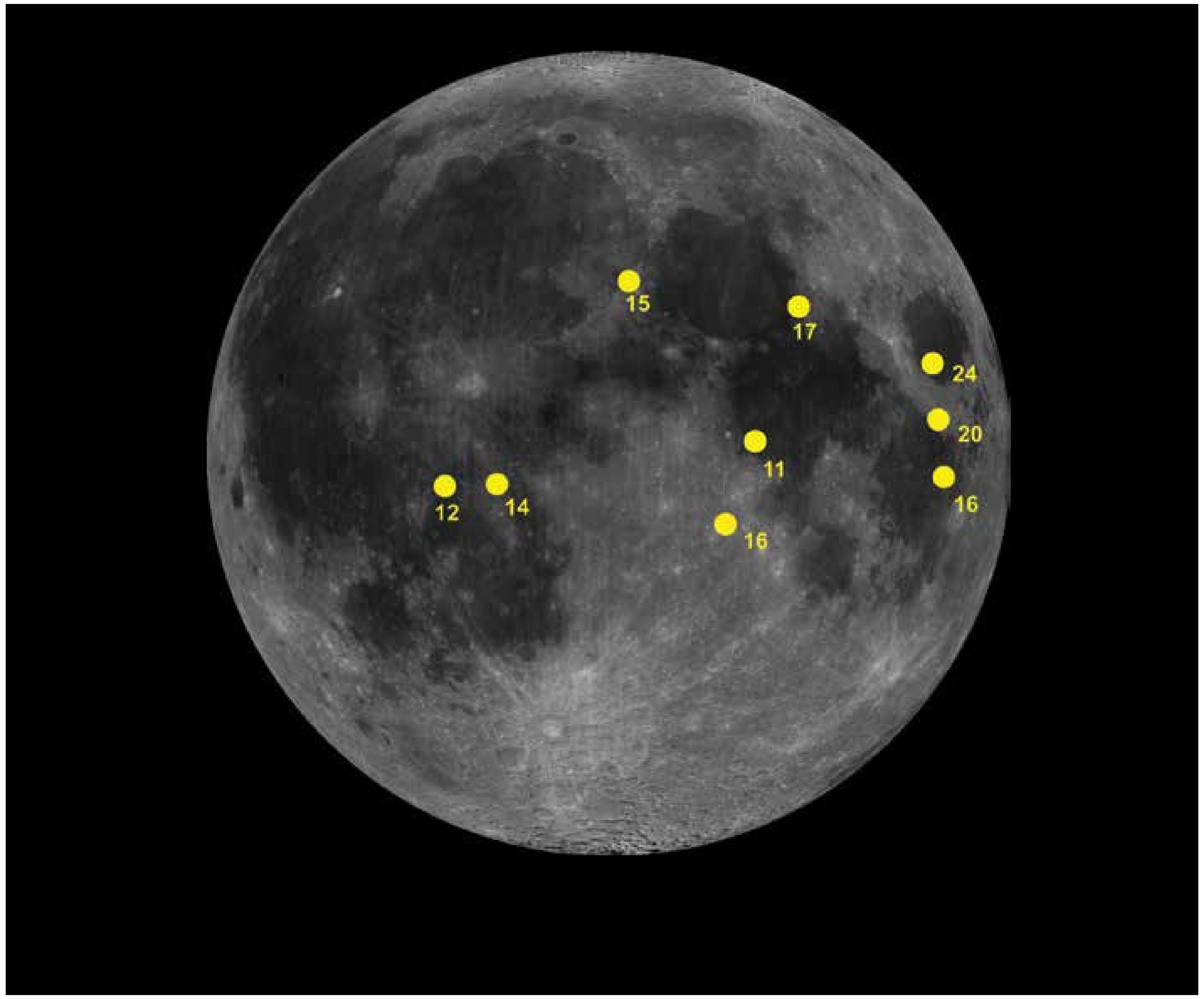
At an average distance of 384,400 km, the Moon is our closest neighbour in the Solar System and even from the Earth a variety of features on the lunar surface can easily be identified. With the naked eye the pale, ancient mountainous highlands can be distinguished from the darker, smooth basaltic lava plains (called Maria) and the numerous craters on the lunar surface give an indication of the ancient surface presented by this small body. While the Earth has a surface that is geologically active, with plate tectonics, resurfacing and weathering, together with a global magnetic field and a dense atmosphere, the surface of the Moon has been exposed to the space environment since the formation of the Earth–Moon system approximately 4.5 billion years ago. As a result the Earth has not retained a lot of its early history and collects less material from Space than the Moon. As our closest neighbour, and with no magnetic field or atmosphere, the ancient surface of the Moon has the potential to provide a valuable archive of information about early Solar System processes and about the accretion and evolution of planetary bodies, including formation of the Earth–Moon system[1], together with a detailed history of impact events that we are unable to gain from terrestrial studies.

> **“As our closest neighbour, and with no magnetic field or atmosphere, the ancient surface of the Moon has the potential to provide a valuable archive of information about early Solar System processes and about the accretion and evolution of planetary bodies.”**

Because the Moon has no magnetic field or atmosphere it is subject to intense bombardment by meteorites. This leaves behind the numerous craters on the lunar surface with a vast range of sizes, from micro-pits on glass beads up to the South Pole–Aitken basin, which is 2,500 km in diameter. This constant bombardment also breaks down the bedrock and mixes crustal materials to form the lunar regolith, a layer of unconsolidated and fragmental material that covers the lunar surface[2]. The lunar regolith is the main source of knowledge about the composition of the Moon, since most remote sensing measurements can only look at the surface, and the *Apollo* samples returned from the lunar surface were also mostly taken from the regolith.



▲ **Figure 1. Lunar nearside image taken by the Clementine mission to the Moon: Image number PIA00302 with *Apollo* (11, 12, 14, 15, 16, 17) and *Luna* (16, 20, 24) sampling locations highlighted. (NASA/JPL/USGS)**

LUNAR SAMPLES

Studies of these regolith samples have revealed a wealth of information about the Moon including details of the differentiation of this rocky planetary body and the composition of the lunar mantle (the layer under the crust)[1]. In addition, they have provided valuable information about the materials that the Moon collects and retains from the Solar System and galactic environment, including:

- Meteoritic material, which preserves a record of the evolution of small planetary bodies[3],
- Solar wind particles, which contain a record of the composition and evolution of the Sun[4,5]; and
- Galactic cosmic rays, which can provide information about the energy and matter present in the Solar System and beyond dating from the last 4 billion years[1,6,7,8].

The Moon is currently the most-sampled non-terrestrial body, and there are two main categories of material from the Moon: samples returned by missions and meteorites that have landed on the Earth's surface.

The *Apollo* missions to the Moon returned nearly 382 kg of material from six landings between 1969 and 1972 at sites on the lunar nearside (see **Figure 1**). In addition, 300 g of samples were returned by the Russian *Luna* robotic sample return missions (see **Figure 1**). These samples are still being studied today, as instrumentation improves and ideas and theories change. The study of samples returned from the *Apollo* missions can help to answer questions concerning the differentiation of the Moon and the evolution of the lunar mantle[1].

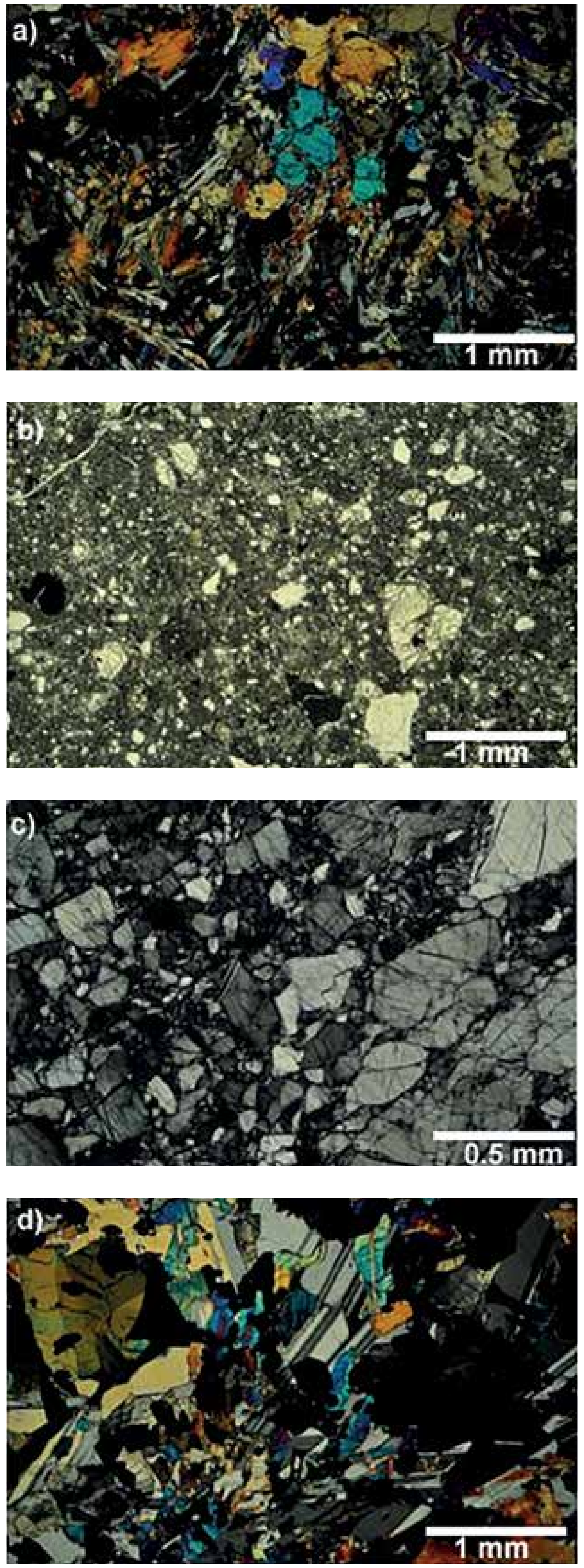
A problem with the returned samples is that they are from geographically restricted areas on the lunar nearside. Therefore lunar meteorites have provided additional material from areas not previously sampled, adding diversity to the lunar collection and extending our knowledge of the lunar surface. Differences in the chemistry of meteorites compared to the *Apollo* samples have shown that the Moon cannot be understood from the chemistry of *Apollo* samples alone[1]. Unfortunately, the sites where individual meteorites originated have not yet been accurately determined. Therefore, in order to understand how samples relate to a particular region of the Moon we need samples collected from specific sites, and this is why the *Apollo* samples are so important for these studies.

By examining the petrology and geochemistry of lunar samples and dating them, we can learn about their origin, the composition of the Moon and hence the heterogeneity of the lunar mantle as well as the formation of the crust and the duration and evolution of lunar volcanism. Dating lunar samples is important because the age of the lunar surface is calculated indirectly based on observational crater counts of the surface. Dates obtained from returned samples are used to calibrate these observed ages. Future missions will also hopefully return samples from the lunar poles which will help to answer questions about the amount and nature of volatiles present on the Moon, as it is believed that water ice is present in permanently shadowed craters at the poles[1].

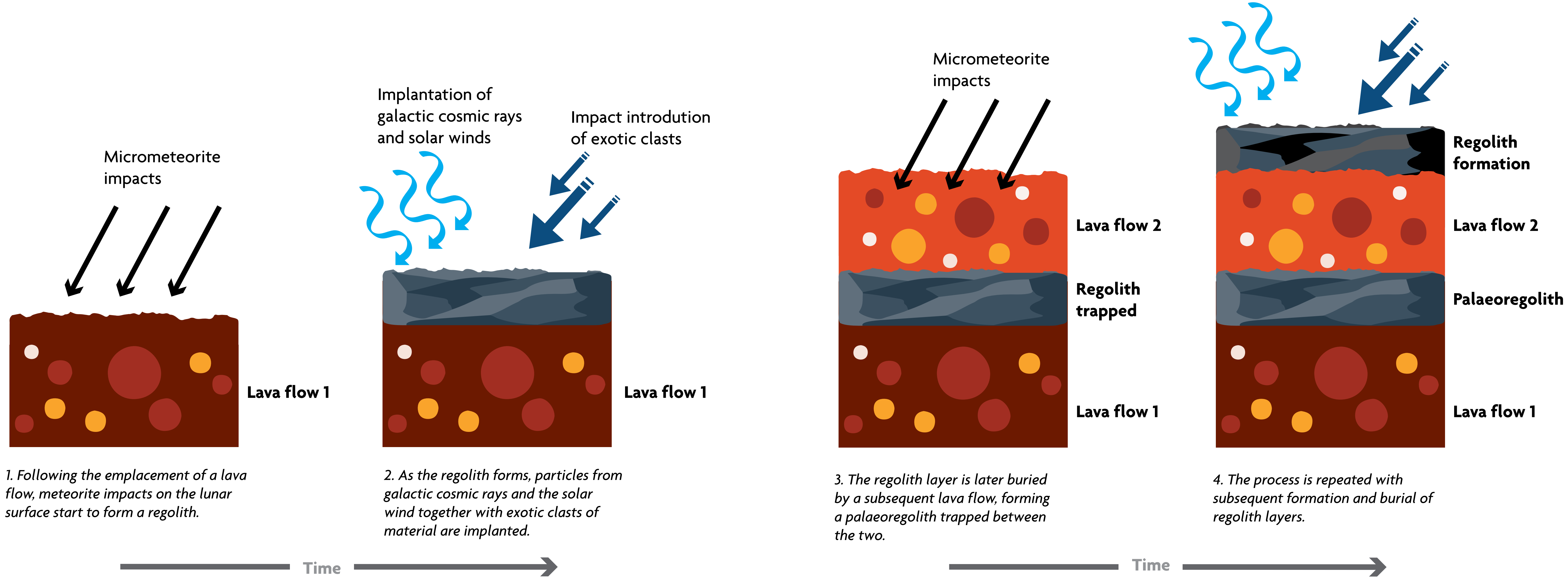
GALACTIC HISTORY

The Moon can also answer questions about the galactic environment. Since the formation of the Sun ~4.6 billion years ago, the Solar System has orbited the Galaxy approximately 20 times and been exposed to a wide range of galactic environments as it passes through the spiral arms and star-forming regions. Supernova explosions and associated supernova remnants occurring in close proximity to the Solar System as it passes through the Galaxy will result in an enhanced galactic cosmic ray (GCR) flux which may be recorded in the lunar geological record[7,8]. Reconstructing this history would provide information on the structure and evolution of the Galaxy and also information relevant to understanding the past habitability of our own planet[7,8] since an increased supernova rate would lead to an increased amount of radiation at the Earth's surface and therefore has the potential to influence life on Earth.

In order to examine this history, it may be possible to use cosmogenic nuclei in lunar regolith samples as a recorder of astronomically induced changes in the GCR flux[7,8].



▲ **Figure 2. Photomicrographs of different lunar rock types in cross-polarised light (a, c and d) and plane-polarised light (b). a) Low-titanium basalt, b) breccia, c) anorthosite (higlands rock), d) high-titanium basalt. (Louise Alexander).**



1. Following the emplacement of a lava flow, meteorite impacts on the lunar surface start to form a regolith.

2. As the regolith forms, particles from galactic cosmic rays and the solar wind together with exotic clasts of material are implanted.

3. The regolith layer is later buried by a subsequent lava flow, forming a palaeoregolith trapped between the two.

4. The process is repeated with subsequent formation and burial of regolith layers.

▲ **Figure 3. The formation of palaeoregolith layers[7,8] (Adapted from the Royal Astronomical Society/K.H. Joy).**

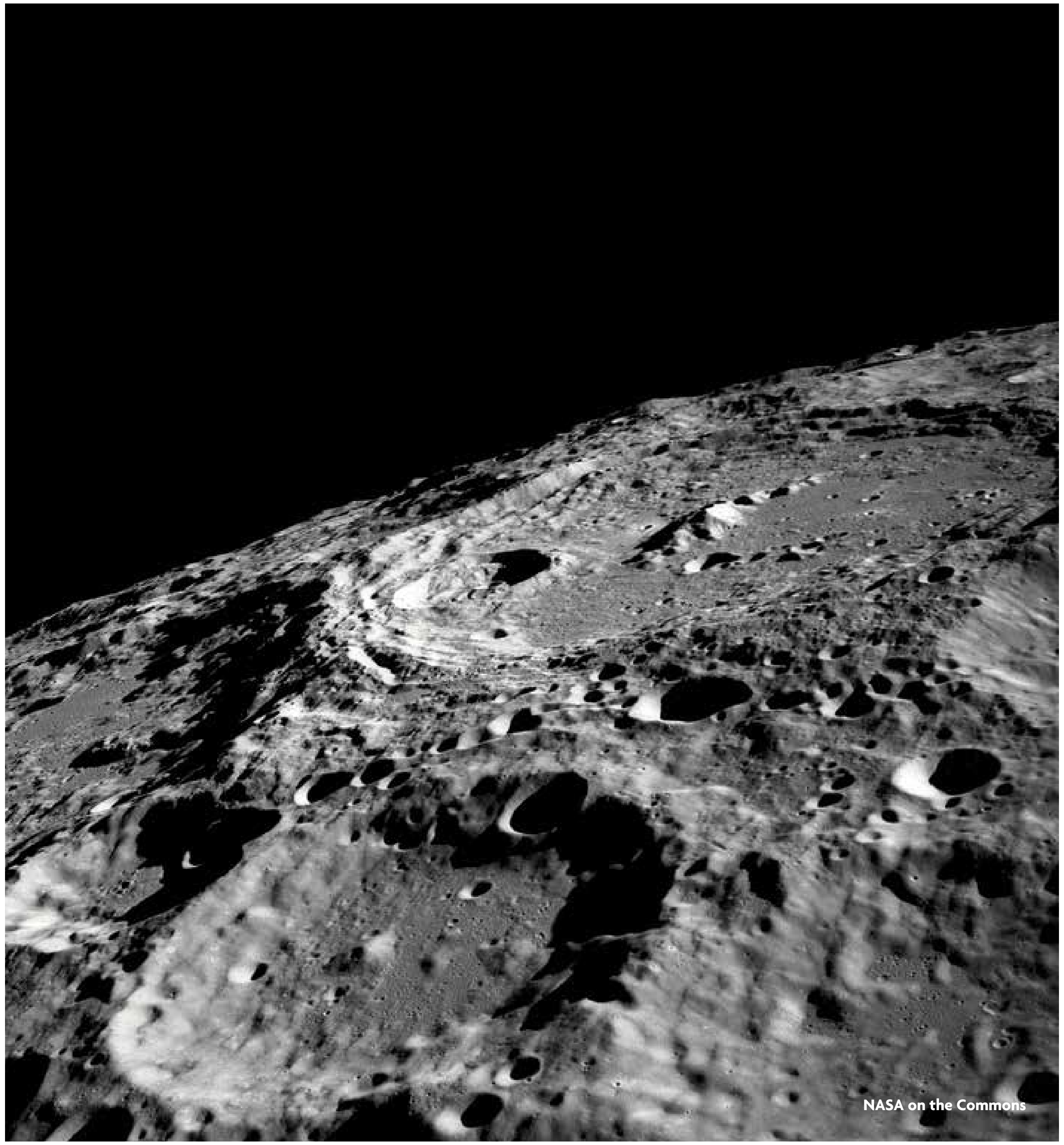
> **"Providing they can be effectively accessed, and the problems outlined can be overcome, then these lunar geological records could provide a unique archive of information about the early evolution and environment of the Sun, the Earth, the Solar System and the Galaxy"**

The solar wind and cosmic rays interact with the lunar regolith and form isotopes. Cosmogenic nuclei are produced by the interaction of high-energy cosmic rays with the nuclei of atoms in surface materials[9,10]. These can then be measured to calculate the exposure age of the samples, i.e. the length of time the sample was exposed to the space environment. The longer something has been exposed to cosmic radiation, the greater the concentration of cosmogenic nuclides. By measuring the concentrations of cosmogenic isotopes such as helium-3, neon-21 and argon-38 in lunar regolith samples of independently determined ages, it may be possible to provide an estimate of how the GCR flux has varied over time[7,8]. In addition, the solar wind exposure histories of the samples can also be investigated by measuring the concentrations of solar wind implanted argon-36 and argon-40.

There are a range of materials that exist in the lunar meteorite and *Apollo* sample collections that can be analysed in order to research these ideas (see in **Figure 2**). Samples available include samples from the pale lunar highlands (anorthosite) and samples of the darker mare basalts. These are the rock types visible from the Earth's surface. The most useful samples for this project however, are likely to be regolith breccias (composed of fragments of rocks in the form of mineral grains, clasts and impact melts set in a matrix of finer-grained materials), basaltic lavas and impact melt glasses. The GCR records will be obtained from independently dated samples with known exposure histories. However, one of the major problems with this is that it can be difficult to know how long samples have been exposed on the lunar surface. This is because smaller impactors continually mix material in the regolith at the surface in a process called 'gardening'. It can therefore be difficult to establish the accurate history for a particular sample, which may have been subject to different periods of burial and exposure on the lunar surface as a result of this. As such, it is one of the main limitations in interpreting the GCR record in this way[11,12].

MORE SAMPLING IS NEEDED

Providing they can be effectively accessed, and the problems outlined can be overcome, then these lunar geological records could provide a unique archive of information about the early evolution and environment of the Sun, the Earth, the Solar System and the Galaxy. However, with the samples available, it will not be possible to reconstruct the entire history and structure of the Galaxy. Therefore, locating suitable deposits for sampling is an important scientific objective for future



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lunar missions. In order to access this historical archive it would be particularly useful to find layers of ancient regoliths known as 'palaeoregoliths'. These are formed as lava flows cover existing regolith in a repeated process resulting in the formation and burial of subsequent regolith layers (see **Figure 3**)[7,8,13]. These palaeoregoliths contain material in different layers with potentially different cosmic ray histories. To collect samples of this type and to sample the different horizons within an outcrop will require advanced drilling and sample return capabilities. It is possible that such an ambitious mission will only be achieved as a result of future human exploration of the lunar surface. ES

Dr Louise Alexander is a post-doctoral researcher at Birkbeck, University of London, looking at cosmogenic isotopes in lunar samples. She is funded by the Leverhulme Trust (grant RPG-2015-020). Email: l.alexander@bbk.ac.uk Twitter @LouiseEAlex

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