Scientia

DRIVING DISCOVERY IN EARTH SCIENCE AND ASTRONOMY

HIGHLIGHTS:

- Understanding Permafrost Responses to Climate Change
- Exploring Winds in the Polar Thermosphere
- Measuring Meteorites to Reveal the Origins of the Earth
- Simulating Flows Between Clustered Galaxies

EXCLUSIVES:

- The Association for Women Geoscientists
- The Australian Meteorological and Oceanographic Society
- The African Astronomical Society

Issue: #140

WELCOME...

This exciting new edition of Scientia celebrates scientists who are driving discovery in Earth science, astronomy, and related disciplines.

With only days to go until the launch of the 2021 United Nations Climate Change Conference (COP26), our first section focusing on climate and atmospheric science is particularly pertinent. Here, we introduce researchers who are advancing our understanding of climate breakdown in all its complexity, including how aerosols are impacting the progression of climate change.

Next, our geophysics and planetary science section opens with an exclusive interview with the President of the Association for Women Geoscientists. We then showcase some of the most exciting geophysics research, before venturing beyond our atmosphere to explore the effects of the solar wind on Earth's magnetic field. We also meet scientists who are exploring strange phenomena on the Red Planet, and those who are advancing the quest to find extra-terrestrial life.

In our final section, we explore the mind-bending fields of astrophysics and cosmology. To introduce this section, we have had the pleasure of speaking with Dr Jamal Mimouni, President of the African Astronomical Association, who discusses astronomical achievements in Africa and how the Association supports and advances astronomy research and education across the entire continent. We then highlight three particularly exciting research projects – from advancing our understanding of how the universe evolved, to simulating the behaviour of plasma that exists within the unimaginably vast spaces between galaxies.

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Meet The Team...

CONTENTS

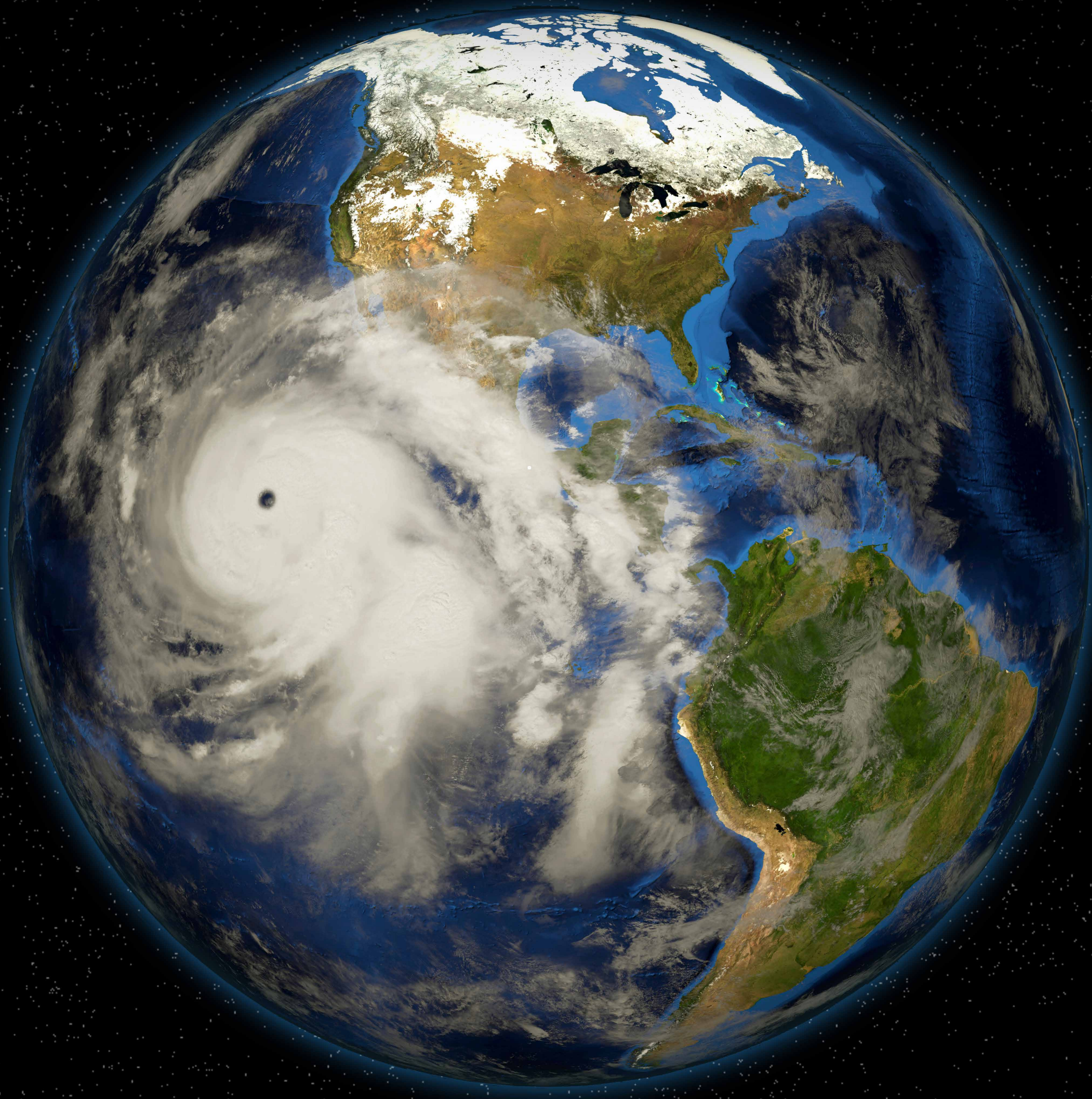
ISSUE : #140

CLIMATE & ATMOSPHERIC SCIENCE

GEOPHYSICS & PLANETARY SCIENCE

ASTRONOMY & COSMOLOGY

CLIMATE & ATMOSPHERIC SCIENCE



THE AUSTRALIAN METEOROLOGICAL AND OCEANOGRAPHIC SOCIETY

The Australian Meteorological and Oceanographic Society (AMOS) is an independent learned society representing over 500 atmospheric and oceanographic scientists. Its vision is to advance the scientific understanding of the atmosphere, oceans and climate system, along with their socioeconomic and ecological impacts, and promote applications of this understanding for the benefit of all Australians. In this exclusive interview, we speak with Angela Maharaj, President of AMOS, who describes how the Society advances scientific research and communicates the latest climate science to the public and policy-makers.

To start, give us a brief history of AMOS.

The Australian Meteorological and Oceanographic Society (AMOS) stemmed from the Royal Meteorological Society. Fellows of the Royal Meteorological Society resident in Australia, many of whom were eminent Australian meteorologists and oceanographers and Fellows of the Australian Academy of Sciences, forged an Australian branch of the Society in 1973. They subsequently helped with the transition to an Australian Meteorological and Oceanographic Society in 1987.

The society was initially established as a professional meteorological society, then a professional body for meteorology and oceanography. AMOS now represents over 500 members working and studying in weather, oceans, climate and other allied fields and we will be celebrating our 35th anniversary next year (2022).

In what ways does the Society advance and support scientific research?

AMOS members have historically collaborated on many international scientific initiatives such as the Global Atmospheric Research Programme, the World Climate Research Programme, Tropical Ocean Global Atmosphere program and of course the International Panel on Climate Change (IPCC). An important national contribution is on a suite of modelling systems for weather, climate and Earth systems, known as ACCESS which stands for The Australian Community Climate and Earth-System Simulator.

AMOS supports our members in their work, most ostensibly by providing national and international conferences for members to present and discuss their research. AMOS also provides workshop opportunities to help researchers at all career stages with broadening and advancing their skillsets.

In the past 12 months, we have held science workshops on radar, air quality, probabilistic forecasting. We also regularly hold workshops to help our members improve more generic skills such as data management, software carpentry, stakeholder engagement and science communication.

How does AMOS foster interest in meteorology and oceanography amongst people of all age-groups?

Our regional chapters run local science talks and National Science Week events. Public symposia are a common feature of our annual conference where we also offer a Teacher Open Day. School teachers can attend our conference for free on that day and use the opportunity to engage with AMOS scientists and attend our education and outreach special session.

Our education and outreach committee runs art competitions with stage categories ranging from childcare through to high-school. Bringing in the childcare category was a great way to engage with a younger demographic than in we had in the past. We use artistic and scientific criteria in the judging. We also sometimes run a weather forecasting video competition where school children send us their version of a news weather forecast. We were lucky enough to have a well-known forecaster help us create a training video with tips on how best to do this, and the competition aligns well with early-stage school curricular.

'Australian mean temperatures have increased by more than 1.4°C since the early 20th century. That is a greater increase than global average temperatures which have increased by closer to 1.1°C.'

We don't just cater to the young. A number of our members regularly present talks for Probus and Rotary clubs as well as the University of the Third Age (U3A). We also offer an AMOS enthusiast membership category at a very reasonable rate so that those who have a keen interest in our sciences but wouldn't meet the professional member criteria can also be part of our community.

Describe how Australia's climate is changing in recent years, and what your members' research has shown.

Australian mean temperatures have increased by more than 1.4°C since the early 20th century. That is a greater increase than global average temperatures which have increased by closer to 1.1°C. Australia is particularly vulnerable to the impacts of climate change. We are expected to experience not only intensified extreme events such as droughts, floods, heatwaves and bushfires but also increased coastal erosion and flooding due to sea-level rise.

AMOS members contribute to a range of important research in weather and climate. For example, Australia is known as a land of extremes and understanding rainfall predictability and the nature of droughts is a national priority in our research. Many of our members are attempting to understand the key drivers of precipitation and its variability. Australia's reliance on our oceans for food, recreation and defence has also driven a focus on oceanographic research.

But I suppose our members' contributions to anthropogenic climate change research is the highest profile work right now. Many of our members contribute to this research from assessing climate risks at a local level through to participating in global modelling efforts such as the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP).

Finally, how does AMOS inform the public and policy-makers about climate change, and the need for drastic action?

Our outreach efforts are a key strategy for informing the public about climate change. We also produce information and position statements as well as engage in government consultation. We are currently developing a new climate change statement in line with the release of the IPCC AR6 report which hopefully will be reviewed by members and ready for release in time for COP 26.

We use our statements to communicate key scientific messages on climate change, often with a national focus and in simple enough language to be useful to a range of stakeholders. This is an important role for the Society. Many of our professional members are not in a position to publicly make personal statements on policy positions. It can be a tricky balance for those who work outside of academia such as in government agencies or for private companies. The society with its critical mass and scientific clout is able to provide a voice for the entire scientific community. I believe this is one of the main benefits of membership into a learned and professional society like AMOS.

www.amos.org.au

Australian Meteorological & Oceanographic Society

UNDERSTANDING PERMAFROST RESPONSES TO CLIMATE CHANGE

It is not just the polar ice caps that are melting. On our warming planet, the ice buried within the layers of ground around the Arctic Circle is thawing, irreversibly changing these spectacular landscapes and posing risks to the communities that call these areas home. Understanding the dynamics of 'permafrost' is vital for predicting its future responses to climate change. The long-term research of permafrost expert **Dr Christopher Burn**, from the Department of Geography and Environmental Studies at Carleton University, Canada, is integral to shaping our collective knowledge of these icy environments.

Revealing Our Planet's Frozen Secrets

In the vast dramatic wilderness of northwest Canada, you could be forgiven for thinking that you are far outside the influence of human activity. But in places on Banks Island and near the western Arctic coast, the ground is quite literally falling apart.

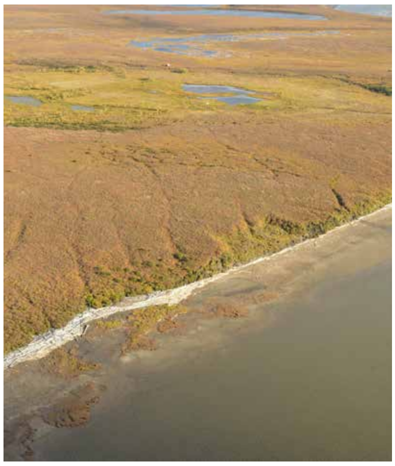
In its simplest terms, this is because rising temperatures and increasing rainfall are causing frozen soils and ice deposits – formed over thousands of years – to melt away. With the icy scaffolding removed, surface soils collapse in on themselves. For people inhabiting these remote regions, permafrost thaw threatens transportation and other public infrastructure, while at the coast enhanced erosion is rapidly removing the ground.

With climate change progressing at an alarming rate, understanding the dynamics and processes behind *permafrost* – ground in and around the circumpolar North and in high mountains that has remained at or below 0°C for at least two consecutive years – is becoming increasingly important.

World-leading permafrost expert and President of the International Permafrost Association, Dr Christopher Burn, has devoted his research career to shaping our knowledge of permafrost terrain. Building on the work of the late Dr J. Ross Mackay, Dr Burn's field research near Mayo, central Yukon, and the Mackenzie Delta area, Northwest Territories, began in 1982. His research includes observations from Illisarvik, the lake experimentally drained by Dr Mackay in 1978, which is the longest continuously monitored permafrost field experiment in North America.

With data collected from remote field sites even in the gruelling depths of the Arctic winter, Dr Burn's long-term research provides field evidence to predict the response of permafrost to future climate change.

His team's research has covered four overarching themes. First, he focuses on understanding the factors controlling the variety of permafrost environments in western Arctic Canada. The second theme aims to elucidate the Earth surface processes that shape the geomorphology of permafrost landscapes. The third focuses on building our understanding of permafrost responses to climate change, and finally, he aims to help manage and mitigate the effect of climate warming on infrastructure in permafrost environments.



The Illisarvik lake basin, Richards Island, Northwest Territories, Canada. The basin was drained on 13 August 1978 in a full-scale field experiment to study the growth of permafrost.

A block of permafrost eroded from the north coast of Pelly Island, Northwest Territories. The active layer is at the top of the ground and below it there is a black layer of organic-rich permafrost. This is an example of the material that may lead to emission of CO_2 or methane.

A 10-metre-high exposure of ice-rich permafrost near Mayo, Yukon. The uneven texture is from veins and lenses of ice. The horizontal line separating the light-coloured ground from the dark material represents the deeper active layer of the early Holocene climate optimum.

'The ultimate justification for the research is to assist regulators of development projects and operators of public infrastructure to identify and manage risks to new facilities and the transportation network posed by climate change and ground-ice dynamics,' explains Dr Burn. His research helped to inform the public review of the proposed Mackenzie Gas Project (2003–2010) and development of the all-weather road between Inuvik and Tuktoyaktuk in the Northwest Territories (2012–2017).

Permafrost Structure

Permafrost terrain consists of an 'active layer' – or seasonally thawed layer – underlain by perennially frozen ground. Permafrost varies in thickness between regions from a few metres in southern Yukon to over 600 metres near the western Arctic coast, 1000 kilometres further north. The differing depths reflect the varying ground conditions controlled by climate, with a mean annual ground temperature of around −1°C in southern Yukon, and around −7°C at the coast. Dr Burn's research has captured data from sporadic discontinuous permafrost, where only 20% of the surface is underlain by perennially frozen ground, to continuous permafrost in the western Arctic, where permafrost is ubiquitous.

Long-term observations from the Illisarvik site have shown that the active layer in Canada's Arctic is growing steadily thicker in response to climate warming. In other words, the depth of seasonal thaw is increasing with each passing year. By 2018, the active layer in tundra near Illisarvik was 10 centimetres deeper than 35 years prior. The deepest available measurements show temperature changes in permafrost since 1970 extending to depths of 53 metres, while calculations suggest the warming has reached 120 metres depth. The ground warming has been accompanied by subsidence of the surface, at rates measured near Illisarvik of over 3 centimetres per year since 2006.

Although permafrost is defined purely in terms of temperature, the ice content controls the loss of structural integrity when such ground thaws and its deformation when it freezes. Permafrost ice may consist of veins and lenses of various sizes interspersed with soils and rock or bodies of massive ice. Some of these massive ice bodies have survived since the last Ice Age, and are only now becoming exposed. Other ground ice has developed in the soil itself, forming lenses that are millimetres to centimetres in thickness.

The distribution of ground ice shapes the permafrost landscape. *Thermokarst* describes terrain with ditches, marshy hollows and lakes, formed as ice in the ground melts. The occurrence of thermokarst, especially large thaw slumps, is increasing in the western Arctic.

Because the structure and dynamics of permafrost vary greatly across spatial scales, Dr Burn's investigations have spanned from the sub-millimetre scale – such as the movement of water through soil pores towards the freezing front – through to scales of thousands of kilometres. Investigating such large scales is necessary for understanding the original development of permafrost in the tectonically active setting of northwest Canada.

A Hidden Threat

Thawing permafrost has consequences more insidious than slumping ground damaging infrastructure and the beauty of the natural landscape. Permafrost formation halted many natural processes in these soils, such as vegetation decomposition, effectively trapping carbon, which would otherwise have been released into the atmosphere as carbon dioxide or methane. As the permafrost thaws, this carbon can now be released to enter the global carbon cycle, enhancing the greenhouse effect and contributing to climate warming.

Dip in a road surface near Tuktoyaktuk, Northwest Territories. Only two weeks before this photograph was taken the road had been levelled. The subsidence is due to melting of ground ice below the road.

Permafrost ranges in age from a few tens of years to hundreds of thousands of years old. Some of the oldest permafrost ice discovered, from Dominion Creek in the Klondike gold fields of Yukon, is around 750,000 years old. As such, thousands of years' worth of carbon could be lurking beneath the surface like a ticking time bomb. The thawing process could lead to a devastating positive feedback loop – as more carbon escapes throughout the circumpolar North, climate warming is accelerated, causing more permafrost to thaw and release more carbon, and so on. Most permafrost carbon is contained in the uppermost 2 metres of permafrost, meaning that its release may begin relatively soon, potentially over the next century.

However, much of the world's deep permafrost has survived the warmer periods in between the colder glacial periods of the planet's history. Dr Burn's research examining the dynamics and response of permafrost helps to quantify the risks. He has examined timescales ranging from epochs – more than three million years – through to thawing patterns within a single season. 'Integration of processes active at these different scales is required not only to understand the genesis of the landscape, but also the response of the landscape to thawing,' he explains. In the early Holocene, about 9,000 years ago, active layers were about 1 metre thicker in the western Arctic than at present, partly due to a warmer climate and partly because the coast and the cooling influence of the ocean were a further 50–100 kilometres north of their current location.

Dr Burn's work on the patterns of climate warming also suggests that the magnitude of changes across permafrost terrain may not be uniform. Although annual mean air temperatures have increased across Canada since 1970, in the western Arctic the rate has been 0.75°C per decade, while in other areas the rate is lower. In southern Yukon, for example, the increase is about 0.45°C per decade. Adding a further layer of complexity, these increases have not been uniform across all seasons, with warming particularly significant during the autumn and winter months. Nevertheless, conditions similar to the early Holocene may reoccur before the end of this century.

Putting Research into Practice

Permafrost research in many countries is a relatively new. According to the *Web of Science*, before 1990 fewer than 60 research papers in permafrost science were published in peer-reviewed journals each year. A surge in permafrost research since then, especially in the last 15 years, has led to this number reaching over 1800 articles per year by 2020. This increase in interest was partly catalysed by the International Polar Year of 2007 to 2009 – an extended observation period allowing for a complete annual cycle in both the Arctic and Antarctic regions – with coordinated study of the polar regions by scientists from across the world, but also by the widespread interest in the changing Arctic. Because of permafrost science's short history, Dr Burn's field evidence spanning more than 40 years is remarkably valuable and unique.

Building positive relationships with First Nations people and Inuvialuit field partners has allowed Dr Burn to collect data from remote field sites during the inhospitable and treacherous winter months. Only residents can provide valuable observations year-round. 'The field observations we have reported from these sites will remain foundational information for the region, because it is most unlikely that new programs will be sustainable in such areas in the next few decades,' says Dr Burn.

Mitigating the risks to infrastructure and communities in these Arctic and sub-Arctic permafrost regions posed by a changing climate requires the regional geographic knowledge and perspective offered by Dr Burn's work. 'However, to be effective, this information must be available and useful to engineers, planners, and others who are responsible for implementing adaptation projects,' he says. In addition to his collection of published research papers, Dr Burn has also made his approach and findings available to non-specialists by authoring two books.

With the dynamics of permafrost terrain likely to switch from being dominated by freezing to being dominated by thawing over the coming decades, Dr Burn's research is going to become increasingly significant. Although halting the devastating effects of climate change may be an impossible goal, the work of researchers like Dr Burn may help northern residents, communities, and agencies adapt to the inevitable difficulties.

Meet the researcher

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Having completed his undergraduate degree at the University of Durham, UK, Christopher Burn moved to Canada, earning both his master's and doctorate from Carleton University. He currently holds the position of Chancellor's Professor at Carleton University's Department of Geography and Environmental Studies, and is also the President of the International Permafrost Association. Dr Burn's commitment to long-term field investigations has helped to shape our understanding of permafrost. His research interest is particularly focused on the relationship between permafrost and climate, providing valuable tools to predict the response of these terrains to future climate change and to ensure the continuing integrity of infrastructure built on permafrost. In 2018, he was awarded the Canadian Polar Medal and a DSc by Durham University for his contribution to permafrost research. In addition to his research activities, Dr Burn also devotes time to supervising Carleton University's Graduate Programs in Northern Studies, and lecturing on permafrost.

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The late Dr J. Ross Mackay, University of British Columbia, Canada
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Aurora Research Institute, Inuvik
First Nation of Na-Cho Nyak Dun, Mayo
Northwest Territories Geological Survey, Yellowknife
Geological Survey of Canada, Ottawa

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Carleton UNIVERSITY

PROTECTING ARCTIC INFRASTRUCTURE AS THE PERMAFROST DEGRADES

Roads, bridges, and airports are now being built all across the Arctic. However, as this happens, the future of the sturdy permafrost these structures are built upon is looking increasingly uncertain. In his research, **Dr Marolo Alfaro** at the University of Manitoba uses both computer modelling and real-world sensing to assess the impact that the Arctic's warming climate is having on this infrastructure. Starting from analysis of a newly-constructed highway in Canada's Northwest Territories, his team's efforts could soon provide local communities with vital guidance as to how their infrastructure should be maintained and protected.

Building on Permafrost

Covering roughly 15% of the entire surface of the Northern Hemisphere, permafrost can be found extensively within Arctic regions, where temperatures rarely rise above freezing. Within this ground, materials including soil and rock are held together by solid ice, making it incredibly hard and incompressible.

Although regions containing permafrost are some of the most sparsely populated places on Earth, there are still many thousands of people who call them home. As a result, engineers have needed to overcome enormous challenges to design, build and maintain the infrastructures required to connect these communities with the rest of the world.

Dr Marolo Alfaro and his colleagues at the University of Manitoba play an important role in these efforts. 'Our research involves evaluating the performance of a variety of infrastructure projects that include highway embankments, riverbanks, hydroelectric facilities, and underground nuclear waste repositories,' he explains.

In many cases, highway embankments – raised areas that allow roads to smoothly pass across rough terrains – are built using compacted, locally-sourced permafrost as a fill material. In recent years, however, this frozen fill material has come under increasing and unprecedented threat. As the climate warms due to human activity, nowhere on Earth is experiencing a faster rise in temperature than the Arctic. Increasingly, local communities are finding that the near-constant freezing temperatures required to sustain frozen fill material can no longer be relied upon.

Providing Smart Recommendations

When temperatures rise above 0°C, structures built from frozen fill material, as well as the permafrost they are built upon, can be far more easily distorted under their own weight. Such deformations lead to cracks in the fill material, which remain when the

temperature drops back down below zero, threatening the stability of entire structures.

Already, many Arctic communities are suffering from these damages, and must spend increasing amounts of time and money to maintain and repair vital infrastructures. To assess this impact, Dr Alfaro and his team use cutting-edge computer simulations to predict how real-life structures will deform and crack as temperatures rise. 'These studies are providing important guidance for advanced design and

The Inuvik to Tuktoyaktuk Highway

construction practices, by providing engineers with modelling and analysis recommendations,' says Dr Alfaro. 'This helps them to predict and mitigate excessive deformations and instabilities of earth structures and foundations.'

The quality of predictions made using these models can be improved by incorporating real climate data, gathered by both satellites and ground-based weather stations. Crucially, this enables researchers to compare their results with measurements of deformations in real structures – allowing them to fine-tune the predictions of their simulations. Ideally, these models could one day allow Arctic communities to monitor their infrastructures in real time – informing them when and where maintenance needs to take place. Yet before this can happen, several key challenges must first be addressed.

Studying Structural Stability

To ensure the best possible accuracy in their models, it is crucial for researchers to characterise the mechanical properties of particular structures. So far, Dr Alfaro and his colleagues have largely focused on highway embankments. In the Arctic, embankments are often constructed using frozen fill material, sourced from nearby permafrost.

Prior to their latest research, Dr Alfaro's team remained uncertain of the mechanical behaviours exhibited by embankments as they experience natural thawing. This created the goal of accurately describing the strength and deformation of their constituent fill materials as they thawed over summer, and froze over winter. In particular, the researchers would focus on three key aspects of embankment deformation.

Firstly, to comply with road construction standards, embankments can often reach several metres in height. As permafrost degrades, these embankments are particularly vulnerable – causing material to slough away from their sides. The problem can be further exacerbated as permafrost thaws beneath embankments, compressing under the weight of the structures. Finally, variations in the material structures of fill and permafrost can create weak points in embankments, further threatening their stability.

Together, these factors threaten to render vital roads undriveable. For Dr Alfaro and his colleagues, this made it incredibly important to investigate how embankment deformation mechanisms are triggered, and to recreate the behaviour as accurately as possible in their models. In 2017, the team was presented with an ideal opportunity to address these issues.

The Inuvik to Tuktoyaktuk Highway

That year, a new highway opened in Canada's Northwest Territories, linking the Arctic communities of Inuvik (which was already connected to the outside world via a highway) and Tuktoyaktuk – a previously isolated village on the coast of the Arctic Ocean. As the first road to Canada's Arctic coast that can be driven on year-round, the project was an enormous feat of engineering, costing $2.2 million per kilometre to construct, and another $12,000 to $15,000 per kilometre to maintain each year.

For Dr Alfaro's team, the highway was the perfect testbed for assessing the capabilities of their models. In their experiment, they fitted several embankment sections along the road with sensors to monitor their temperatures, and to detect any mechanical deformations.

In addition to these efforts, they also assessed the performance of a technique commonly used to protect embankments against thawing – based on hardy, permeable fabrics named 'geotextiles'. When placed in the embankment side slopes, this material can reinforce the weakened slopes during thawing, while also improving the drainage of meltwater during the thawing season.

Assessing Year-round Changes

Over the six years following the highway's construction, Dr Alfaro's team closely monitored any changes in the highway's embankments. In the test sections, they found that the central and lower portions of embankment remained frozen over the summer, even as air temperatures occasionally rose above 0°C. Compared with uncovered embankments, thawing rates were higher at the very bottom, where the slopes reached the ground.

Altogether, these results confirmed a critical need for researchers and engineers to consider both the near- and long-term impacts of climate change as they design and construct embankments, and draw out plans for their maintenance. In addition, they provide important recommendations for the team's modelling techniques.

By adapting simulations to recreate their field observations more closely, the researchers hope that highway operators could use them to accurately assess the impact of thawing on embankment deformation. Furthermore, this could be done without relying entirely on real-time sensing techniques – which can't realistically be applied along the entire length of a highway.

Improving Infrastructure Designs

The team now plans to expand on these efforts even further. 'Our recent research improves the design and performance of Arctic transportation infrastructure, related to the effects of climate change,' Dr Alfaro describes. 'It provides recommendations for modelling and analysis that help engineers predict and mitigate excessive deformations and instabilities.'

Alongside the use of geotextiles, the researchers also plan to test out a wide variety of other methods to mitigate against excessive embankment deformations and instabilities. Among these is the use of 'geogrid-geofoam composite'. Geogrid is a type of geosynthetic used as reinforcement, while geofoam is a form of polystyrene that is often used as an insulator

and lightweight embankment fill material. When placed over roughly-textured ice on the ground, it can prevent the permafrost underneath from thawing over the summer. If it does thaw, the geogrid-geofoam composite will bridge any empty gaps that form beneath the embankment.

Another proposed method suggests that thawing could be accelerated before embankments are built. Once the road is constructed, the structures won't deform as readily as the permafrost and fill material thaws naturally. Alternatively, some researchers suggest that heat exchange devices could be incorporated into embankments, which continuously cool the permafrost and fill material, after the road has been constructed.

As each of these methods are considered, a combination of field experiments and precise computer models will be vital, as researchers, engineers and highway operators determine the future of Arctic infrastructure.

Securing the Arctic's Future

In the coming years, local authorities predict that the usage of the Inuvik-Tuktoyaktuk highway will steadily increase, especially due to tourism and mining. Furthermore, a recent uptick in economic activity across the Arctic has led to unprecedented rates of road construction. As this happens, rapid warming in the Arctic is widely expected to accelerate, making it ever more important to monitor highway embankments, and to provide adequate resilience against future degradation of fill material, and the permafrost underneath.

Dr Alfaro's team also hopes that the scope of their research could soon expand to consider many other types of infrastructure – each vital to sustaining remote Arctic communities. 'The outcomes of this research project are also applicable to other northern transportation infrastructure including airports, railways, river crossings, pipelines, and electric transmission lines,' Dr Alfaro summarises.

With increasingly large swathes of the Arctic experiencing above-zero temperatures for a significant portion of the year, the experimental results and modelling techniques produced by Dr Alfaro and his colleagues come at a crucial time. Through the profound changes to come, the team's efforts could provide communities with the vital tools they need to survive in a rapidly changing world.

Meet the researcher

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Dr Marolo Alfaro is a Professor in the Department of Civil Engineering at the University of Manitoba. He has worked as a geotechnical engineering consultant for a wide range of infrastructure projects. His research focuses on structures built using earth fill materials and reinforced soil – including hydroelectric dams, pile foundations, stabilised artificial slopes, and underground disposal sites for nuclear waste. He is now a member of the Canadian Geotechnical Society's Research Board, where he will serve as Chair after 2023. In 2019, Dr Alfaro received the Society's Geosynthetics Award, recognising his outstanding contributions to the applications of geosynthetics in civil, geotechnical and geo-environmental engineering, both in Canada and internationally.

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FURTHER READING

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University of Manitoba

MAPPING THE IMPACT OF CARBON EMISSIONS ON THE OCEANS

The climate crisis and the chemistry of the oceans are inextricably connected. The oceans have absorbed close to a third of our carbon dioxide emissions since the beginning of the Industrial Revolution, leading to an increasingly acidic environment and making it more difficult for organisms such as corals, molluscs, and plankton to form their shells and skeletons. Mapping future changes in ocean chemistry is the first step in developing mitigation strategies. However, our knowledge of the future state of the oceans relies on mathematical models that are often not calibrated with modern ship-based observations. **Dr Li-Qing Jiang** of the University of Maryland and his collaborators are improving ocean acidification predictions by coupling millions of past and present ocean chemistry measurements with the best model projections at each location of the global ocean.

The Ocean as a Carbon Sink

The global oceans have absorbed about 30% of the carbon dioxide released by human activity over the past 200 years. As it dissolves in seawater, carbon dioxide reacts with water to form a weak acid called carbonic acid. Therefore, as atmospheric carbon dioxide increases, so does the acidity of the oceans – a process called ocean acidification.

When ocean acidity rises, calcium carbonate saturation – which describes the tendency of calcium carbonate minerals to form or dissolve – decreases. As many marine organisms need calcium carbonate minerals to build their protective shells and skeletons, they can suffer from slow growth and even dissolution when the ocean is too acidic. Ocean acidification is already having catastrophic effects on coral reefs, some of the world's most important and biodiverse ecosystems.

With increasing acidity, however, we stand to lose more than just coral reefs. Ocean acidification, in conjunction with future climate change, could cause a knock-on effect on the whole marine food web. A decline in these species, which are prey for larger creatures, would also be disastrous for the commercial fishing industries and the people who rely on them.

Mitigating the worst effects of ocean acidification requires knowledge of how fast ocean chemistry is changing and which areas are most vulnerable. Past and future ocean acidity can be extracted from global mathematical models of the whole Earth system. However, precise predictions for the future require accurate past and present ocean chemistry records.

Dr Li-Qing Jiang of the University of Maryland, and his collaborators at the NOAA's Pacific Marine Environmental Laboratory in Seattle and the University

of Bergen in Norway, use state-of-the-art mathematical models, along with modern seawater measurements spanning the entire globe, to provide better ocean acidification predictions than ever before.

Using millions of measurements, Dr Jiang's team can more accurately map ocean chemistry and predict variations in the ocean's response to

human carbon emissions on a regional scale. Building an accurate map of future ocean acidification is critical for Earth's large coastal populations. Such communities not only rely on the oceans for their food, but coastal economies are also heavily dependent on the aquaculture and tourism industries.

Measuring and Predicting Ocean Acidification

There are several different ways to assess ocean acidification, but two of the most common indicators are ocean pH and calcium carbonate saturation. These two metrics are sensitive to carbon dioxide emissions, and they both play a role in the health and wellbeing of marine ecosystems.

Some pH measurements date back to the early 20th century, but early records suffer from larger uncertainties and can be unclear about the measurement methods used, making it difficult to compare them with current data. For example, until the late 1980s, scientists typically measured pH with glass electrodes, which have high measurement uncertainties. More precise measurements are now possible due to the development of spectrophotometric techniques, where a pH-sensitive dye is added to seawater samples.

Dr Jiang and his colleagues use modern, accurate carbon dioxide measurements from the Surface Ocean CO2 Atlas (SOCAT) data product to calculate pH and combine the data with Earth System Models to build a trajectory of past, present and future ocean acidity for all locations of the global ocean. They were able to derive 23 million surface ocean pH values based on carbon dioxide measurements collected between 1991 and 2018, with historical and future trends from an Earth system model. Models can give accurate predictions of the temporal pH change, but the team's addition of local observations means better predictions of regional acidification trends, which could help guide local adaptation strategies. The result is a detailed map of surface ocean acidity changes spanning the past and present, and more accurate predictions for the future.

Dr Jiang and his colleagues discovered that the average pH of the ocean surface fell by 0.11 between 1770 and 2000, meaning that the ocean is now 30% more acidic than in pre-Industrial times. The drop is more prominent in areas where the ocean has a lower buffer capacity – which is a measure of how much carbon dioxide can be added before profound chemical changes occur. The Arctic Ocean showed the most considerable decrease in pH of 0.16.

Using a range of possible future emissions scenarios, the team predicted future changes in ocean pH. Assuming a 'business as usual' scenario in which our current emissions trajectory continues, known as RCP 8.5, ocean surface pH is expected to decrease by about 0.33, corresponding to an acidity rise of over 110%, between 2000 and 2100. This value is larger than the entire modern pH range of surface seawater. Under RCP 4.5, described as an intermediate scenario, pH would decrease by 0.13.

The most significant pH changes will occur at high latitudes, while regions of upwelling around the equator will

change more slowly. This is because rising deep water tends to have low concentrations of human-produced carbon dioxide.

Perhaps most worryingly, the buffer capacity of the ocean is projected to decrease. While the sea will continue to take up more carbon dioxide in the future due to the higher levels of atmospheric carbon, its role in absorbing emissions will gradually diminish. With a reduced buffer capacity, the chemical changes observed by Dr Jiang and his colleagues will accelerate.

Mapping the Saturation of Aragonite

The shells and skeletons of marine organisms are made up of calcite or aragonite – two mineral forms of calcium carbonate. Oceanographers are particularly interested in aragonite, which is more soluble than calcite. Organisms with aragonite skeletons include some species of coral, plankton, and molluscs. When aragonite saturation in the water is low, meaning that aragonite has a tendency to dissolve, these organisms struggle to grow. Therefore, aragonite saturation in seawater is a valuable indicator of the ecological impacts of ocean acidification.

Dr Jiang and his colleagues found that between 1970 and 2010, aragonite saturation decreased by 0.4% per year – a critical indicator that ocean acidification is taking its toll. While most of the tropical and subtropical ocean still has high aragonite saturation, there are significant zones of low saturation around the polar regions.

The team's research has highlighted vulnerable areas where aragonite saturation is already low, such as the high latitude areas. Deep water in the North Pacific Ocean and the northern Indian Ocean is deficient in aragonite because it is older than deep water in the Atlantic – meaning it has spent more time accumulating carbon dioxide at depth. Chemical reactions caused by the decay of organic matter create a build-up of carbon dioxide in the deep ocean, making it more acidic. In the surface, aragonite saturation is lower in areas where more acidic water from the deep sea rises to the surface, adding to the acidity caused by human emissions.

Dr Jiang's work also highlighted that at the ocean's surface, pH is relatively uniform across the globe, but aragonite saturation is lower near the poles and higher near the equator due to the temperature difference. Because aragonite saturation varies with temperature, future predictions of aragonite saturation will need to take into account changes in sea surface temperature in a warming world.

Predicting the Trends of Acidification on a Local Scale

Dr Jiang and his colleagues have recently been funded to synthesise and quality-check ocean acidification data in coastal areas, where it can have significant societal and economic impacts. Coastal regions are home to 50% of the world's population, and this figure is rising. We are dependent on coastal oceans, which produce 90% of the global fisheries yield and contain 80% of known marine fish species.

Predicting chemistry changes in the coastal oceans is no easy job. The continental shelves surrounding coastlines are very different from the open ocean due to the shallow water depth and the influence of rivers.

The complexity of coastal ocean processes means there can be significant differences between coastal seas. For example, in the US, ocean acidity along the west coast is controlled by the upwelling of acidic deep water. In contrast, riverine input of low pH water has more of an impact along the east coast.

Unlike the open ocean, coastal seawater chemistry data are often collected by multiple labs using different instruments and varying quality control methods. Building an accurate picture of coastal ocean acidification requires compiling and synthesising decades of data from numerous sources, which is a mammoth task.

Dr Jiang's initial plan is to build such a data product for the coastal oceans bordering the US. Developing future predictions of pH and aragonite saturation on a regional scale will provide actionable information for local decision makers. He and his colleagues hope that their methodology could be replicated in other regions and could catalyse future ocean acidification research worldwide.

Understanding just how the oceans are changing and which areas are most vulnerable is an essential first step in avoiding an ecological catastrophe.

Meet the researcher

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Dr Li-Qing Jiang is a chemical oceanographer specialising in ocean acidification caused by human carbon dioxide emissions. He received his PhD in Oceanography from the University of Georgia in 2009, subsequently securing a postdoctoral research position at Yale University. In 2011, Dr Jiang moved to the University of Maryland, where he is currently an Associate Research Scientist working at NOAA's National Centers for Environmental Information. Dr Jiang has published numerous studies in prestigious peer-reviewed journals on the global carbon cycle and mineral saturation in the ocean. His current work focuses on the synthesis and quality control of seawater chemistry data to better predict future ocean acidification trends on a local scale. Dr Jiang has been awarded multiple prestigious fellowships and awards for his contributions to science.

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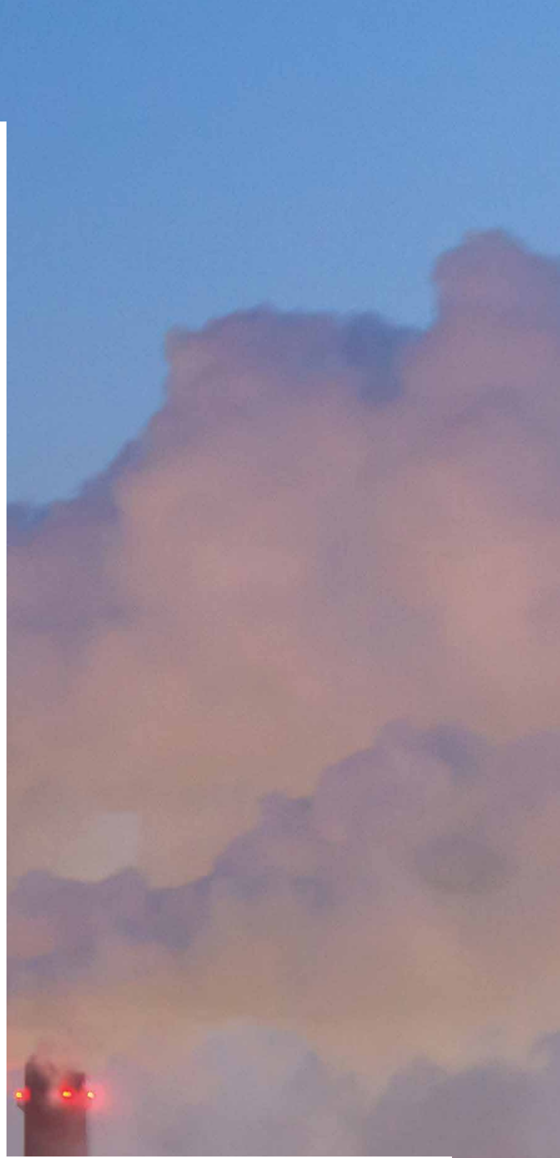
MAPPING CITIES' CARBON EMISSIONS THROUGH ADVANCED DATA COLLECTION



As global emissions of greenhouse gas continue to rise, it is increasingly important for researchers and policymakers to identify exactly where and how much greenhouse gas is emitted and absorbed worldwide for global climate change mitigation. Over the past decade, **Dr Tomohiro Oda** of the Universities Space Research Association (USRA) in Maryland has aimed to realise this need by combining emission data with night-time observations from satellites. Through this work, his team has now produced global maps that distinguish sources of carbon at unprecedented resolutions – high enough to identify variation across the regions where emissions are most intense: Earth's cities.

Monitoring with Accuracy

As the urgency of humanity's need to tackle climate change becomes increasingly apparent, it has never been more critical for us to monitor our emissions of carbon dioxide (CO_2) – the most significant greenhouse gas emitted due to human activity – with pinpoint accuracy.

The technology required to support this has seen significant improvements over the past decade, both on the ground and in space. While intricate sensor networks have allowed some businesses and governments to accurately quantify their emissions, carbon-observing satellites, including the Greenhouse gases Observing SATellite (GOSAT), developed by Japanese space agencies and NASA's Orbiting Carbon Observatory-2 (OCO-2) sensor, have given researchers an improved perspective on CO_2 sources, as well as 'sinks', where the gas is taken out of the atmosphere, and absorbed by plants and the ocean.

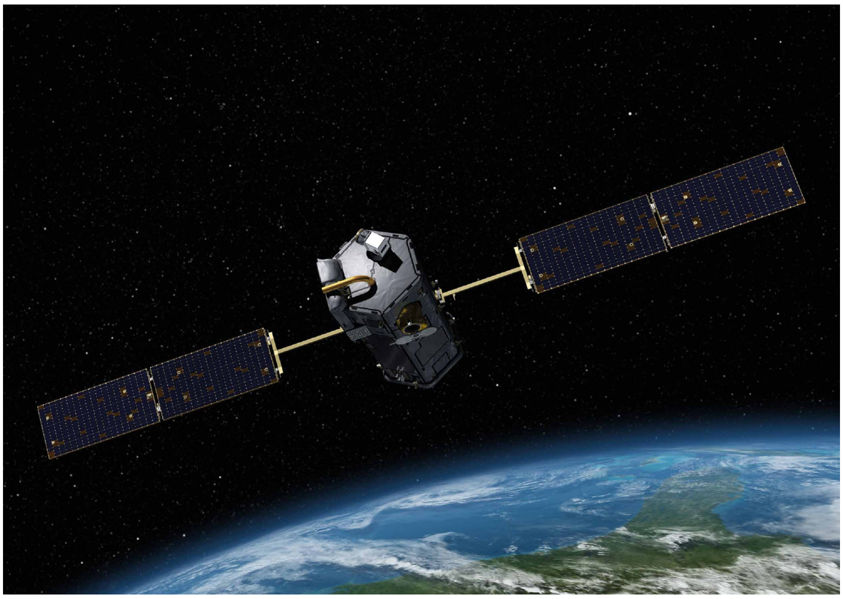
Despite these advances, however, the detection capabilities of these current monitoring techniques are not at their full capacity, and require further improvement. The main challenge they face is that sources of CO_2 can be hugely diverse. Ranging from forest fires to road traffic, they can vary depending on the time of day or year, and can be located across regions of vastly different sizes. So far, the many difficulties presented by this diversity have prevented climate scientists from gaining a clear enough picture of emission sources to keep track of their emissions – particularly in more densely populated regions.

The Problem with Urban Emissions

Currently, the world's cities are responsible for around 70% of all CO_2 emissions globally. With their dense populations, they must concentrate carbon-intensive activities including power generation, industry, transport, and the heating and cooling of buildings into small areas.

As urbanisation brings an even higher proportion of the population into cities, it would initially seem that these emissions can only be expected to rise. However, the increasingly urgent calls to reverse this trend are now beginning to be shared with scientists and a growing number of city governments worldwide. From expansions of public transport to greener manufacturing techniques, meaningful efforts for climate change mitigation supported by science are now taking root.

Central to each of these schemes is the ability for local governments to track how their cities' greenhouse gas emissions are changing over time. In



OCO-2. CREDIT: JPL-NASA.

many cities, however, shortcomings in data collection methodologies, as well as the limited quality of the data itself, mean that these inventories are not always detailed enough to support decision making. At the same time, the observations of space-based CO_2 detectors, which can capture the emissions of entire cities over extended periods, do not yet have the capability to directly monitor individual sources in cities.

Ultimately, since no single technique appears to be effective in monitoring Earth's most intense CO_2-emitting regions on its own, the key for achieving monitoring of global cities' emissions is to fuse the emission inventories and space-based observations of CO_2.

Combining Data

In a 2011 study, Dr Tomohiro Oda, then working on the GOSAT project at the National Institute of Environmental Studies (NIES) in Japan, reported on an improved CO_2 emission mapping technique by combining emission estimates for countries with another seemingly unrelated dataset: satellite observations of night-time lights.

His team mapped out the likely sources of these emissions by correlating them with a specialised dataset of night-time lights, which could distinguish between the brightest features of individual cities. The rationale behind this was simple: the brightest parts of cities, including roads, factories, and dense commercial districts, are typically the most intensive CO_2-emitting regions. Power plant emissions, which are typically very large but not correlated with population, were mapped using other data sources.

This technique enabled Dr Oda's team not only to create the yearly emission maps of individual countries, but to pinpoint the exact locations of potential emission sources down to resolutions of just one square kilometre. This resulted in a grid spanning the entire globe, with each square representing one square kilometre. Compared with more traditional mapping techniques, this procedure gave the researchers far more information about areas corresponding to human settlement and land transport.

Improvements Through ODIAC

The advances brought about by Dr Oda's previous research culminated in the Open-source Data Inventory for Anthropogenic CO_2 (ODIAC), developed at NIES, in collaboration with co-founder Dr Shamil Maksyutov. ODIAC used a combination of emission data with global night-time light observations to intricately map the intensities and locations of CO_2 sources worldwide.

This technique produced a worldwide grid of square-kilometre sources. Yet unlike previous global-scale maps created from similar aporoaches, individual cities displayed their own characteristic shapes and structures, based solely on their CO_2 emissions. In addition, the method could distinguish between sources created by the combustion of different types of fuel, and between different activities, including gas flaring and aviation.

In more recent years, the researchers tested a variant of ODIAC to reliably map the sources of all CO_2 emitted by many global cities across different continents, including Los Angeles, London, Tokyo, Bangkok, Cape Town and Beijing. Dr Oda and his colleagues have also developed an extended geospatial modelling approach to map emissions down to even higher resolutions, creating a grid with squares just 30 metres across to resolve emissions at the scale of human activities. By combining ODIAC's estimations with observations and models, the team could even track characteristic variations in emissions over time.

Such intricate detail would have only been possible for cities that benefit from dense networks of accurate CO_2 sensors, allowing for extensive data collection. However, Dr Oda's latest research, as well as an upcoming satellite mission, promises to bring about monitoring techniques that can be applied far more generally.

Upcoming Measurements with OCO-3

Since the success of these studies, Dr Oda has aimed to push the capabilities of his monitoring techniques even further, with the help of NASA's OCO-2 instrument, which was launched in 2014. Using the most cutting-edge CO_2 observing techniques available, OCO-2 has provided researchers with vital emission data over the past several years.

CREDIT: Joshua Stevens/NASA

However, OCO-2 has frequently missed its observation targets due to its fixed narrow range of vision. As the instrument was not designed for city observations, the city data it has produced are quite limited. Further difficulties have arisen due to factors including clouds, aerosols and land topographies, which can vary widely between different cities. These issues can be difficult to resolve with the limited resolutions of most atmospheric models that are currently available.

Now, NASA has launched the next iteration of the instrument, OCO-3, which orbits Earth from aboard International Space Station. Through improvements in engineering, OCO-3 can reliably scan dozens of global cities and take 'snapshots' of CO_2 being emitted every day, while retaining the coverage of its global CO_2 measurements. As this important project begins, Dr Oda's contributions will likely prove critical to ensuring effective mission planning, early monitoring of data quality, and the development of high-resolution global city emission estimates.

Incorporating NASA's Black Marble Data

Dr Oda and his colleagues are now working to create a truly reliable, luminosity-based inventory of greenhouse gas emissions globally, using data gathered by NASA's Black Marble project, in collaboration with Dr Miguel Roman, who pioneered NASA's Black Marble nightlight product. Derived from the Day Night Band of the Visible Infrared Imaging Radiometer Suite (VIIRS-DNB) instrument onboard Suomi-NPP, Black Marble products are available at 15 arc second resolution from January 2012 onward and is being processed daily within 3–5 hours after acquisition.

Though the primary purpose of the VIIRS-DNB is to track clouds at night, Black Marble has enabled the use of VIIRS-DNB for monitoring manmade night lights at unprecedented levels of radiometric, spatial, and temporal detail. Compared with previous approaches, it is more effective at identifying variations in brightness arising from natural sources, including clouds, snow, terrain, atmospheric variations, and moonlight.

The quality of Black Marble's observations allows these sources to be removed from night-time light images, without removing any of the brightness from electrical lights – improving their time and spatial resolutions even further.

For Dr Oda's team, this capability provided the opportunity to track emissions changes corresponding to human activities that distinctly vary in time and space, such as differences in energy usage over time as settlements expand, or differences between urban and rural areas. Dr Oda and his colleagues hope that Black Marble data will enable them to greatly improve city emission estimates, while capturing time variations, and rigorously quantifying any errors and uncertainties.

Dr Oda plans to combine the new Black Marble-based emission inventory with data collected by NASA's Earth Observation System fleet of satellites, such as OCO-2 and OCO-3, as well as current and future carbon observing satellites from Japan and Europe, further improving current emission monitoring capability for global cities.

Improving Prospects for Climate Action

Looking further ahead, Dr Oda now hopes to expand the usage of this advanced data collection technology. Afterwards, he aims to establish systems to support emission reporting and monitoring, tailored to the varied requirements and restrictions of individual cities and countries. If achieved, these systems would make it significantly easier for communities to plan out emissions reduction schemes and implement global emission monitoring under the United Nations Framework Convention on Climate Change (UNFCCC) towards Paris Climate Agreement goals.

In the future, emission monitoring support frameworks could be provided to groups including local city councils, giving them access to far more accurate emissions inventories than are currently available. If achieved, this would enable policymakers to precisely pinpoint any prominent sources of emissions in their cities, and subsequently, to set goals to reduce their emissions to net-zero.

As a growing number of cities worldwide come to acknowledge the widespread call for rapid CO_2 emissions reductions in the coming decade, Dr Oda's approach comes at a pivotal moment in our history. Using his techniques, parties who are not specialised in climate science, yet hold the power to make decisions, could soon make meaningful choices about the future development of their cities. Ultimately, they provide a new source of hope that the worst effects of climate change can be avoided and mitigated.

Meet the researcher

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Dr Tomohiro Oda is a senior scientist at Universities Space Research Association (USRA), Maryland. He has a particular research focus on greenhouse gas emissions from human activity, as well as using remote sensing data gathered from Earth observation satellites, such as NASA's Orbiting Carbon Observatory (OCO) 2 and 3, and Japanese Greenhouse gas Observing Satellites (GOSAT). Dr Oda obtained his Masters and PhD in Engineering from Osaka University in Japan, and held research and teaching positions at the National institute for Environmental Studies, Colorado State University/NOAA Earth System Research Lab, and NASA's Goddard Space Flight Center. Currently, Dr Oda serves as Lead of global surface atmospheric flux products at the Earth from Space Institute (EfSI), a newly established program at USRA. In collaboration with space agencies, such as NASA and JAXA, as well as university partners, Dr Oda continually works to improve his ODIAC emissions model, which is now widely used in carbon cycle modelling, and provides Earth observation-based global emission products in support of science and policy applications. Dr Oda is an Adjunct Professor at the Department of Atmospheric and Oceanic Science, University of Maryland, College Park, and a Visiting Researcher at the Graduate School of Engineering, Osaka university in Japan, where he enjoys science research and educational activities.

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MONITORING ATMOSPHERIC POLLUTION WITH LASER IMAGING

Lidar (Light Detection and Ranging) is a laser-based remote sensing tool that can measure the concentration of small particles, called aerosols, in the atmosphere. Monitoring aerosols is crucial for climate modelling, air quality measurements, and understanding the health impacts of atmospheric pollution. However, existing lidar systems require sophisticated and expensive equipment and are usually deployed by research technicians. They also have trouble measuring atmospheric pollutants near the ground, where they impact human health. Scientist **Dr John Barnes** at NOAA in Boulder, Colorado, and his colleagues have developed an inexpensive and straightforward commercial lidar solution using widely available camera and optical equipment.

Measuring Air Quality

Aerosols are tiny solid particles or liquid droplets suspended in the atmosphere. When the particles are large enough, they scatter and absorb sunlight. Aerosols are the cause of atmospheric haze, which reduces visibility. They also give sunrises and sunsets their eye-catching red colours.

Aerosols can be natural, including sea salt, dust, pollen and ash from volcanic eruptions, or released by human activity, such as factory and vehicle emissions. Mainly concentrated in the lowest few kilometres of the atmosphere, aerosols can be extremely damaging to human health. Polluting aerosol emissions have been linked to increased rates of heart disease, lung disease and asthma, in addition to a range of other conditions.

Because aerosols scatter the sun's rays and interact with other chemicals in the atmosphere, they can also profoundly impact local weather systems and climate. Their effect on visibility also affects aircraft safety. Understanding and mitigating this broad range of aerosol impacts requires the ability to monitor them over both time and space.

Scientists can map aerosols as a function of altitude using lidar technology. With this method, a pulsed laser transmits light into the atmosphere. A detector then measures the amount of laser light scattered in its direction by air molecules, clouds, and aerosols. The sensor uses the intensity of the scattered light signal to measure aerosol concentration.

Lidar also determines the altitude of the aerosols it measures. In most lidar systems, the laser and detector are placed at the same location. The detector measures height in the atmosphere using the timing of the light returned from the scattered particles. This method requires expensive timing detection hardware and a pulsed laser. These systems also have difficulty measuring near the ground, where aerosols can significantly impact human health.

CREDIT: Gregory Tran, PIXOPHIL.

To address these challenges, Dr John Barnes and his colleagues have been developing more effective and inexpensive instruments for sensing atmospheric aerosols. One technique, called Camera Lidar – or 'CLidar' – involves transmitting a laser beam vertically into the atmosphere. A camera with a wide-angle lens positioned a few hundred metres away then captures

Prototype laser optics box deployed at Ny Alesund.

Data file that was analysed to achieve an aerosol profile.

images of the laser beam to measure aerosols. Another of Dr Barnes' inventions, the imaging polar nephelometer, can measure the size and shape of the aerosols.

His team's new techniques are based on inexpensive and widely available components, making the technology more accessible to educators and scientists in developing countries, for whom the high cost of traditional lidar systems could be prohibitive. Dr Barnes and his collaborators are currently working hard to improve their instruments and make them available to scientists worldwide.

Building a Camera Lidar

The team's CLidar system consists of a laser beam transmitted vertically upwards into the atmosphere. A continuous wave laser can be used, which is less expensive than the pulsed laser needed for lidar. A camera, with a filter and a wide-angle fisheye lens, positioned a few hundred meters away, serves as a detector. The camera images the entire laser beam, from the ground to its zenith. The laser beam intensity in each pixel of the camera image provides information on light scattering by aerosols: brighter portions of the laser beam indicate more aerosols.

To construct a CLidar system, air quality scientists need only a few simple components. Along with the laser, they need a camera with a wide-angle lens, which is necessary to capture the whole laser beam at once. The camera is controlled by a computer through a USB connection and can be networked for remote control. 'The camera lidar technique is much simpler than a regular lidar,' says Dr Barnes.

Unlike traditional lidar, the CLidar system doesn't need to measure height in the atmosphere using expensive hardware to time the arrival of light at the detector. As the camera is stationed at a distance from the laser the angle between the camera and the beam can be calculated using simple geometry. Using this method, a scientist can calculate the height at each point along the beam.

Aligning the camera lidar simply means getting the beam in the image away from the edges. To analyse the image, a user must separate the scattering of light by aerosol particles from the background scattering by air molecules, which varies by altitude. Separating the signals means calibrating the system by taking measurements in a clear, aerosol-free region of the sky, usually several kilometres in altitude. This region must also be free of clouds, as water vapour interferes with the measurements.

The team's technology can provide accurate and detailed measurements near the ground, which is vital for measuring sources of pollution originating close to the surface. The new system can also produce an aerosol profile every minute. Multiple consecutive images can allow researchers to study atmospheric dynamics. For example, Dr Barnes and his colleagues took the instrument to coastal Hawaii to observe aerosol injection from waves breaking on the seashore.

Camera box deployed at Ny Alesund, Norway in February, 2020.

As it relies on taking pictures of light from a laser beam aimed skyward, the process requires darkness and can only be used at night. However, the team has plans to modify the instrument to use an infrared camera and laser, allowing daytime operation. The camera and laser need to be positioned to avoid interference from buildings and streetlights. Dr Barnes also recommends angling the camera away from the moon; in the Northern Hemisphere, it should be pointed north.

Dr Barnes recently travelled somewhere suitably isolated to test their CLidar system under more difficult conditions. Ny-Ålesund, a remote research station on the Norwegian island of Svalbard, is the world's northernmost settlement. In the freezing Arctic night, with temperatures from −3 to −22°C, he set up and operated a prototype laser and camera.

The instrument performed well under challenging conditions, allowing his research team to gather 152 hours of data. The CLidar produced detailed low-level data, which revealed more aerosols at about 60 metres height compared to ground level. This pattern was unexpected, but could be explained by cold, clean air flowing down glaciers and displacing the air at the surface.

Measuring Aerosol Properties

So far, the team has published more research on their CLidar system, but they also have high hopes for the potential of a related invention, called an imaging polar nephelometer or IPN. The word 'polar' refers to a mathematical polar plot of radius and angle. 'I think both instruments have equal potential,' says Dr Barnes.

Although aerosols scatter light in every direction, lidars and camera lidars only measure light scattered along a single path: the angle between the laser beam and the camera. To convert this single-angle data into more valuable quantities such as visibility and aerosol concentration, scientists use mathematical functions. The functions rely on knowledge of the size, shape and composition of the aerosol particles. However, very few scientists measure these aerosol properties, meaning that such equations are among the most significant sources of error in lidar measurements.

Dr Barnes invented the IPN to solve this problem. This device uses the same simple components as the CLidar system: a camera, wide-angle lens, and a laser beam to measure aerosols. This is not a remote sensing measurement, like the camera lidar, but draws the air into the IPN located near the ground or on an aircraft. The IPN measures scattered light at multiple angles which vary greatly for aerosols. While the CLidar system measures aerosol concentrations, the IPN can give more detailed information about the aerosols' size, shape, and composition.

Air quality scientists classify particles by size according to their health impacts: smaller particles can penetrate further into the lungs. Using the IPN, they can measure the concentrations of specific particle size classes that are particularly hazardous to human health.

Improving Access to Aerosol Measurements

Improving air quality worldwide means improving access to reliable aerosol measurement techniques. The CLidar and the IPN systems developed by Dr Barnes and his team are lower cost and may provide more accurate data than existing commercial lidar systems. The laser, camera and lens cost about $7000. To be used operationally, they also require weather-proof cases and a computer connection.

Camera lidar technology has previously only been operated by technicians and scientists. By building a more automated system, the team has opened up the possibility of commercial camera lidar. A commercially available instrument would be valuable for air quality, visibility, and cloud-base-height monitoring. For this reason, Dr Barnes has set up a small company to develop the CLidar and IPN commercially.

His team also developed streamlined software that quickly transfers data from the instrument to the user and analyses it. The same software can analyse data from both devices, and users can also operate the camera remotely via the internet.

In the future, Dr Barnes and his colleague, Dr Sharma, a physics professor at Central Connecticut State University, hope to extend the global reach of the instruments. 'We have been working with a Physics teacher from the University of the Bahamas, Dr Amin Kabir. In 2012 I set up a group at Peking University working with the camera lidar,' says Dr Barnes. By continuing this collaborative international effort, his team strives to make accurate aerosol measurements accessible to all.

CREDIT: Kendal Lyon

Meet the researcher

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Dr John Barnes earned his PhD in atmospheric physics in 1988 from the University of Minnesota. After a research position at the University of Michigan, Dr Barnes moved to the NOAA/GML Mauna Loa Observatory in Hawaii. He has worked at NOAA for over 23 years, including 17 years as the station chief. He is currently a visiting scientist at the NOAA Global Monitoring Laboratory in Boulder, Colorado. Dr Barnes has dedicated his career to measuring atmospheric particles that play a central role in human health, aircraft safety, and climate change. At NOAA, his research has focused on developing new and accessible tools to measure atmospheric particles and water vapour using laser techniques. Alongside his academic work, he has also started a small business to commercialise his inventions. He has published numerous articles published in peer-reviewed journals and has received multiple awards for his contributions to science.

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EXPLORING ATMOSPHERIC SOOT TO PROTECT PEOPLE AND THE PLANET

From wildfires to cargo ships, soot particles can originate from many different sources. Once emitted, these particles can be easily spread throughout Earth's atmosphere. **Dr Andrew Metcalf** at Clemson University, and his graduate students Nilima Sarwar and Walt Williams, use advanced aircraft observations to investigate how the diverse characteristics of soot can be influenced by their sources, and assess their subsequent influence on air quality and cloud formation. Their work is now helping researchers to better predict the coming impacts of climate change, and to inform urgently-needed efforts to reduce our emissions.

An Understudied Emission

As Earth's climate heats up, a deep and detailed understanding of how human activity is altering the atmosphere has never been more important. Although emissions of carbon dioxide and other greenhouse gases such as methane and nitrous oxide, have clearly been identified as a human-induced drivers of climate change, one particularly significant aspect of our emissions has so far received comparatively little attention.

Named aerosols, these tiny particles can originate from a diverse array of sources. One form of aerosol with an oversized influence on the atmosphere is 'refractory black carbon' – more commonly known as soot. Soot particles form when fuels don't have sufficient access to oxygen to combust completely. The result is a mass of impure carbon, which is typically light enough to be carried upwards in the column of heat generated by the combustion and then to freely travel through Earth's atmosphere.

Because they are so dark, soot particles are highly efficient at absorbing light, which causes them to heat up and warm the surrounding atmosphere. Alongside greenhouse gas emissions, the heat-trapping effects of soot particles exacerbate the climate-warming effects of fossil fuel combustion and wildfires. As wildfires are increasing in frequency and severity due to climate change, soot emissions from these fires could create dangerous climate feedback loops.

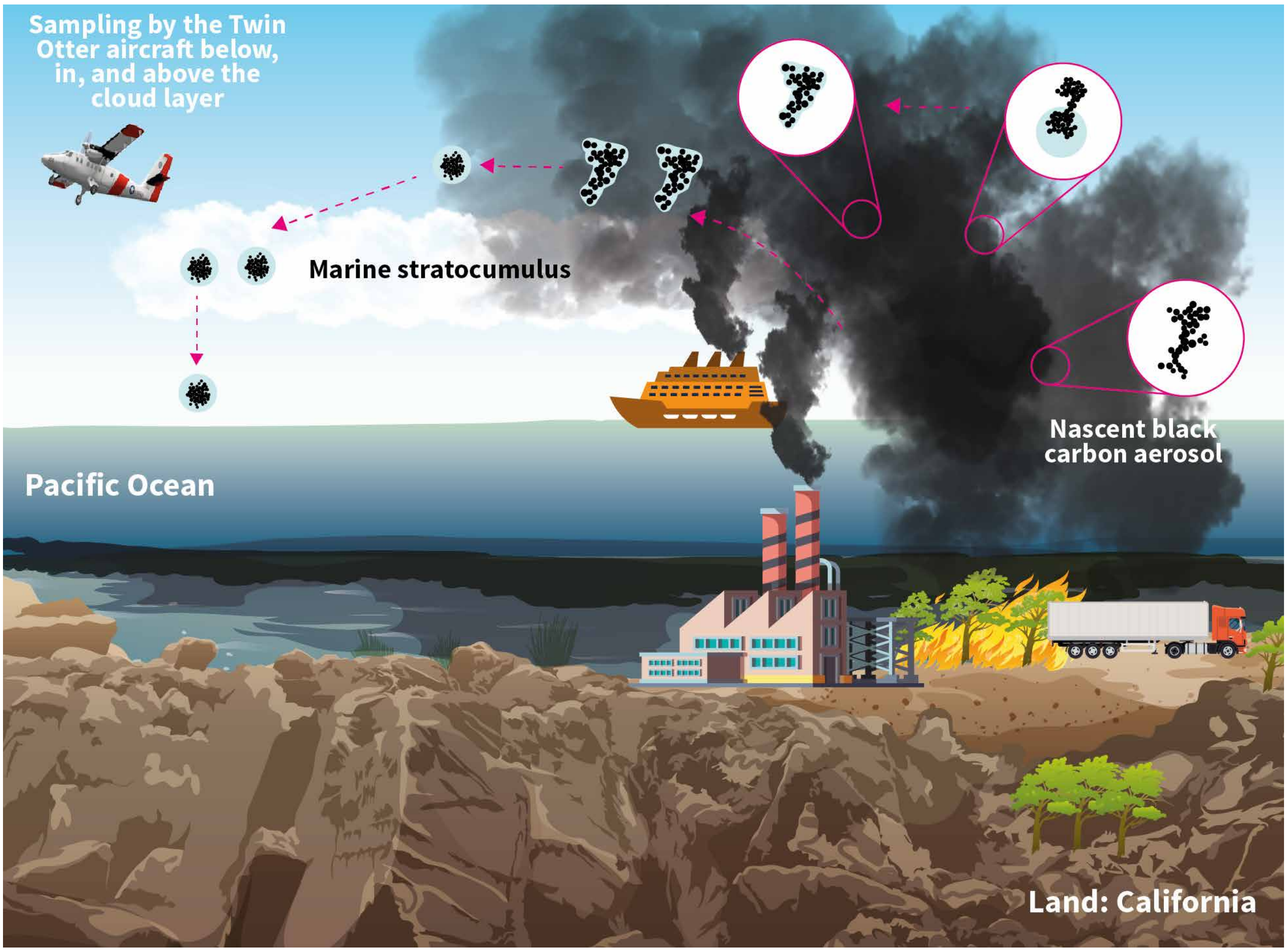
As well as influencing weather patterns and the global climate, soot also significantly influences air quality. As a result, a detailed understanding of their properties is crucial to researchers assessing levels of atmospheric pollution, threats to public health, and alterations to atmospheric processes – which can go on to affect the behaviour of Earth's climate as a whole.

A Diversity of Characteristics

As Dr Andrew Metcalf of Clemson University points out, the physical properties of soot particles are far from uniform. For a start, they can originate from a wide range of possible sources,

including wildfires, and the engines of ships, aircraft, and land-based vehicles – which all burn different types of fuel, and at different rates and temperatures. As a result, the aerosols can come in a diverse array of shapes, sizes, and chemical compositions, profoundly altering the ways in which they interact with light.

Yet the variations don't stop there. After soot particles are emitted, they can interact with gas vapours and other types of aerosols – which may coalesce on the particle's surface to form a coating. These coatings can make particles even more light-absorbing, alter the way in which they scatter light, and affect the way these particles interact with the environment.



Depending on the types and concentrations of naturally occurring aerosols they mix with in the atmosphere, their light absorption and scattering properties are altered to varying degrees. Dr Metcalf and his team aim to explore these properties in more detail – using measurements taken directly from the sky.

The MACAWS Project

In 2018, Dr Metcalf and his colleagues conducted the Marine Aerosol Cloud and Wildfire Study (MACAWS), which aimed to assess the impact of manmade aerosol particles from the marine shipping industry. To do this, the researchers used the Naval Postgraduate School (NPS) Twin Otter aircraft, which they equipped with several advanced instruments. These instruments included a Scanning Electrical Mobility Analyser, which can measure distributions of aerosol particle sizes, and an Aerosol Mass Spectrometer, which measures the chemical compositions of particles by breaking their constituent molecules into smaller fragments.

Although these devices had been used in previous aerosol measurement studies, MACAWS made one important addition to the arsenal of instruments aboard the NPS Twin Otter – the Single Particle Soot Photometer (SP2). This device allowed the team to measure how laser light interacts with a sample of particles. This interaction takes place in two possible ways: either by scattering the laser photons in many different directions; or through light emission after the particles have been heated by the laser. The light emission measurement is how soot is specifically identified in the SP2.

Observations from the Sky

For a month over the summer in 2018, the plane took several flights off the coast of Monterey, California, allowing Dr Metcalf's team to characterise the nature of soot particles over the Eastern North Pacific region. While much of the California coastline is famously hot and sunny during the summer, conditions are very different on the central coast – the region close to San Francisco Bay which includes Monterey.

Each day, banks of large, low 'marine stratocumulus' clouds form in this region. As they hug the coastline, these formations keep the weather far cooler and cloudier than other coastal regions nearby. These conditions provide an ideal testbed to study interactions between soot particles and clouds, in an otherwise largely clean and unpolluted marine environment. Over the course of the MACAWS project, the researchers took measurements from several different flights of the NPS Twin Otter – both on clear and cloudy days.

In doing this, they hoped to answer several questions: including the effects of aerosol composition on the properties and formation mechanisms

of clouds; the relationship between particle size, liquid water content of the cloud and 'wet scavenging' – through which water droplets form around aerosol particles and accelerate their removal from the atmosphere; and the effects of aerosol on accelerating the rates at which clouds lose their water content through precipitation. In addition, they hoped to discover how the sizes, distributions, and mixing of aerosols in the region compare with those found in other remote marine environments, and whether these characteristics can be used to determine aerosol sources.

Impacts on the Atmosphere

Through her graduate thesis project, Dr Metcalf's graduate student Nilima Sarwar described how soot particles can have a profound influence on the processes that play out within the 'marine boundary layer'. This part of Earth's atmosphere lies just above the ocean, meaning the physical properties of both systems are closely linked. Through the MACAWS project's observations, she discovered several clouds off the central California coast that had been polluted by the aerosols – with concentrations that became notably higher above the cloud layer.

Sarwar also found that due to wet scavenging, the liquid water content of these polluted clouds was around 22% lower than that in cleaner clouds. In addition, through empirical models of the interaction between clouds and soot particles, she predicted a maximum possible concentration for the aerosols within water droplets – providing a useful indicator for their influence on wet scavenging.

Alongside the measurements taken aboard the NPS Twin Otter, Sarwar used a combination of satellite images, and data on wind directions, to track the sources of soot particles. Through observations of wildfire smoke and exhaust plumes emitted by ships, she found that the above-cloud layer was strongly impacted by the long-range transport of soot from inland fires, while the lower parts of clouds could easily be polluted when the paths of ships passed directly beneath them.

Studying California Wildfires

Another graduate student of Dr Metcalf, Walt Williams, delved deeper into the characteristics of soot particles emitted by wildfires in California. Compared with aerosols from other sources, these particles have particularly distinctive size distributions and chemical compositions. In his graduate thesis, he aimed to gain a better understanding of background concentrations of soot particles during the summer wildfire season, as well as their size distributions, and their concentrations relative to other types of aerosols.

To do this, Williams used the NPS Twin Otter to measure the plumes emitted during the 2018 County Fire – which burned an area of 90,000 acres in the Sacramento Valley during July of that year. Through his analysis, he discovered that the air surrounding the fire carried as much as 100 times more soot by mass, and also displayed a larger characteristic aerosol size than would normally be present in the background airmass outside of the fire season.

Williams hopes that his results could help firefighters to better estimate the impact of future fires. In addition, they could allow health officials to estimate the chemical compositions of wildfire emissions – including those of other types of aerosols, simply based on measured concentrations of soot. This could provide critical information about air quality, and potential dangers to public health.

Improving Climate Predictions

The MACAWS project's findings come at a critically important time in our efforts to prevent and mitigate climate change. For California, the threats posed by climate change are now a stark reality: in recent years, wildfires on unprecedented scales have increasingly come to capture news headlines around the world, and the trend is only expected to accelerate.

On a global scale, the threats posed by a warming climate have been made more abundantly clear than ever, by the Intergovernmental Panel on Climate Change's most recent Assessment Report – with wildfires alone being expected to unleash ever greater damages on every inhabited continent in the coming decades.

As we come to realise the urgency of these warnings, a detailed knowledge of the role played by soot in influencing atmospheric processes, and how the properties of the particles can vary depending on their source, will allow researchers, including aerosol scientists, cloud physicists, meteorologists, and atmospheric modellers, to gain a far clearer picture of Earth's climate as a whole and how it will change in the future. In turn, the team's efforts could help us to better prioritise efforts to reduce our emissions, and to better prepare for the reality of a warmer world.

Meet the researcher

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Dr Andrew Metcalf earned his PhD in Environmental Science and Engineering at The California Institute of Technology in 2012. Upon graduating, he pursued postdoctoral roles at both Sandia National Laboratories and the University of Minnesota. Dr Metcalf has been an Assistant Professor of Environmental Engineering and Earth Sciences at Clemson University since 2017. His main research interests lie in air pollution and air quality, with a particular focus on atmospheric aerosol particles. As leader of the Clemson Air Quality Lab, he explores the properties of air pollution on many different scales: from measurements taken under a microscope to samples taken from large-scale field projects. Alongside his research, he also dedicates his time to training the next generation of scientists and engineers, by teaching several courses on air pollution engineering, combustion, and aerosols and climate, and supervising students conducting research projects.

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Nilima Sarwar completed her Master's degree at Clemson in 2021. She is now pursuing opportunities to study for a PhD.

Walt Williams, Clemson University
Walt Williams graduated with a Master's degree from Clemson in 2019. He now works as an air quality consultant at TRC, Inc., where he focuses on ambient air monitoring and greenhouse gas emission reduction projects.

The MACAWS research team also consisted of researchers from the California Institute of Technology and the University of Arizona.

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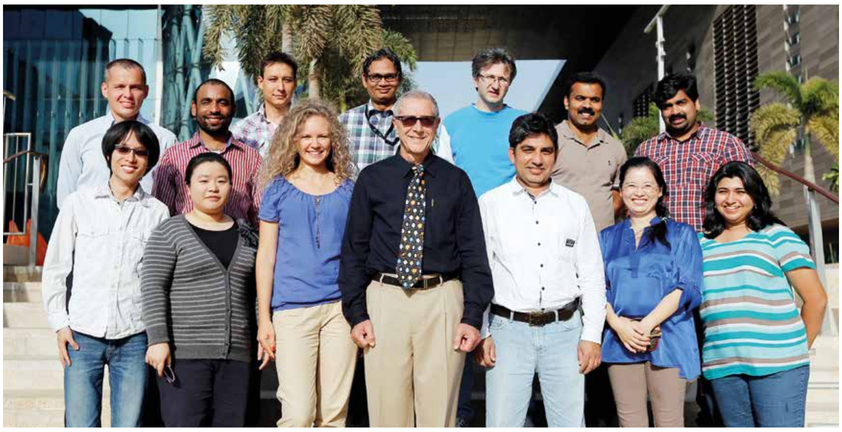
EXPLORING THE EFFECT OF AEROSOLS ON THE ARABIAN PENINSULA'S CHANGING CLIMATE

Today, the Arabian Peninsula already faces a more daunting array of environmental challenges than most other regions on Earth. Yet as the climate changes, it is now expected to feel these adverse effects even more strongly in the coming decades. Using the latest modelling techniques, combined with ground-based observations, **Dr Georgiy Stenchikov** at King Abdullah University of Science and Technology in Saudi Arabia aims to make better predictions of how these changes will unfold. His work now provides critical guidance on how governments in the region should prepare for future shifts in climate and air quality.



The Arabian Peninsula's Climate

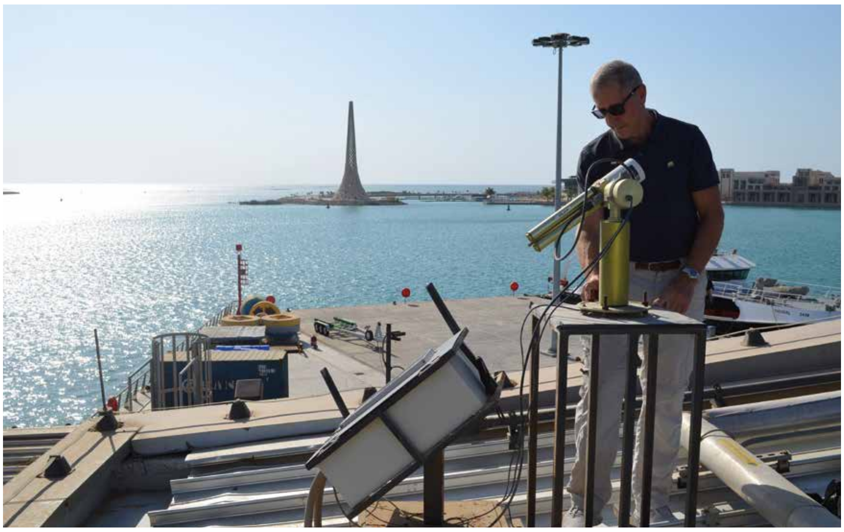
The Arabian Peninsula is well known for its harsh natural environments. Not only are large swathes of the region covered in inhospitable desert; it is also one of the most water-scarce regions on Earth, with many communities relying on the desalination of seawater for their survival. On top of this, the peninsula's climate is highly sensitive to a phenomenon named 'radiative forcing'. Radiative forcing describes the change in Earth's energy balance (the difference between the sunlight absorbed by Earth, and the infra-red light radiated back into space), which is associated with greenhouse gas emissions, desertification, urbanisation, and shrinking vegetation cover. This effect is strongly influenced by an abundance of particulates including sand, dust and anthropogenic pollutants suspended in the air – together named 'aerosols'.

Over the past three decades, both observations and computer simulations have shown that the Arabian Peninsula's average temperature has increased by about 0.5°C per decade exceeding almost twice the trend observed in the northern hemisphere as a whole. This means that effects including an increasing frequency of extreme weather events, such as heat waves, sandstorms and flash floods, are now being felt increasingly strongly.

As these changes have unfolded, the population of Saudi Arabia alone has exploded from just 4 to 34 million in only half a century. Combined with rapid social and economic development, and urbanisation in the region, these effects are now imposing an unprecedented strain on the region's water resources, agriculture, air quality, and natural ecosystems.

A Need for Better Predictions

To tackle these mounting challenges, detailed evaluations of changes in the Arabian Peninsula's climate and air quality have never been more critical. Ideally, a robust basis for supporting environmental policy in this way would enable regional, national and international policymakers to carry out long-term planning and sustainable developments, and to utilise renewable energy more effectively. This would require advanced, science-based decision making from governments as



they decide how to mitigate and adapt to climate change, with judgements centred around the outcomes of robust observations and predictive models.

Twenty to thirty years ago, there were significant shortcomings in the techniques used by researchers to predict these changes, creating critical oversights in existing climate predictions for the Arabian Peninsula. 'Before, we did not know the optical properties of aerosols, their microphysical behaviour, or their emission sources,' says Dr Georgiy Stenchikov at King Abdullah University of Science and Technology in Saudi Arabia. 'The spatial resolution of our models was very coarse. In many models, aerosols were not included in the radiative transfer calculations, meaning they couldn't affect solar and terrestrial radiation.' Over decades of research, Dr Stenchikov has used cutting-edge simulations, combined with ground-based and satellite observations, to discover how these predictions can be improved.

Diverse Tools for Regional Climate Modelling and Monitoring

Dr Stenchikov and his colleagues have a wide array of techniques at their disposal for achieving these research goals, based around cutting-edge computer simulations of circulations in Earth's atmosphere and oceans. Alongside high-resolution global atmospheric simulations, they now use the regional Weather Research Forecasting WRF model with chemistry and aerosol module (WRF-Chem). The main shortcoming of regional climate models is that without considering how the oceans are influenced by the atmosphere, and vice versa, their individual prediction abilities are limited.

To alleviate this issue, Dr Stenchikov has introduced novel techniques for coupling atmospheric and oceanic simulations together on a regional scale, greatly improving the accuracy of their predictions. He used WRF as an atmospheric component for regional models, and the Regional Ocean Modelling System (ROMS) for the oceanic component. In addition, he implemented NASA's satellite observations in the model, which monitor dust aerosols over the Arabian Peninsula and the Red Sea from space. By running this regional coupled ocean-atmosphere modelling system, Dr Stenchikov and his colleagues have gained critical insights into how aerosols have influenced the Red Sea and the Arabian Peninsula's climate in the past, and how they can be expected to transform it in the future.

Aerosol Catastrophes

When Dr Stenchikov first started out in his career, our perceived threat of climate change was dwarfed by the very feasible prospect of another global catastrophe: an international nuclear conflict between global superpowers. If such an event had ever occurred, vast quantities of smoke from urban and forest fires, as well as dust from ground bursts, would have been injected up into the atmosphere, triggering devastating rapid drops in temperature, precipitation, and sunlight.

Together known as 'nuclear winter', these effects were widely studied through simulations at the time, producing predictions of a brief yet devastating shift in the Earth's climate. Dr Stenchikov and his colleague Dr Aleksandrov, then at the Computer Center of the USSR Academy of Sciences, conducted the first general circulation model simulation of climate perturbations following the hypothetical nuclear war based on TTAPS (group of American Scientists Turco, Toon, Ackerman Polack, and Sagan) scenarios.

Later on, Dr Stenchikov was involved in research exploring the climate effects of volcanic explosions. He also studied how particulates spread through New York and the surrounding area following the 2001 attacks on the World Trade Centre, conducted simulations of the hypothetical nuclear conflict between India and Pakistan, and investigated the feasibility of Solar Radiation Geoengineering to counteract global warming. As Dr Stenchikov describes, nuclear winter studies heavily influenced his subsequent research, as well as that of many other world leaders in the wider field of aerosol research.

'Problems including the effects of volcanic eruptions on climate; dust storms; the effect of dust on air quality and radiation transfer; and transport of the World Trade Centre fire's plume are all physically related to the effects causing nuclear winter,' he says.

Impacts of Volcanic Eruptions

In 1991, the eruption of Mount Pinatubo in the Philippines exerted the largest volcanic climate impact in the 20th century. The globally averaged volcanic cooling exceeded 0.5°C and this was twice as strong in the Middle East.

However, even 25 years afterwards, these effects were still not completely understood. Through his research, Dr Stenchikov improved our understanding of the physical mechanisms controlling climate responses to volcanic radiative forcing. To study the volcanic impact on the Middle East climate, Dr Stenchikov and his team coupled the regional atmospheric model, WRF, with the regional ocean model, ROMS, and comprehensively accounted for the radiative effects of volcanic aerosols. Critically, his team found that atmospheric circulation had a greater influence on the climate of the Middle East than direct regional cooling from aerosols.

In a further study, Dr Stenchikov produced new simulations of the Toba super-eruption: a particularly devastating event that occurred in Sumatra around 75,000 years ago and emitted about 2 billion tonnes of sulphur dioxide. By better accounting for the radiative effect of sulphur dioxide, his team found that the effects of volcanic winter following the super-eruption were softened by the greenhouse effect of sulphur dioxide. They also found that the development of sulphate aerosols was delayed by the ability of sulphur dioxide to absorb UV and to inhibit the breakdown of ozone developing an equatorial ozone hole.

Altogether, these studies suggested that major volcanic eruptions can significantly alter the Earth's climate, and should be carefully considered when assessing long-term climate variability and warming trends.

Calculating Anthropogenic and Natural Pollutants

Together, North Africa and the Arabian Peninsula are the two largest sources of dust in the world. Mixtures of mineral dust, sea salt, sulphate, black carbon and organic matter, when suspended in air, can profoundly influence air quality, radiative heating, and atmospheric circulations in the region. The size distribution, and chemical composition of aerosols are crucially important to evaluate these effects. However, as Dr Stenchikov describes, these cannot be effectively monitored using conventional observation techniques.

'It is a difficult problem for satellites to distinguish between different types of aerosols,' he says. 'Passive satellite instruments measure the aerosol optical effect, or depth, at different wavelengths. This helps to make some conclusions about the size distribution and compositions of aerosols. Active lidar instruments have better capabilities – but the composition and size distribution of atmospheric aerosols are still poorly observed, and not well modelled.'

To combat this issue on a regional basis, Dr Stenchikov established NASA AERONET and MPLNET sites at KAUST's campus – which enable his team to precisely determine the size distribution and thickness of the aerosol layer. The team also conducted first multi-year systematic measurements of aerosol deposition rates, mineralogy and size distribution of aerosol samples.

Combined with simulations, these empirical studies revealed how aerosols become concentrated over the southern Red Sea producing in this place world's largest radiative forcing– behaviour consistent with observations from satellites. In turn, Dr Stenchikov's discoveries have clearly revealed the extent to which natural and anthropogenic aerosols impact regional climate, solar panel efficiency, air quality and human health.

Informing Future Decisions

Climate change, combined with a rise in air pollution, are now severely threatening the livelihoods of many millions of people in the Arabian Peninsula – with potential disasters ranging from rising instances of respiratory diseases and lung cancer, to diminishing water resources for agriculture. 'The Middle East's climate is at the border of liveability,' Dr Stenchikov summarises. 'Global warming is faster here than the global average, so inevitably, adaptation and mitigation measures must be applied. Our work is meant to help in the planning and preparation of such actions and should be accounted for in environmental decision making.'

Dr Stenchikov's research has now clearly shown that a combination of coupled atmospheric and oceanic simulations, and ground-based aerosol measurements, are the best tools for informing governments as they make these critical decisions. Through future research, he now hopes to create more accurate climate forecasts for the Arabian Peninsula for both 2050 and 2100. He also aims to show how the elaborated distribution of solar panels over the Red Sea coastal plain could enhance breezes in the Red Sea – which are some of the strongest in the world – forcing precipitation in the most arid region on Earth.

Meet the researcher

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Dr Stenchikov completed his PhD in the Numerical and Analytical Study of Weak Plasma Turbulence at Moscow Physical Technical Institute in 1977. Afterwards, he headed a department at the Russian Academy of Sciences, which used computational analysis to carry out crucial early research into the impact of humans on Earth's climate and environmental systems. From 1992 until 1998, Dr Stenchikov worked at the University of Maryland in the USA, after which he held a position as a Research Professor in the Department of Environmental Sciences of Rutgers University for almost a decade. Since 2009, he been a Professor and a Chair of the Earth Sciences and Engineering Program at King Abdullah University of Science and Technology in Saudi Arabia. His work has brought about important advances in fields including climate modelling, atmospheric physics, fluid dynamics, radiation transfer, and environmental sciences. Dr Stenchikov also co-authored the Nobel Prize winning report from the Intergovernmental Panel on Climate Change IPCC-AR4 of 2007.

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KAUST

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EXPLORING THE SAHARA DESERT'S PAST TO UNDERSTAND ITS FUTURE

The Sahara Desert in Africa is one of the driest places on Earth. Because of its dry conditions, fine sand particles from the desert can easily become airborne, leading to dust emissions that affect the global climate. However, between 11,000 and 5,000 years ago, this region experienced wetter conditions, known as African humid period, causing reduced dust and a dramatic greening of the land. In the near future, human-induced climate change could dramatically alter rainfall patterns in the Sahara, causing reductions in dust emissions that may further impact the global climate. By examining past humid periods, **Dr Francesco Pausata** and his colleagues at the University of Quebec in Montreal aim to understand potential future changes.

The Saharan Climate

The Sahara in northern Africa is the largest hot desert on Earth. Because of its dry conditions, fine sand particles from the desert earth can easily become airborne. This mineral dust from the Sahara significantly affects the global climate. It scatters light from the Sun and influences cloud formation, consequently affecting atmospheric circulation, rainfall and storm formation. Changes in Saharan dust emissions are therefore inextricably linked to the global climate system.

However, the Sahara wasn't always dry and dusty. During the early and middle Holocene – 11,000 to 5,000 years ago – the arid region transformed into grasslands with trees, lakes and rivers. The evidence for this Saharan 'greening' interval comes from several paleoclimate archives such as pollen found in sediments, along with archaeological evidence indicating that humans once lived, hunted and gathered deep within the current desert.

The Holocene greening is the last of a sequence of African humid periods. These are caused by the gradual shift in the orientation of Earth's rotational axis, which occurs in cycles lasting about 26,000 years. During periods in this cycle when the African summer Sun is at its strongest, a larger temperature gradient forms between the land and sea. This increased gradient strengthens the African monsoon, bringing rainfall deeper into the Sahara.

The current period of climate change, caused by human emissions, could significantly impact the African monsoon. Greenhouse gases trap the Sun's radiation close to the Earth's surface. Land absorbs more radiation than water, heating up faster – again increasing the temperature difference between land and sea, which could strengthen the monsoon and bring increased rainfall to parts of the desert.

Mineral dust emissions from the Sahara depend on dry conditions, so they are susceptible to changes in rainfall.

Therefore, the climatic impacts of future changes in dust emissions in the Sahara and the neighbouring Sahel region could be felt worldwide.

However, the impact of the greening of northern Africa and the African humid periods on the global climate is poorly understood. Scientists are particularly concerned about changes in rainfall patterns, which could impact agricultural production and communities. It could also affect tropical cyclones, some of the deadliest weather hazards.

By studying past Saharan greening events preserved in marine sediment cores, Dr Francesco S.R. Pausata and his colleagues at the University of Quebec in Montreal aim to understand these profound shifts in the desert climate. Scientists previously knew that the Sahara was wetter and greener in the past. However, there is uncertainty around which parts were wetter, how much wetter they were compared to today, and how this increased moisture affected the global climate. By answering these fundamental questions, Dr Pausata's team is shedding light on current and future climate change.

Rainfall in the Desert

From 11,000 to 5,000 years ago, wetter conditions meant that the current Sahara Desert was home to diverse vegetation and human settlements. Understanding the rainfall rates, the extent of the wet conditions and their effects on human life in this period relies on analysing clues, such as pollen grains, preserved in sediment records.

Researchers often rely on marine and lake sediments to provide insights into past climates. Dr Pausata's team analysed ocean sediments from four marine cores along the west African coast. These cores contain dust, pollen and other materials blown offshore from the land over the last 25,000 years. By analysing ocean sediments deposited over a wide area, the researchers revealed ancient rainfall patterns and the spatial extent of the Saharan greening.

The team measured carbon and hydrogen atoms with different numbers of neutrons in their nuclei – called isotopes – in waxy substances produced by plant leaves. This leaf wax washed into the ocean and was preserved in ocean sediments laid down during the greening period. The number of neutrons in the atomic nuclei of carbon and hydrogen are valuable tracers of rainfall and vegetation changes.

Dr Pausata and his colleagues found that the green Sahara period was associated with very high rainfall rates recorded in the sediment cores. Their isotope data across all the sites indicated that the green Sahara may have been up to ten times wetter than today. The region had a seasonal tropical climate, with most of the rain arriving in the summer monsoon. Wet conditions extended as far north as Morocco, but persisted for a shorter time here than in the southern Sahara.

The team also discovered a drier interval in the middle of the Saharan greening around 8,000 years ago. Lasting about 1000 years, this pause in rainfall caused humans to temporarily abandon the region, as indicated by archaeological records.

The abandonment of the southern Sahara coincides with a cultural shift among early humans. While those occupying the Sahara before the dry period survived by hunting, fishing and gathering, those who returned afterwards had a more diverse diet, subsisting partly on meat and dairy from cattle farming. Dr Pausata and his colleagues suggest that the changing climate was a powerful motivation to abandon hunting and gathering, which are very vulnerable to environmental change, in favour of cattle herding.

Climate Impacts of Increased Rainfall

The team found that rainfall dramatically increased during the greening of the Sahara. However, mathematical models could not reproduce these high rainfall rates, nor could they accurately simulate the full northward extension of the Saharan greening inferred through sediment analysis.

The researchers set out to understand the complex feedbacks between Saharan desert dust, vegetation, and rainfall in enhancing the intensity of the African monsoon. By incorporating the reduction in dust emissions and the vegetation changes into a mathematical climate model, they could replicate the observed rainfall during the greening phase. The absence of atmospheric dust allowed more solar radiation to reach the ground and be absorbed by a now darker vegetated soil, increasing the land-sea temperature gradient and strengthening the monsoon.

As the Saharan environment directly influences the global climate, understanding these feedbacks could improve scientists' understanding of global atmospheric processes. For example, the El Niño-Southern Oscillation (ENSO) is one of Earth's most fundamental climate phenomena. The ENSO is a cyclic warming and cooling of the equatorial Pacific that influences temperature and precipitation worldwide. It responds to changes in radiation from the Sun due to Earth's orbital cycles, but this can't explain the full range of past ENSO variability.

Using mathematical climate models, the researchers examined the impact of the Saharan greening on ENSO. They adjusted the models to account for the increased vegetation cover and reduced dust emissions in this period and found that modelling the Saharan greening reduced the predicted ENSO variation. The duration of El Niño events – the ENSO phase with warmer ocean surface temperatures – was reduced by as much as 50%. They also found that warm El Niño phases were shorter during the Saharan greening due to more intense monsoon rainfall, which cooled the Atlantic Ocean and affected its surface temperature variability. Such changes in the Atlantic could then impact the circulation in the equatorial Pacific, affecting the ENSO state and intensity.

Models of future climate change suggest that the West African monsoon could strengthen again in the future, causing changes in vegetation cover and dust emissions in the Sahara and Sahel regions. Dr Pausata and his colleagues have shown that these changes could have a considerable effect on ENSO variability. Their work shows that future climate change projections will have to consider potential changes in Saharan vegetation and dust.

Saharan Dust and Tropical Cyclones

Tropical cyclones are among the most destructive weather phenomena on Earth, claiming thousands of lives globally each year. They are intense, rotating storms that form over warm seas. Understanding their causes is essential for forecasting their future variability. However, historical records of cyclone activity are short, and sedimentary evidence is sparse. Therefore, scientists use mathematical models to investigate cyclone activity under different climate conditions and predict how it might change in the future.

Dr Pausata and his colleagues investigated how the environmental changes during the Saharan greening would have affected tropical cyclone activity. They ran model simulations that accounted for increased solar radiation in summer, increased vegetation cover, and reduced dust emissions.

Tropical cyclones are driven by heat and moisture from warm oceans. However, some previous studies had suggested cyclone activity could decrease in a warming world, despite warmer sea surface temperatures. Dr Pausata's team found that when they considered the Saharan greening and reduced dust concentration, the models simulated a global increase in cyclone activity during the greening period. They found that the most significant rises in cyclone activity were in the Caribbean and along the East Coast of North America.

In our present climate, with its unprecedented rates of warming caused by human emissions, rainfall may increase in Sahara Desert. Dr Pausata's research shows that a wetter Sahara and Sahel would profoundly impact our planet's future. These impacts could be felt globally through the effects of decreased dust, and increased moisture and vegetation, on large-scale atmospheric circulation. The effects could include a reduced ENSO variation and an increase in the number of devastating tropical cyclones. Understanding the part climate of the desert is a crucial step in predicting and mitigating future climate change impacts.

Meet the researcher

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Dr Francesco Pausata gained his PhD in Geophysics from the University of Bergen, Norway, in 2010. After graduating, he worked as a postgraduate researcher at the European Commission's Joint Research Centre and the University of Stockholm, Sweden. He currently holds the position of Associate Professor of Atmospheric Sciences at the University of Quebec in Montreal, Canada, where he also directs the master's program in Atmospheric Sciences. Dr Pausata's diverse research interests include past and current climate variability caused by human emissions, volcanic eruptions, vegetation changes and dust emissions. At the University of Quebec in Montreal, he supervises undergraduates, graduates and postdoctoral researchers alongside his research activities. Dr Pausata has been interviewed by national and international news outlets and has been awarded multiple honours and awards for his contributions to science.

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FUNDING

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UQÀM

PREDICTING THE HEALTH OF THE OZONE LAYER TO ENSURE ITS PROTECTION

The phasing out of ozone-depleting gases has set the ozone layer on the road to recovery. However, atmospheric changes wrought by rising greenhouse gas levels may represent a new threat to Earth's protective shield. **Dr Susan Strahan** from the NASA Goddard Space Flight Center and **Dan Smale** from the National Institute of Water and Atmospheric Research (NIWA) in New Zealand combine atmospheric measurements with simulations to track and explain recent changes to the ozone layer, towards ensuring its protection into the future.

Monitoring Ozone

The complexity of the atmosphere is considerable, and scientists continue to devote much time to further our understanding about how it functions. An increased understanding about how human activity influences the atmosphere enables governments and industries to reduce their environmental impact when making decisions.

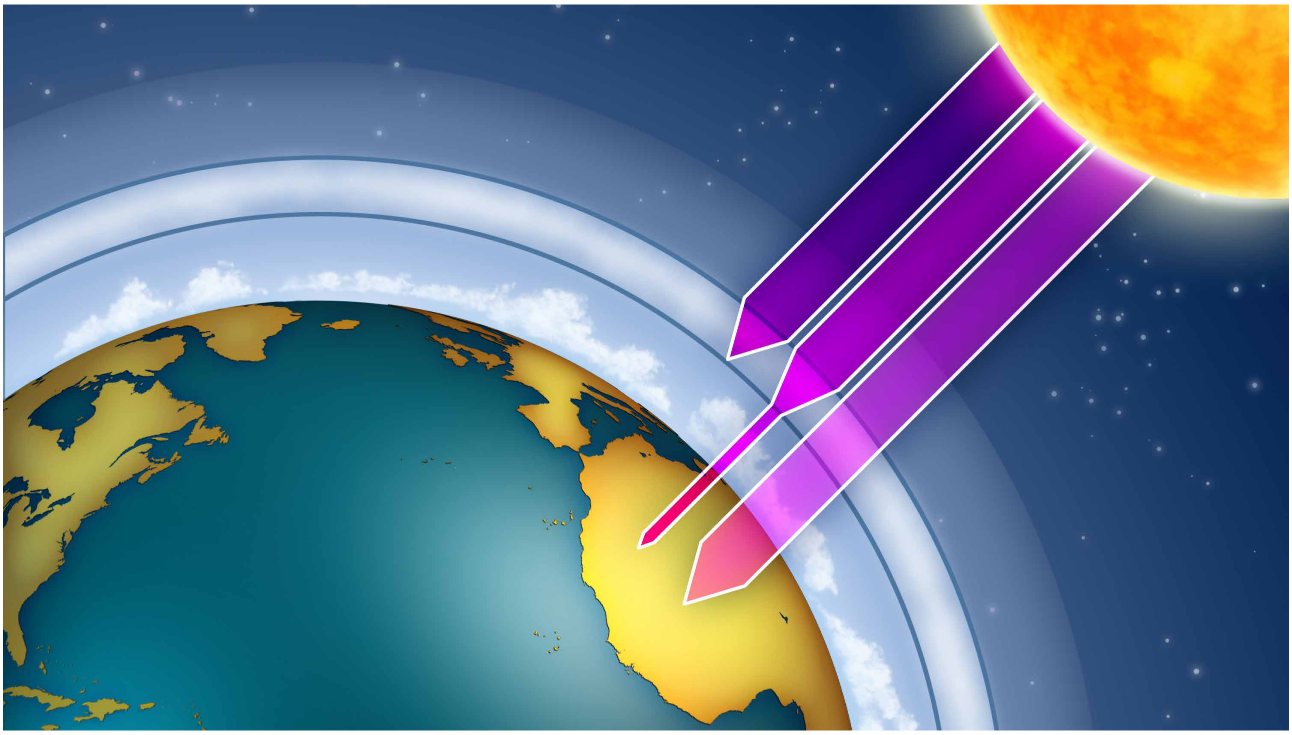
One especially important example of a response to an environmental crisis is the Montreal Protocol. Drawn up in 1987, this protocol established a worldwide commitment to reducing the production of substances that deplete atmospheric ozone, particularly chlorofluorocarbons 'CFCs', which had been used for decades in air conditioners, refrigerators and aerosol sprays. By the early 1990s, the production and consumption of CFCs was completely banned in many countries.

Because of their inertness and widespread use over a long period, high levels of CFCs ultimately ended up in the atmosphere. When exposed to ultraviolet light in the upper atmosphere, these CFCs release chlorine atoms, which can then go on to break down ozone molecules. The combination of chlorine atoms and the very cold atmosphere over Antarctica in winter led to a region of severe seasonal depletion – or the 'ozone hole' – allowing more harmful UV radiation to reach the Earth's surface.

Since the Montreal Protocol was conceived, scientists have been monitoring the state of the ozone layer to understand its response to reduced CFC emissions. However, rising levels of greenhouse gases, such as carbon dioxide, represent a new and poorly understood threat to atmospheric ozone. High-quality data collection, alongside atmospheric modelling, can allow scientists to build an accurate picture of how the ozone layer is changing, and how it is likely to evolve in response to further increases in greenhouse gas levels.

With their global team of scientists, Dr Susan Strahan of the Universities Space Research Association and NASA Goddard Space Flight Center in the US, and Dan Smale from the National Institute of Water and Atmospheric Research in New Zealand, are using real-world data to test whether models can accurately simulate atmospheric processes influencing the ozone layer. 'We want the atmospheric models to be as good as they possibly can be, because we use them to predict how the ozone layer may change as levels of greenhouse gases rise,' explains Dr Strahan. 'The ozone layer is our planet's sunscreen, so it's quite important to know whether we're doing anything to harm it.'

Dr Strahan and Smale are both members of the Network for the Detection of Atmospheric Composition Change (NDACC), a global collaboration between scientists created in 1991. NDACC's primary objective is to create global long-term records of high-quality atmospheric composition in order to detect trends. Smale is a Principal Investigator of one of the NDACC instrument working groups and Dr Strahan is a member of the NDACC Steering Committee who provides model simulations that support analysis of NDACC observations.



Experiments First, Models Second

Over the past few years, Dr Strahan and her collaborators have published observational evidence and modelling research showing that the ozone hole is healing. This research was challenging, as CFCs can linger in the atmosphere for decades, making it difficult to identify clear signs of ozone recovery. Eventually, the team demonstrated how the reduction in chlorine levels (released from CFCs) correlated with the extent to which ozone was recovering. Interestingly, the increase in ozone levels is greatest near the edges rather than the centre of the hole.

'Using model simulations and measurements of the chemical composition of the ozone hole over the past three decades, we now know that the Montreal Protocol has been a success,' says Dr Strahan. 'The ozone hole is shrinking and it's because levels of ozone-depleting substances are declining. We wouldn't know this without models and measurements working together.'

For decades, Dr Strahan has used high-quality observational data, such as those collected by Smale, to improve the accuracy of atmospheric chemical models that simulate the past. Those improvements, along with computational advances and more sophisticated weather models, have made it possible to develop a robust model that describes the chemical state of the atmosphere at a given location and point in time in the recent past.

The improved chemistry in this model can then be used in climate models that make predictions of future scenarios. For example, Dr Strahan can input variables that describe expected future levels of carbon dioxide, and then find out how this greenhouse gas will affect atmospheric circulation, which may damage the ozone layer. 'Such predictions are tricky because there are competing effects,' she explains. 'While carbon dioxide is increasing, the CFCs that destroy ozone are also greenhouse gases and they are decreasing.'

Dr Strahan, Smale and other researchers in the field present their combined results in documents such as the 'Scientific Assessment of the Ozone Layer', which is published by the World Meteorological Organization (WMO). This document is used by policymakers and industry leaders to make informed decisions about how to minimise any future impacts on atmospheric ozone. As such, it is vital that the models are reliable and that any discrepancies with real-world findings are rectified. 'Measurements provide critical feedback to models, showing us what the models are getting right and where improvements are needed,' says Dr Strahan.

However, different research groups publish work based on different models, which don't always lead to the same conclusions. These differences introduce doubt and undermine the credibility of atmospheric models and their subsequent recommendations. These conflicting issues are one of the focal points of Dr Strahan's latest research.

Modelling Atmospheric Chemistry

Dr Strahan focuses on a type of model known as a Chemistry Transport Model, or CTM. CTMs utilise meteorological analyses, produced by the same models that predict the weather – which assimilate temperature, humidity, wind speed, and other data measured at locations spread out over the Earth's atmosphere. The meteorological analyses are able to accurately model other unexplored regions, filling in the blanks, and thus yield an overview of the state of the entire atmosphere with remarkable accuracy. Using these analyses, the CTM then calculates the global chemical composition.

'CTMs allow us to "look under the hood" and see in detail how the atmosphere has been evolving over the past 30 or so years,' Dr Strahan explains. 'This is about how long we've had meteorological analyses good enough to do this kind of work.' However, CTMs only represent sequences of events that have already occurred. To forecast future atmospheric composition, the chemistry provided by CTMs is used in climate models, such as Chemical Climate Models (CCMs).

CCMs make predictions by applying fundamental physical laws that govern the behaviour of energy and matter in the atmosphere. If a CCM consistently produces changes in chemical composition and meteorology similar to what has been observed in the past, then it may reliably predict results for a future date. Like all models, however, CCMs are not perfect and do not consider all factors. Specifically, CCMs do not fully accommodate the effect of minor atmospheric motion, which can have a significant influence on how energy and matter are distributed. Additionally, many CCMs do not include the oceans. This can greatly affect predictions, considering that significant heat exchange occurs between the atmosphere and ocean.

'Studies using CCMs try to predict how atmospheric composition will change in the future as greenhouse gases increase and CFCs decline,' describes Dr Strahan. 'We try our best to make CCMs that generate realistic meteorology, but they have shortcomings. For example, we know that they are unable to produce as much composition variability as we observe in the ozone layer and this is because CCMs can't represent all the small-scale waves that are important drivers of atmospheric motions. This can lead to errors predicting atmospheric circulation trends in the future, thereby impacting ozone predictions.'

Discrepancies Between Simulations

One example that illustrates the discrepancies between simulations is about how the so-called 'age of air' across each hemisphere has changed. Gases emitted from the ground can migrate to the stratosphere, where the ozone layer resides, and back down to the lower atmosphere. The average time taken for air to travel from the Earth's surface to the stratosphere is known as the average age of air. This value is not measured directly but inferred from trace gas and meteorological data. Dr Strahan and Smale performed an analysis of 25 years' worth of NDACC nitric acid and hydrogen chloride observations in the atmosphere. Their analysis indicated that the time air spends in the stratosphere in the southern hemisphere is decreasing with respect to that in the northern hemisphere. A parallel analysis of the CTM over the same time period produced very similar results, allowing them to look inside the model to learn additional details of how atmospheric chemistry and meteorology were changing. These results contrast with most CCM studies, some of which predict the opposite change, while many predict a decrease in the travel time in both hemispheres.

The circulation of air can influence the distribution of ozone and CFCs across the stratosphere, and so it is important to model the circulation accurately. The differences between CTM and CCM results are a concern because climate scientists use CCMs to predict the future state of the ozone layer.

When Strahan, Smale and their team zoomed in on the 25-year trend line, they noticed that the line was not straight, but oscillated over a five-year period – a feature not produced by the CCMs. The oscillation indicated that the age of air trends in both hemispheres

seesaws over periods of about five years. This may explain the different conclusions given by other reports that used shorter data records.

Over a longer period of 25 years, the team noticed an overall trend showing that the age of air in the southern hemisphere was getting younger relative to the northern hemisphere. But the trend was small and required a long data record in order to see beyond the oscillations. Consequently, the team recommended in their report that all trend analyses examine observations spanning a time period of at least 20 years to avoid bias due to the oscillations. The team proposed that the oscillating nature of the trend line was a result of the interaction between the oscillating easterly and westerly winds near the equator and the circulation of air from the warmer tropical regions to the poles. CCMs are known to struggle to realistically produce these oscillating winds, which may explain their inability to match the observations.

The work of Dr Strahan, Smale and their colleagues demonstrates the need to constantly improve models by testing them with real-world data, so that they yield reliable predictions. Long-term measurement networks such as NDACC play an essential role in filling this need. The end goal of their efforts will instil more confidence in the models and help global leaders make better informed decisions, towards protecting the ozone layer in the face of rising greenhouse gases.

Meet the researchers

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Dr Susan Strahan received her PhD in Chemistry from University of California, Berkeley in 1986. She is currently a Principal Scientist for the Universities Space Research Association at NASA Goddard Space Flight Center. Here, she uses models and measurements to learn how chemistry and meteorology affect the ozone layer. Dr Strahan's research focuses on the analysis of satellite and ground-based trace gas data sets with the goals of improving the understanding of atmospheric transport processes and their representation in models. Her contributions have been recognised with multiple prestigious awards, including the GESTAR award for Exceptional Contribution in Stratospheric Research in both 2016 and 2018.

See this video for information on Earth Science Research at NASA Goddard Space Flight Center.

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Dan Smale received his MSc in physics from the University of Auckland in New Zealand in 2001. He is currently a Principal Atmospheric Technician at NIWA, where he is involved in instrument design, operation and data analysis. As part of his role, Smale spends three weeks a year visiting Scott Base training the Antarctica New Zealand's science technicians to operate NIWA's equipment. He is also the principal investigator for the remote sensing trace gas measurement programmes at Lauder and Scott Base, and responsible for the greenhouse gas measurement project at Lauder.

See this video for information on NIWA.

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ILLUMINATING NEW INSIGHTS INTO LIGHTNING INITIATION THROUGH INTERFEROMETRY

Radio frequency inteferometric lightning maps are important tools for researchers exploring the electrical processes that unfold within storm clouds. **Dr Xuan-Min Shao** and colleagues at Los Alamos National Laboratory in New Mexico, who first introduced broadband interferometry to lightning research over two decades ago, have now developed an advanced 'beam steering' interferometry technique to significantly improve the accuracy of lightning mapping. This approach, together with their recently developed polarisation detection technique, has begun to reveal new physics involved in lightning discharges. Their recent work shows how lightning initiation, which has been poorly understood until now, may be linked to high-energy cosmic particles entering Earth's atmosphere.

Lightning

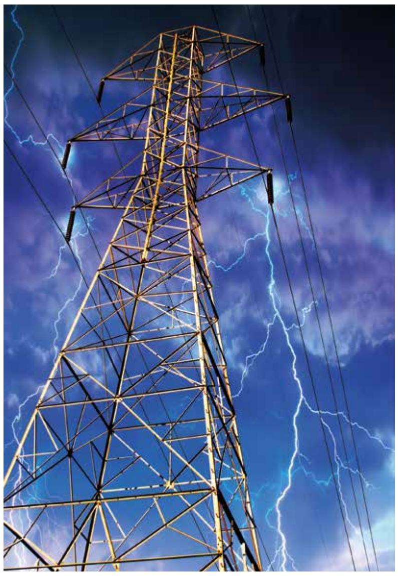
Of all the widely known phenomena to occur in Earth's atmosphere, perhaps none are more fascinating than lightning. The effect arises as updrafts within a brewing storm cloud cause hail and ice crystals to rub together – causing positive charges to build up at the top of the cloud, while negative charges collect at the bottom. In sudden bursts, these build-ups can then become equalised, as particles either travel between charged layers within clouds, or between negatively-charged lower cloud layers and the ground. In the process, colossal amounts of energy are released over barely perceptible timescales.

Although beautiful, lightning strikes can quickly unleash devastation on human-made infrastructures and natural ecosystems alike. In dry conditions, lightning storms are notorious for triggering wildfires. Meanwhile in cities, an unfortunate strike to a power grid can leave many thousands of people without power. Despite many years of studies, a great number of processes involved in a lightning flash are still not well understood. Among these, how lightning gets started in a cloud is one of most fundamental and mysterious questions scientists have been trying to answer in this field of research.

Through their research, Dr Xuan-Min Shao and his colleagues at Los Alamos National Laboratory aim to address this issue directly.

Triggering Lightning Breakdown

When an insulating material is subjected to a high enough voltage, changes in the properties of its constituent molecules can force the substance to become an electrical conductor – in a process named 'electrical breakdown'.



This property is key to the formation of lightning: while the Earth's atmosphere is a strong electrical insulator in most circumstances, the situation can drastically change in the vast voltages that form within storm clouds. Here, the electric fields that build up between

positive and negative charge layers can accelerate electrons to considerable fractions of the speed of light.

As they collide with molecules in the air, these electrons then trigger the release of more fast-moving electrons, creating a downward avalanche of charges. Within microseconds, lightning strikes can form along the paths of these avalanches, in an overall process known as 'fast positive breakdown'. As they seek to build maps of lightning strikes, it is critical for researchers to accurately capture this process as it unfolds. So far, this has widely involved a technique named 'broadband interferometry'.

Mapping Lightning Sources

Interferometry is an incredibly versatile technique, and it is now widely used by researchers spanning numerous disciplines. For researchers aiming to capture lightning as it strikes, the process first involves recording the electrical signals produced during fast positive breakdown. To do this, they use networks of antennas separated by tens of meters. When lightning strikes in a certain position, the electrical signal it produces will travel outwards, creating digitised signals in broad ranges of radio frequencies as it is picked up by these antennas.

As this happens, different antennas will receive the signal after varying time delays, which depend on their positions relative to the strike. If signals are superimposed onto each other, these delays produce characteristic misalignments in the peaks and valleys of their amplitudes. As a result, pairs of signals will destructively interfere with each other to varying degrees, depending on the time delay between them. Therefore, by comparing the strengths of the superimposed signals produced by different pairs of antennas, researchers can calculate both the position and time of the lightning strike that produced them.

Over the past 20 years, cutting-edge developments have led to significant improvements in the data acquisition and processing required for this technique of 'broadband interferometry'. However, to further improve the spatial and time resolutions of the lightning maps they produce, researchers are now in need of better ways to minimise uncertainties in their measurements. Ultimately, the goal for these efforts is to reach a set lower bound in uncertainty, which was calculated through previous theoretical work.

Until now, studies have largely assumed lightning bolts to be stationary, with long time windows in which interferometry can be carried out. Clearly, this picture is wholly unsuited for capturing fast, short-lived lightning flashes – resulting in uncertainties far higher than their theoretical lower bound.

Lowering Uncertainties

In their research, Dr Shao and his colleagues present a sophisticated new technique for reaching this lower

bound in broadband interferometry measurements. Their ideas are based around the idea that if the timings of interferometry signals are precisely aligned, uncertainties in their outcomes can be significantly reduced. As a result, any uncertainties in lightning strike positions and timings will correspond directly with their theoretically calculated lower bound – ensuring researchers that their maps are as accurate as possible. To do this, Dr Shao's team presents an approach named 'beam steering' interferometry.

While this technique processes the same raw data as previous approaches to broadband interferometry, it occurs over two separate steps in this case. Firstly, conventional interferometry is used to find the rough direction of a lightning source occurring within a chosen time interval, and computes the time delays between antennas receiving these signals. As before, this procedure is used to calculate the rough direction of the lightning source.

Secondly, this direction measurement provides a basis to shift the timings of the raw data gathered by each antenna so that they are all roughly aligned – analogous to the researchers pre-emptively rearranging the network of the antennas facing in the direction that the lightning will strike. Finally, the aligned signals are processed by interferometry a second time, producing a far more accurate and detailed interferometric final image. As a result, uncertainties in the positions and timings of individual lightning strikes can finally approach their lowest possible value – producing maps with high resolutions in both space and time.

Investigating Positive Breakdown

To demonstrate the advantages of beam steering interferometry, Dr Shao and his colleagues applied their technique to study the characteristics of a fast positive breakdown process initiated by intra-cloud lightning – where charged particles travel between the layers within a storm cloud. In previous studies, researchers had discovered that the process occurs in the first few microseconds of both intra-cloud and cloud-to-ground lightning – initiating lightning flashes. Yet when Dr Shao's team observed fast positive breakdown using beam steering interferometry, they discovered that the process could become far more complex than they first thought.

Through the higher mapping resolutions made possible through lower uncertainties, the researchers found that fast positive breakdown can occur in two distinct groups of breakdown processes. Within these groups, charged particles travel downwards in slightly different ways over time, while their paths also follow different patterns. However, their most important result relates to a phenomenon that has never before been observed with lightning formation, with origins reaching far beyond Earth's atmosphere.

Spotting a Key Connection

Cosmic rays take the form of atomic nuclei with exceptionally high energies, which travel through space at close to the speed of light. While some of these rays are known to originate from violent eruptions on the Sun's surface, others likely started their journeys from ancient supernovae in distant galaxies. Regardless of their source, cosmic rays can trigger fascinating phenomena as they interact with Earth's atmosphere. On impact with air molecules, they can produce showers of secondary particles with similarly high energies – which sometimes reach Earth's surface. Named 'cosmic ray showers', these cascades of ionised particles can measure hundreds meter across.

As they travel downwards through the atmosphere, cosmic ray showers develop arc-shaped fronts with characteristic geometries. This effect may have seemed entirely unrelated to lightning formation when Dr Shao and his colleagues began their study – yet through their analysis, the team discovered that both groups of fast positive breakdown processes they observed appeared to originate in front of these arc-shaped fronts. From this observation, the researchers developed an intriguing theory: as a cosmic ray shower enters a storm cloud, it can enhance its already strong electric field by over three or more times. In this altered environment, avalanches of electrons can be triggered far more readily – explaining the occurrence of fast positive breakdown observed during intra-cloud flashes.

The team's results represent a breakthrough in our knowledge of lightning formation, and how it is linked to a cosmic phenomenon. Beyond this fascinating discovery, Dr Shao and his colleagues show that their beam steering interferometry technique can significantly improve on existing methods for producing high-resolution maps of lightning flashes over a wide range of directions and time periods. Ultimately, their work could soon lead to an even deeper understanding of how lightning flashes form and develop, and how their impacts on both natural ecosystems and manmade infrastructures can be better assessed.

Meet the researcher

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Dr Xuan-Min Shao completed his PhD in Physics at the New Mexico Institute of Mining and Technology in 1993. He has now worked at Los Alamos National Laboratory ever since, and became a Senior Scientist at this institution in 2008. Dr Shao is a world leader in the field of lightning physics and detection. He now has contributed to a wide variety of innovative theories, models, and experiments in areas including atmospheric and ionospheric radio wave propagation, lightning mapping techniques, and space-based radio detection. Elsewhere, he has headed many projects to develop advanced instruments and modelling capabilities required for his research, securing funding from organisations including the US Department of Energy. Dr Shao has been recognised for his scientific and national security contributions with numerous awards, including the Director's Distinguish Performance Award for Mighty Saber in 2015, and DOE/NNSA's Defense Programs Award of Excellence for Contributions in EMP Capability Development in 2012. He is also committed to training the next generation of scientists, and currently mentors several students and postdoctoral researchers.

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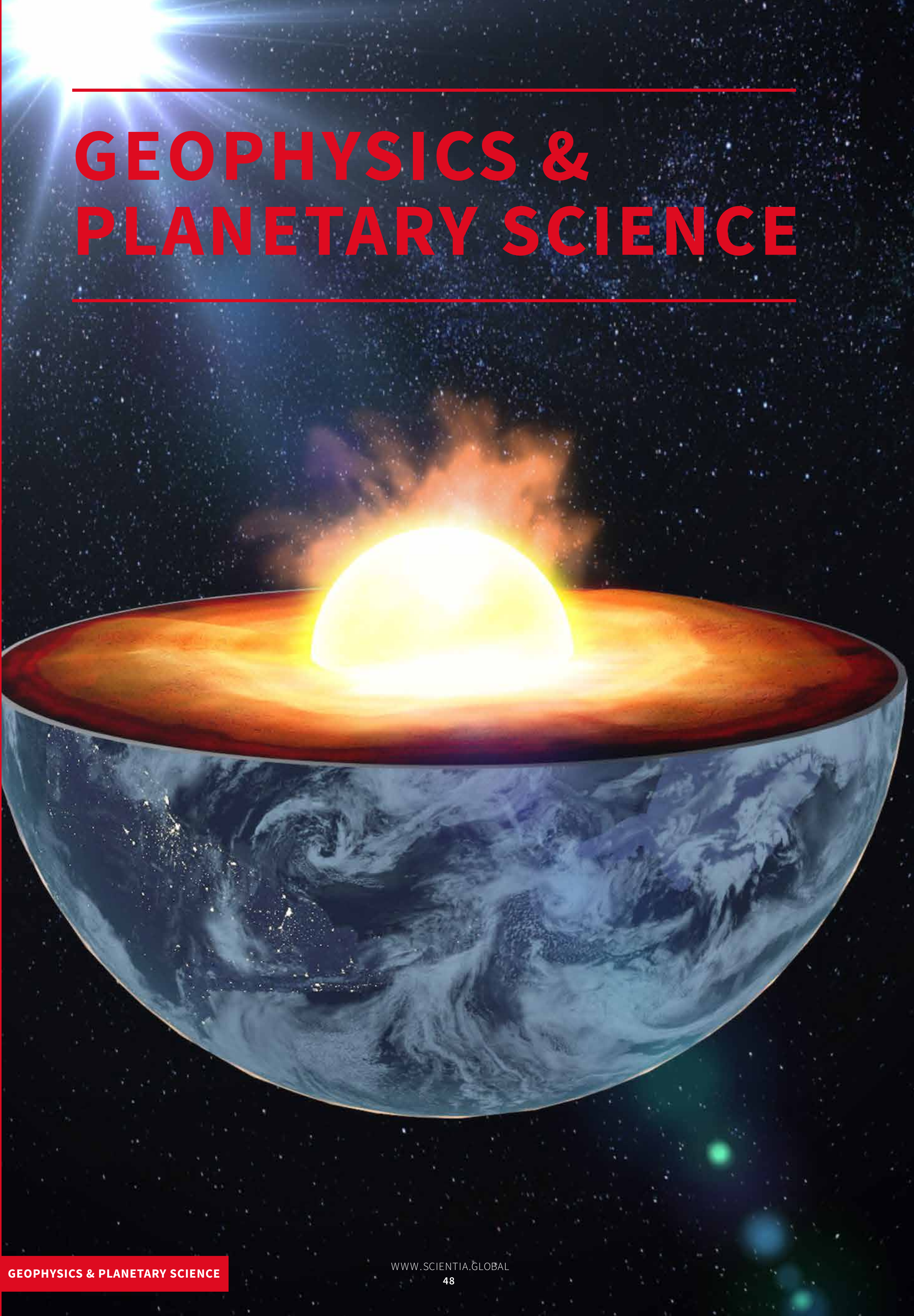

THE ASSOCIATION FOR WOMEN GEOSCIENTISTS

The Association for Women Geoscientists (AWG) is an international organisation devoted to increasing the participation of women in geoscience, and inspiring girls and young women to pursue careers in geoscience-related disciplines. In this exclusive interview, we have had the pleasure of speaking with Dr Noelia Beatriz Carmona, AWG's past president, who describes how the Association supports the professional development of its members, provides education and outreach to young women and girls, and encourages the participation of women in geoscience.

Please start by giving a brief history of AWG. Why was the Association founded, and what is its mission?

AWG is a non-profit, international organisation founded in 1977, in San Francisco. Since its origin, AWG has been devoted to enhancing the quality and level of participation of women in geosciences and to introducing girls and young women to geoscience careers.

In fact, the formation of the Association is credited to inspiration from the development of the Women Geoscientists Committee in 1973, which was a committee created by nine women from the American Geosciences Institute. Among their great achievements, these women were able to gather and analyse a great amount of data, which reflected the problems and challenges related to unequal treatment of women in the workplace. This was the prelude to the formation of the AWG in 1977.

The mission of the Association is to follow the three E's: **Encourage** the participation of women in geosciences; **Exchange** educational, technical and professional information; and **Enhance** the professional growth and advancement of women in geosciences.

Who makes up your membership today?

Our members include professionals from industry, government, museums, academia, and K-12 teachers, students, retirees, and all the people interested in supporting our goals. Today, we have approximately 1000 members who are either affiliated with an AWG local chapter or are members-at-large.

Although the majority of our members are from North America, we are striving to increase our representation worldwide, and this has been a key objective for the AWG Board in the past few years. Our diverse interests and expertise cover the entire spectrum of geoscience disciplines and career paths, and we look to provide excellent networking and mentoring opportunities. Our membership is brought together by a common love of Earth science and the desire to ensure rewarding opportunities for women in the geosciences.

How does AWG encourage girls and women to pursue careers in geoscience?

There are several ways in which the Association encourages girls and women to pursue careers in geoscience. One way is through student awards and scholarships.

Examples include the AWG Maria Luisa Crawford Field Camp Scholarship, which helps support young women to gain field experience which is vital for pursuing a geoscience career; the Geoscience Inclusion, Diversity, Equality, and Accessibility (IDEA) Scholarship Program, which encourages women from underserved communities with the objective of enhancing diversity in the geosciences; the Harris-Chrysalis Scholarship, which provides degree-completion funding for women geoscience graduate students whose education has been significantly interrupted by life circumstances; and the AWG Sand Student Research Presentation Travel Award, which provides women geoscience students with support to present their research at the Annual Meeting of the Geological Society of America. AWG chapters also offer specific programs, awards, and scholarships to their members.

'The mission of the Association is to follow the three E's: Encourage the participation of women in geosciences; Exchange educational, technical and professional information; and Enhance the professional growth and advancement of women in geosciences.'

Another way that the Association encourages girls and women to pursue careers in geoscience is through mentoring. AWG, with other Earth and space science organisations, is sponsoring the Mentoring365 Program, which is a 'virtual mentoring program developed to facilitate an exchange of professional knowledge, expertise, skills, insights, and experiences through dialogue and collaborative learning'.

We are trying to provide support to girls and women geoscientists in different stages of their careers, using diverse strategies, but also considering different life circumstances. We are also thinking about new awards and scholarships to implement in the future.

What are some of the benefits of increasing female participation in geoscience?

I would like to refer to the book *Women in the Geosciences: Practical, Positive Practices Towards Parity* by Mary Anne Holmes and her colleagues, which mentioned that 'Diversity of the geoscience workforce matters because we need a variety of minds asking a variety of questions and posing a variety of solutions'.

As these authors also stated, more diverse working environments are more innovative and productive, as people provide their personal experiences and knowledge when looking at problems. This is particularly crucial now, as we are facing this period of environmental crisis; we need more diverse voices to find the proper solutions. And when I refer to the need of more diverse voices, I am not only thinking about women, but also all of the underrepresented groups in geosciences.

Tell us a bit about AWG's field trips.

Our field trips are excellent opportunities for our members to visit and discover new places worldwide, as well as to share knowledge and experience with the other participants. Unfortunately, during the past year, it was necessary to cancel scheduled trips, but hopefully, as the COVID-19 pandemic is addressed with vaccinations, fewer restrictions will allow us again to offer a full variety of options.

We have two categories, field trips organised directly by the Association, and field trips organised by individual AWG chapters. We are lucky to have a field trip committee completely dedicated to providing the best services, and we have had several discussions on the Board regarding safety procedures during the pandemic.

Just prior to the pandemic, AWG held field excursions to New Zealand and England. Plans for an Iceland trip are on hold but will likely occur in 2022. We are now exploring options to organise

'I also believe that the pandemic gave us the opportunity to expand our contacts worldwide, to meet and interact with other groups of geoscientists who share our goals, and of course, this is something that will stay with us.'

field trips to locations we have not visited before, such as South America. We are also thinking about organising field trips particularly designed for students, like training programs. This is something we are discussing right now with the AWG Board.

Finally, as we begin to emerge from the COVID-19 pandemic, what are you most excited about for the future of AWG and the field of geoscience in general?

I believe that the COVID-19 pandemic taught us (or in many cases, stressed the idea) that we are going through an unprecedented environmental crisis, and that our actions to take care of the planet are urgently needed. It also made clear the necessity to strengthen scientific cooperation worldwide, and the need to count on diverse views to get out of this crisis and to also prevent and deal successfully with the crises in the future.

For our Association (as for other organisations), the pandemic forced us to be more creative in the way we communicate with our members. In this regard, the work done by all the AWG chapters has been amazing. They have been very innovative about organising online meetings and training events to continue helping their members. Once the world is safer, we are going to be able to organise field trips, and of course, all the in-person activities we usually do (training, outreach, mentoring activities, meetings, etc).

However, I also believe that the pandemic gave us the opportunity to expand our contacts worldwide, to meet and interact with other groups of geoscientists who share our goals, and of course, this is something that will stay with us.

Regarding the field of geoscience in general, the COVID-19 pandemic represented a real challenge, as scientists were not able to conduct essential activities such as fieldwork or lab experiments. But on the other hand, online field trips, meetings and mentoring activities flourished during the last two years, and in this sense, these virtual activities provide more opportunities to those students and professionals that usually, for different reasons, are not able to travel to participate in these kinds of events. So, I hope we can take the good things that we have learned from the pandemic.

In addition, some researchers were able to reorient their investigations according to the progress of the pandemic (for example, some geoscientists used their expertise in data visualisation and mapping to track and predict COVID-19 infection risks). So, I think that this global health emergency and the environmental crisis we are facing will require more geoscientists willing to do interdisciplinary research that provides better and more original solutions for a more sustainable planet.

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THE NONLINEAR EARTH: CORRECTING A LONG-OUTDATED THEORY

Although the theories researchers use to describe the structural properties of Earth's interior have now persisted to decades, the assumptions they make are far from realistic. Through their research, **Dr Hatam Guliyev** and **Dr Rashid Javanshir**, both of the National Academy of Sciences in Azerbaijan, have integrated concepts from both mechanics and Earth sciences to produce ground-breaking new theories about Earth's 'nonlinear' properties. Their discoveries have yet to be widely accepted by the scientific community, but through concerted collaboration efforts, they hope that their 'non-classically linearised' approach could soon become a key aspect of geophysical research.

Observing Earth's Interior

Over several centuries, researchers across numerous different disciplines have used innovative techniques to determine the structural properties of Earth's interior. Through this work, we are now aware that our home planet has a layered structure: containing a solid inner and liquid outer core; a solid mantle; and a solid outer crust. Our knowledge of this structure is based around measurements of how waves travel through Earth's interior, and become distorted by different types of material.

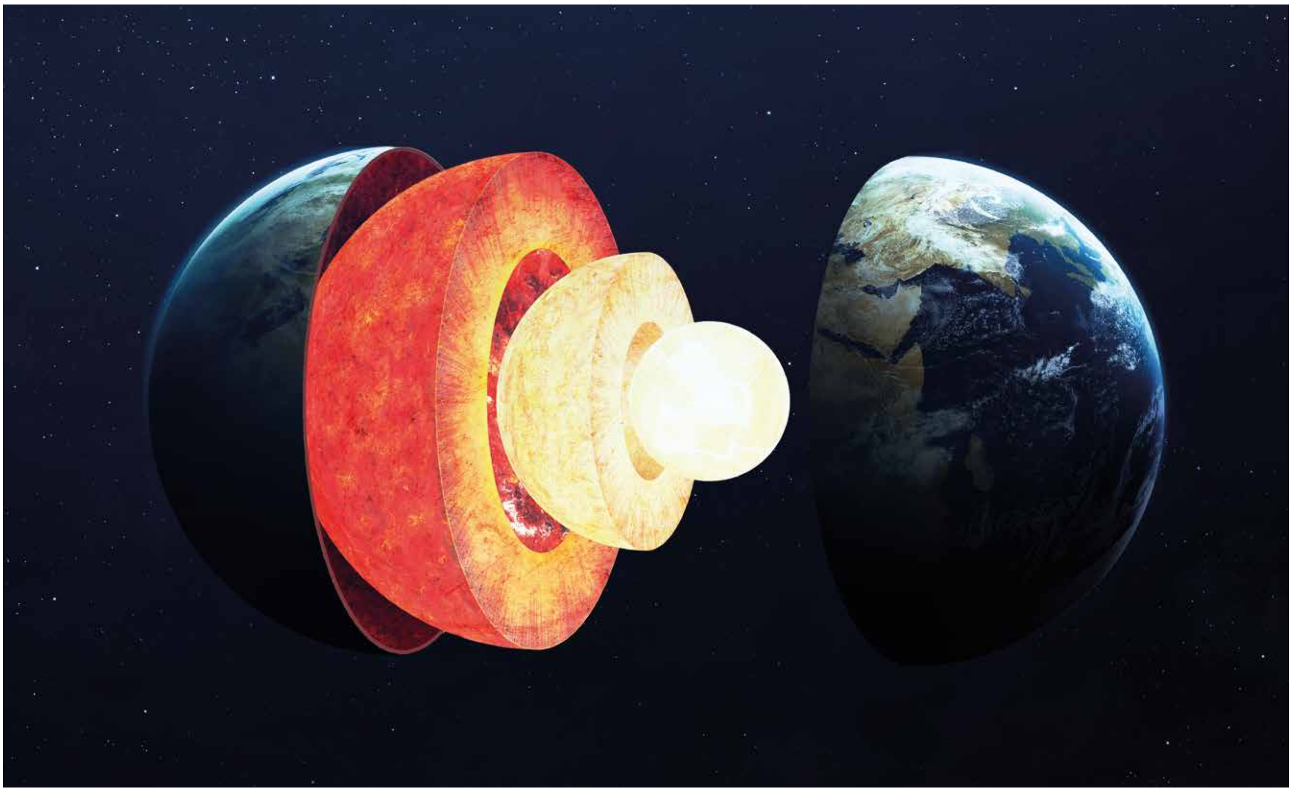
Researchers can carry out this analysis through detections of seismic waves originating from large-scale geological events, including earthquakes and volcanic eruptions. By measuring the properties of waves emanating from single events at different points across Earth's surface, these researchers can determine how they were changed as they passed through different layers of the planet's interior.

From the turn of the 20th century, geophysicists had used these techniques to develop sophisticated theories about the Earth's interior structure, and how it evolves over time. In the following decades, these ideas were integrated with different theories across numerous fields of Earth science, enabling our understanding to progress even further.

Strengths and Weaknesses of the PREM

In 1976, these efforts culminated in a theory named the 'Preliminary Reference Earth Model' (PREM) – first proposed by US geophysicists Adam Dziewonski and Don Anderson. Widely seen as a breakthrough at the time, this model considered each of Earth's interior layers to have their own distinct, unvarying characteristics. Most importantly, it presented linear formulae to illustrate how material properties including density, pressure, and gravity changed at varying distances from the centre of the Earth, accounting for the influence of each layer.

In the decades since its conception, the PREM has seen little change, and has now become a ubiquitous element across many branches of Earth sciences. Amongst the many successes of the model are its ability to determine the positions of the boundaries between different layers of Earth's interior, as well as predictions of how the strength of Earth's gravitational pull will vary at different depths. Yet despite this success, the model was not built to last. Even as Dziewonski later wrote,



the very word 'preliminary' implied that the PREM was only supposed to provide approximate predictions of the Earth's interior, until a better model was created.

Although the model's discoveries have fundamentally sculpted our view of Earth, its many shortcomings have now lingered for decades. Today, seismologists and geophysicists using increasingly accurate equipment are finding that their observations no longer perfectly match up with the predictions made by the PREM, which should be casting serious doubts about its accuracy. So far, however, efforts by the wider Earth sciences community to correct these issues have been all but non-existent.

Accounting for Nonlinear Properties

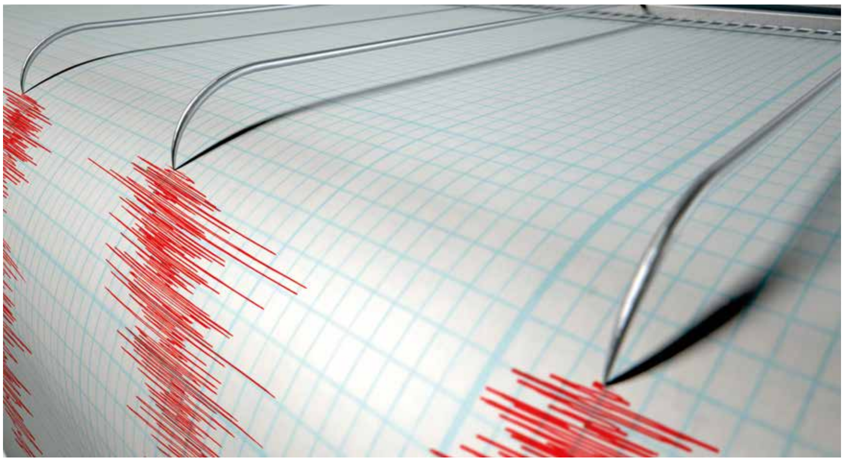
In many natural systems, waves undergo 'nonlinear' propagation as they travel through different materials. Broadly speaking, this means that the properties of waves, which have passed through the systems, show no clear relationship with the properties of those that entered. Therefore, even though they do in fact obey strict physical laws, nonlinear waves can appear to exhibit chaotic, unpredictable behaviours – wholly unlike the clean mechanical laws described by Newton. Because of this, these waves are described as displaying 'non-classical' mechanics. If researchers don't account for these properties when making predictions about nonlinear systems, their results can incur significant inaccuracies.

According to Dr Hatam Guliyev and Dr Rashid Javanshir, the PREM is deeply flawed in its inability account for these properties. The duo first met in the 1980s at the National Academy of Sciences in Azerbaijan, which was then part of the Soviet Union. Their collaboration was unusual: while Dr Guliyev was well known for his research in mechanics, he was first introduced to the field of Earth sciences by Dr Javanshir, whose background was in geophysics. In their earliest collaborative research, the duo proposed that waves passing through Earth's interior couldn't be obeying simple mechanical laws – contrary to assumptions made by a vast majority of studies at the time.

As an alternative, the researchers argued that these waves must experience nonlinear propagation, which would mean that the PREM's predictions are significantly diverged from reality. In the following years, Dr Guliyev and Dr Javanshir began to map out the shortcomings of the PREM, and proposed how they could be amended. Through this work, they have now pioneered new approaches to account for Earth's nonlinear properties – based around the integration of Earth sciences with the separate field of non-classical mechanics.

Introducing a New Model

To build their theories, the two researchers have focused on defining the non-classical mechanical properties of deforming solid bodies. Their ideas are based on the fundamental principles of nonlinear elasticity – which relates to how nonlinear materials temporarily deform as waves propagate through them. In the PREM, Earth's material properties at given distances from its centre are assumed to be the same globally, no matter where they were measured.



Through their updated model, named the 'non-classically linearised approach' (NLA), Dr Guliyev and Dr Javanshir approach the problem in three dimensions. By considering the behaviour of the Earth as a whole, with materials at similar depths displaying varying mechanical properties, this model removes the need for unnecessary mathematical complications.

In eliminating the flaws and inaccuracies associated with the PREM, the predictions made by the NLA can deviate significantly from past predictions of geological processes, including the propagation of seismic waves. For the first 10 kilometres beneath Earth's surface, Dr Guliyev and Dr Javanshir have now shown that predictions made by the NLA and PREM can differ by as much as 30%. Deeper into the Earth, this difference could grow significantly higher still – but this remains a goal for future research. Ultimately, quantifying the Earth's structural properties at these depths will require a vast amount of work.

Improving Our Understanding of Earth's Interior

Moving forwards, Dr Guliyev and Dr Javanshir propose that future studies centred around their NLA should consider three key elements. Firstly, they propose that the model should be used to make a complete analysis of Earth's structural elements, from crust to core, while accounting for the influences of oceans and continents on Earth's surface. Secondly, the researchers call for an end to the use of classical theories when interpreting data; instead, assuming that elastic waves display nonlinear dynamics as they propagate through the Earth's interior.

Finally, Dr Guliyev and Dr Javanshir hope to improve the methodologies and equipment used to collect and interpret geological and seismological data. By assuming from the start that their observations are a result of nonlinear properties, they can adapt their techniques to greatly improve their predictions. Through these efforts, the duo hopes that a more realistic understanding of Earth's interior, and its ongoing evolution, could finally be reached. However, before these goals can be widely achieved, there are still significant barriers to overcome

A Lack of Collaboration So Far

Throughout their decades of research, Dr Guliyev and Dr Javanshir have produced an abundance of robust results – which have been published in hundreds of books and papers, and presented at numerous conferences. Yet despite this success, their theories have still not been widely discussed by researchers in the wider communities of Earth sciences. Ultimately, the duo believes that the acceptance of their theories has been hindered by a persistent lack of collaboration between researchers from different cultural backgrounds. This lack of discussion is deeply rooted in barriers between East and West, which defined the global political landscape when the researchers first began their collaboration.

Even decades after political shifts, and the rise of the Internet, have enabled researchers around the world to collaborate far more easily than ever before, the prejudices that defined this past era have continued to persist. Without sufficient efforts to alleviate the damage to scientific research imposed by these boundaries, long-outdated theories such as the PREM are still in ubiquitous use, even in the present day. According to Dr Guliyev and Dr Javanshir, this factor has been a significant hindrance to scientific progress. However, the picture may not stay this way for long.

Hope for Widespread Discussion

Despite numerous setbacks in the past, Dr Guliyev and Dr Javanshir are now hopeful that attitudes towards their research are shifting in the right direction, and are now increasingly being discussed. In 2019, their theories were finally published in the widely respected academic journal, *Earth and Space Science* – bringing their NLA model to widespread international attention for the first time. In the future, they now hope that this increased publicity could soon initiate new collaborations across numerous disciplines, and between global institutions, to study the NLA in the depth it deserves.

If these outcomes are achieved, they could finally consign the long outdated PREM to history, enabling new generations of researchers to explore the true nature of Earth's interior properties. Ultimately, these efforts may one day lead to large-scale research programs spanning many decades, which will finally uncover the diverse nonlinear characteristics of our home planet.

Meet the researchers

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Dr Hatam Guliyev is a world-renowned representative of the S.P. Timoshenko Institute of Mechanics at the National Academy of Sciences of Ukraine, and a Full Member of the Azerbaijan National Academy of Sciences (NAS). In his earlier research, he pioneered new theories regarding the mechanics instability in the fracturing and cutting of deformable solids. He has since published over 400 books and academic papers, presented his work at international conferences, and supervised young scientists in their early research. Since 1988, Dr Guliyev has closely collaborated with Dr Javanshir to incorporate his ideas into the Earth Sciences, leading to groundbreaking theories regarding non-classically linearized approaches in studies of three-dimensional and nonlinear problems of Earth's interior.

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Dr Rashid Javanshir is a Corresponding member of the Azerbaijan National Academy of Sciences (NAS), who was one of the firsts in the former Soviet Union to establish close cooperation with geoscientists in the West. In 1988 he became the Scientific Director of NAS's Institute of Deep Oil and Gas, where he negotiated joint research agreements with numerous companies in Canada, the US, and the UK. Since 1995, Dr Javanshir has occupied senior leadership positions in BP, including Regional President for Azerbaijan – Georgia – Turkey in 2009–2012, followed by Senior Vice President for Strategy and Integration in 2012–2015. He has published over 200 papers including 35 jointly with Dr Guliyev.

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BUILDING CONTAINERS FOR EXTREME GEOLOGICAL FLUIDS

Earth's crust plays host to many different fluids, which are often pressurised and heated to extreme degrees by the geological processes taking place around them. Harnessing his previous experience at the US Geological Survey, **Dr I-Ming Chou** at the Chinese Academy of Sciences designs vessels suitable for containing these fluids, while also enabling researchers to easily measure them in the lab using advanced optical techniques. Through their work, Dr Chou's team has presented cutting-edge designs based on fused silica capillary tubes. Their designs could soon transform geologists' understanding of the chemical processes taking place far below us.

Underground Fluids

Deep underneath the Earth's surface, immense geological forces can elevate fluids trapped in the crust to extreme temperatures and pressures. Under the right conditions, we can see these superheated fluids as they are ejected all the way to the surface, in dramatic natural features such as geysers and hydrothermal vents on the seafloor.

By studying the unique properties and compositions of these fluids, geologists can learn much about the physical characteristics of the crust, and the chemical reactions that shape its composition. However, while these samples can be studied in their natural state by drilling holes deep into Earth's crust, this is a costly and time-consuming process.

Instead, researchers today are aiming to recreate geological fluids in the lab directly. This poses a significant challenge: without highly advanced equipment capable of containing substances under such extreme pressure-temperature conditions, they will rapidly cool down and lose pressure. Dr I-Ming Chou at the Chinese Academy of Sciences aims to overcome this problem by developing cutting-edge new containers for measuring geological fluids. His team's designs are now offering realistic new glimpses of the processes playing out far beneath our feet.

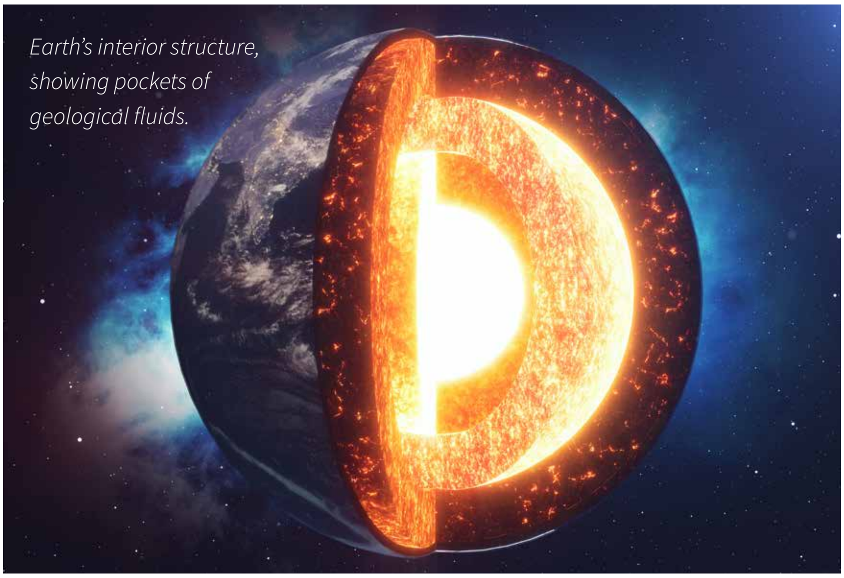
Investigations with Raman Spectroscopy

A key feature of geological fluids is the presence of both organic molecules such as methane (CH_4), and inorganic substances such as hydrogen sulphide (H_2S), contained within them. At extreme temperatures and pressures, these substances can dissolve and diffuse through water in characteristic ways, which are thought to play important roles in geological processes, as well as the chemical composition of Earth's crust.

Researchers observe and study these unique processes through a technique named 'Raman spectroscopy'. This method relies on the fact that the relative positions of a molecule's constituent atoms are never static; rather, depending on the molecule's composition, they will vibrate and rotate in characteristic ways.

When the molecule is exposed to the uniform photons produced by a laser, they will initially interact with these vibrations, either losing or gaining energy in the process. Afterwards, the photons are re-emitted with new energies and directions, in an overall process named 'Raman scattering'. Crucially, the shifts in energy experienced by the photons are unique to the molecule they were scattered from.

So, by detecting these re-emitted photons, researchers can identify molecules by their specific Raman scattering fingerprints. However, even for the most advanced Raman spectroscopy techniques for studying geological fluids at elevated pressures and temperatures, suitable containers are still needed.



Earth's interior structure, showing pockets of geological fluids.

Building Optical Cells

Until now, lab-based studies have largely relied on devices named 'diamond anvil' cells, which exploit the extreme hardness of diamond to compress samples to immense pressures. For fluids, however, this technique faces several shortcomings: including small sample sizes, an inability to directly measure or change sample pressures, and difficulties with loading gas samples onto the cells. In addition, diamond can reduce and interfere with any Raman signals passing through.

To perform Raman spectroscopy effectively, cells containing the fluids must be exceptionally robust – but must also incorporate transparent windows to let laser light in, and scattered photons out. Without extreme precautions, these windows would simply weaken the cells, allowing the pressurised, superheated liquids inside to break out.

In their earlier research, Dr Chou and his colleagues addressed the problem using a glass-like material named fused silica. Containing silicon dioxide (SiO_2) arranged in irregular patterns, this material is both incredibly pure and transparent, and able to withstand considerable temperatures and pressures. Through subsequent work, the researchers have now developed two types of cells that incorporate fused silica, named the 'high-pressure optical cell' (HPOC) and the 'fused silica capillary capsule' (FSCC), finally allowing them to carry out Raman spectroscopy on geological fluids.

The High-pressure Optical Cell

The first device developed by Dr Chou's team contained flexible capillary tubes with either square or round cross sections, each made from fused silica. The use of the square tube minimised any optical distortion, enabling better visual observations. Measuring 300 micrometres across, the tubes were sealed at one end, and connected to a high-pressure valve at the other.

To strengthen the tubes, the manufacturers coated them with a thin layer of heat-resistant polymer, a small section of which was removed by the researchers to provide a clear optical window. In previous studies, high-pressure capillary tube setups were inserted into a temperature-controlling device, with a glass cover for both temperature control and protection. In contrast, the team's new structures were enclosed in a larger capillary tube of stainless steel, with a small part ground away to expose the optical window. The resulting HPOC has numerous advantages over any predecessors, including the diamond anvil cell.

Firstly, the HPOC allowed the researchers to directly load their sample fluids, and continuously monitor their temperatures and pressures in extended experiments. It also enabled them to perform Raman spectroscopy with very little attenuation or interference in the light passing through the transparent window – allowing for precise measurements of their energy shifts. The small volumes of the cells made them suitable for studying rarer samples, which are in limited supply, as well as poisonous samples, such as hydrogen sulphide and carbon monoxide.

Furthermore, pressures inside the capillary tube could be elevated to as high as 160 MPa – a thousand times larger than the pressure exerted by the atmosphere at Earth's surface. Finally, the fused silica walls of the tube meant that the device as a whole was inexpensive, inert to sulphur, and highly permeable to hydrogen – paving the way for some advanced experimental capabilities, such as controlling the redox state of the sample by imposing hydrogen pressure externally through diffusion.

In their subsequent experiments, Dr Chou's team prepared a sample of room-temperature water in the capillary tube, and then introduced a further sample of highly pressurised methane gas. In the hours that followed, the HPOC allowed them to directly observe how methane molecules passed across the gas-water interface, and diffused towards the end of the tube over time. Using Raman spectroscopy, they could then determine the diffusion rate of methane in water by measuring the concentrations of dissolved methane at different sample positions at various time. Further experiments explored other aspects of the interaction between water and organic molecules – including the solubility of methane hydrate.

From these results, Dr Chou and his colleagues showed how the capabilities of the HPOC could be extended to study processes involving larger organic molecules, including ethane, propane

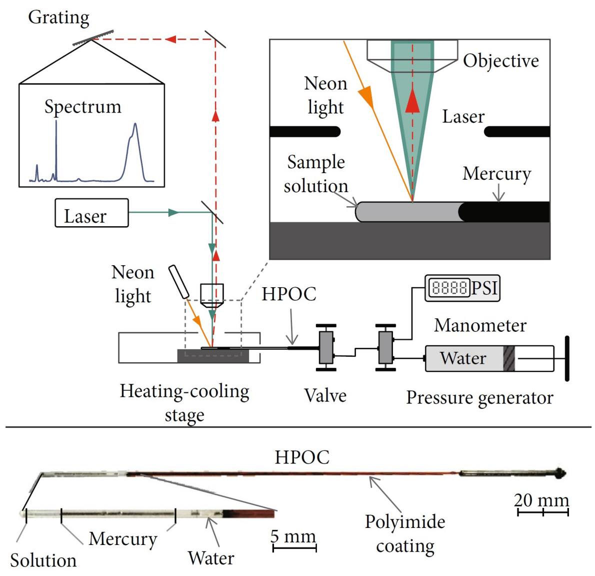


Diagram showing Dr Chou's experimental setup. The lower part shows a prepared HPOC containing sample solution, mercury, and water as a pressure medium.

and butane – as well as salt solutions instead of pure water. In addition, they showed how Raman spectra could be collected across wide ranges of fixed pressures and temperatures. The successes of these early experiments have now set the stage for more complex analysis – involving fluids and mixtures that more closely resemble real geological environments.

The Fused Silica Capillary Capsule

Alongside the HPOC, the second type of cell developed by Dr Chou's team is designed for studying 'fluid inclusions'. These microscopic bubbles of gas and liquid trapped inside crystals contain a variety of both organic and inorganic materials. They are now thought to play a key role in many geological processes – including the healing of fractured minerals, which requires fluid inclusions to be trapped in water. Previously, they could only be studied by synthesising fluid inclusions within fractures in minerals, such as quartz, garnet, fluorite, calcite, and halite. However, any subsequent experiments involving Raman spectroscopy were difficult to carry out at the pressures and temperatures required during synthesis.

In the researchers' FSCC device, samples can be studied by first loading them into a fused silica capillary tube, which is 6 centimetres long and has one end sealed. Then the tube is centrifuged, forcing the samples to its closed end. Afterwards, the open end of the tube is connected to a vacuum pressure line, through which any air in the sample is evacuated. Gaseous samples are then added by immersing the sealed end of the tube in ultra-cold liquid nitrogen, and switching the pressure tube from a vacuum to a sample gas – which is allowed to either condense or freeze over the next several minutes. Finally, the tube is evacuated, and its open end is sealed while frozen and under vacuum.

This setup had several unique advantages for studying fluid inclusions, including the formation of large and uniform gas bubbles, which are still able to tolerate high internal pressures. In addition, since hydrogen can readily pass through the disordered molecular structure of fused silica, researchers can readily initiate useful redox reactions from outside the capsule, without otherwise disturbing the sample.

The further capabilities enabled by the team's FSCC now open up a whole new range of intriguing geological experiments. Raman spectroscopy of fluid inclusions in the lab will be particularly useful for studying reactions between individual hydrocarbons, crude oils containing mixtures of hydrocarbons, and inorganic gases. One such process is 'cracking', where organic molecules containing long chains of carbon atoms break down into smaller chains when under thermal stress, altering the composition of organic material in Earth's crust.

In the case of inorganic samples, FSCCs could be used to study the formation of ions containing uranium, within solutions of lithium chloride. This process is known to take place at extreme pressures in the crust, forming the ores that we use to source uranium for nuclear power stations – as studied by a team led by Jean Dubessy at the University of Lorraine in France. In addition, research headed by Dr Chou showed how hydrothermal circulation within the newly-formed oceanic crust is influenced by the separation of sulphate-bearing seawater – with important consequences for the transport of heat, water, and chemicals throughout Earth's oceans and atmosphere.

Elsewhere, Dr Chou's team showed that their capsules could be applied in calibration for thermocouples, which are a key element of the heating and cooling stages required for microthermometric and Raman spectroscopic analyses of fluid inclusions.

Improving Understanding of Geological Fluids

Over the past three decades, Raman spectroscopy has already contributed significantly to our understanding of the Earth's composition, and the materials involved in its geological processes. Through the use of HPOCs and FSCCs, the capabilities of the technique could soon be enhanced further still, through better analysis of minerals, organic materials, silicate melts, and water-based solutions in the crust.

With transparent windows that are resilient to extreme temperatures and pressures, stable in highly acidic conditions, and inert to reactive substances such as sulphur, Dr Chou's team hopes that their approach will soon enable experiments involving many different chemical systems, which more closely simulate the conditions present deep within Earth's crust. With further improvements, it could even lead to cutting-edge simulations of extraterrestrial ocean waters, such as those on Europa or Enceladus.

Meet the researcher

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Dr I-Ming Chou completed his MS in Geology at National Taiwan University in 1968, and his PhD in Geochemistry at The John Hopkins University (JHU) in 1974. Following postdoctoral training at both JHU and NASA's Johnson Space Centre, he became a Geologist at the US Geological Survey in 1979, where he worked for 33 years until 2013. Then, Dr Chou was appointed as Director of the Lab for Experimental Study under Deep-sea Extreme Conditions at the Chinese Academy of Science's Institute of Deep-sea Science and Engineering in Sanya, China. His main research interests include the physicochemical properties of geological fluids, the stability of minerals at different temperatures and pressures, and the compositions of co-existing fluids. He is a Fellow of both the Mineralogical Society of America and Geological Society of America. In 2018, he organised and chaired the 'Symposium on the combined applications of optical cells with controlled pressures and temperatures and in situ Raman spectroscopic analysis technique', which took place in Sanya, China.

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UNDERSTANDING MEDITERRANEAN TECTONICS TO RECOGNISE EARTHQUAKE-PRONE ZONES

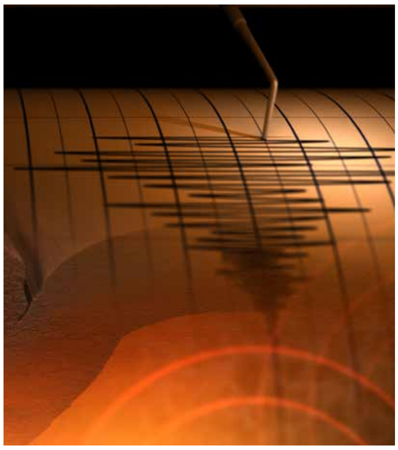
Precisely predicting when earthquakes will happen is still a distant goal. However, local authorities could reduce the damage caused by such disasters if scientists could identify zones that are most likely to be affected by earthquakes. Gaining this information requires an in-depth knowledge of the ongoing tectonic situation in a given area. In the Mediterranean region, this knowledge is surrounded by considerable uncertainty, as different researchers have different hypotheses to explain tectonic processes in this area. **Professor Enzo Mantovani** and his team at the University of Siena, Italy, propose a new geodynamic interpretation that offers a plausible explanation for all major tectonic features observed in this area. Using their hypothesis, along with the seismic history of the region, the team has recognised a connection between the short-term development of tectonic processes and the distribution of major earthquakes.

Tectonic Evolution of the Mediterranean

Over the last 30 million years, the tectonic and morphological situation in the Mediterranean region has undergone profound change. In this area, elongated regions of deformation where the African and Eurasian tectonic plates converge – called 'orogenic belts' – migrated by distances of several hundreds of kilometres and some also underwent strong distortions. In the wake of the migrating belts, crustal stretching occurred, forming thinned zones called 'Back Arc' basins, which are now part of the Mediterranean seafloor.

It is largely accepted that the driving force of tectonic processes in the Mediterranean region is the convergence between the African and Eurasian plates. However, since convergence mostly produces 'compressional' deformations, causing the Earth's crust to become thicker and mountains to form, some researchers propose that other driving forces caused the formation of basins in the Mediterranean.

The most frequently cited hypothesis assumes that basin formation is driven by the gravitational sinking of subducted crust, called a 'slab'. As the slab sinks, the so-called 'subduction zone' at the surface retreats, inducing crustal thinning in the overlying plate and forming a basin. This explanation is called the 'slab-pull' model. However, this hypothesis cannot account for some of the main tectonic features that are observed in the region, as extensively discussed by Professor Enzo



Mantovani and his colleagues at the University of Siena.

In particular, it is very difficult to reconcile the complex evolution of the Tyrrhenian basin, developed in three distinct phases in both space and time, with the main implications of the slab

pull model. For instance, numerical simulations of the tectonic mechanism predict the subsidence of the belt instead of the observed uplift in the Apennines and Calabria.

For over 40 years, Professor Mantovani and his colleagues have gathered vast amounts of data from multiple scientific disciplines, mainly geology, geophysics, tectonics, seismology and mathematical modelling, to reconstruct the past deformation pattern in the Mediterranean region. They accurately tested the compatibility of this reconstruction with geodynamic models. In doing so, they developed a hypothesis that can provide plausible and coherent explanations for a far greater number of the tectonic features observed in the Mediterranean, compared to previous hypotheses.

Explaining Crustal Thinning

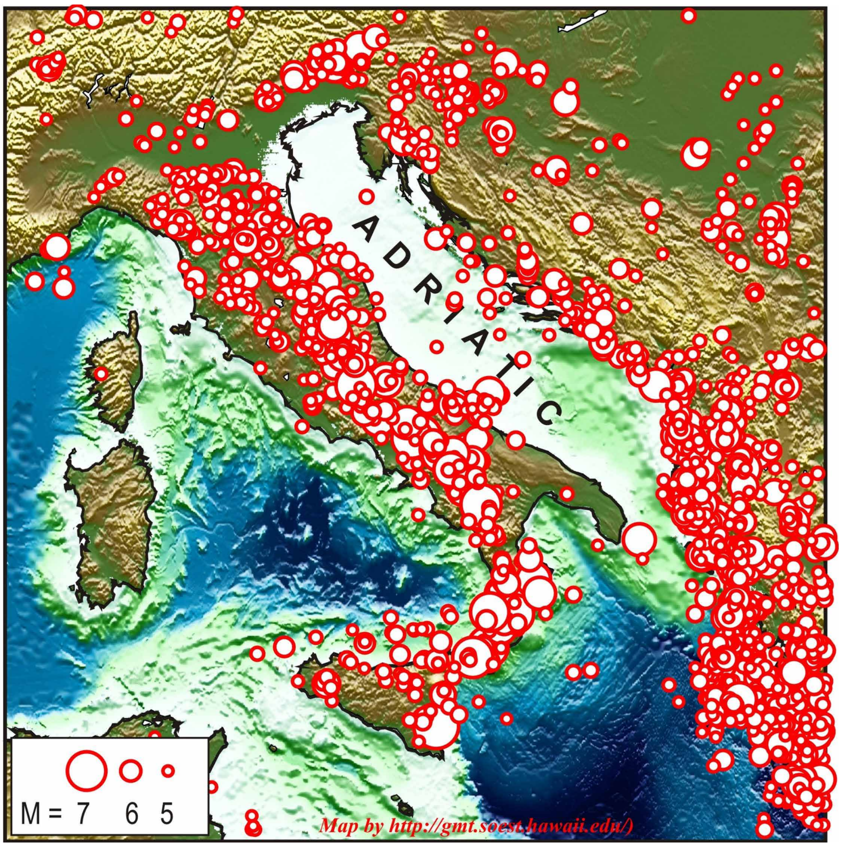
Professor Mantovani and his team suggest that the occurrence of extensional deformation in a compressional context can be explained as an effect of 'extrusion'. This process occurs when an orogenic belt becomes compressed between two converging plates, being flanked by a region of oceanic crust, called an 'oceanic domain'. The shortening of the belt, which happens due to the compression, is accommodated by the lateral escape of buoyant orogenic material (called an extruding wedge), which overthrusts the adjacent denser oceanic domain. The load of this buoyant material perturbs the equilibrium in the collision zone, triggering the downward flexure of the denser oceanic domain. Once initiated, slab sinking continues, driven by plate convergence.

Experiments demonstrate that this extrusion process can generate extensional deformations in the wake of a migrating orogenic belt, which can move much faster than the converging plates. 'The available evidence indicates that this process has generated the Balearic basin and the Central-Southern Tyrrhenian basin, involving the subduction of large old and cold Tethys domains,' explains Professor Mantovani.

In the Balearic basin, a stretching of the crust began in the Oligocene epoch (34–23 million years ago), when the Alpine belt lay along the eastern side of the Iberian domain. Crustal thinning developed in the wake of this belt, which, being stressed by the convergence of the African and Eurasian plates, was forced to migrate eastwards and undergo considerable south-eastward bowing.

In another Mediterranean region, the southern Tyrrhenian basin, the crust began to stretch in the early Pleistocene, about 2.6 million years ago, in the wake of the migrating Calabrian wedge.

'Explaining the generation of this system as an effect of a slab-pull driving force is particularly difficult, since the migrating Calabrian wedge underwent a fast uplift, south-eastward bowing and considerable fracturing,' says Professor Mantovani. 'In particular, it is hard to believe that an uplift of more than 2000 metres in one to two million years was caused by the pull of the sinking slab.'



The basic role of extrusion processes in the Mediterranean evolution is clearly suggested by an important piece of evidence: the fact that subduction of oceanic domains only occurred beneath extruding wedges. When this condition did not occur, for instance during the collisional phase of the Africa-Adriatic plate with Eurasia, the Ionian oceanic domain could very efficiently transmit compressional stresses without undergoing any subduction. This behaviour, also observed in other zones of the world, is explained by the fact that during long (geological) time intervals, the horizontal strength of the oceanic domain is not lower than that of a continental plate.

Finally, one can underline the fact that with the extrusion explanation, there is no need to assume the action of other driving forces in addition to the one provided by Plate Tectonic theory – that is, the convergence of the confining plates.

Tectonics and Earthquake Distribution

'Any attempt at predicting the next development of a physical phenomenon requires the knowledge of its genetic mechanism,' says Professor Mantovani. Thus, exploiting their knowledge of the real tectonic situation in the Mediterranean area, he and his research group have tried to obtain insights into the connection between the short-term development of tectonic processes and the distribution of major earthquakes in both space and time.

This attempt has the highest chance of success in the zones where the tectonic situation is relatively simple, such as the central Mediterranean region, where most seismic activity occurs in the orogenic belts that surround the Adriatic plate, which forms the seafloor of the Adriatic Sea between Italy and the Balkans (see the figure).

This activity is due to the fact that the Adriatic plate, stressed by the convergence of the confining plates, tries to move roughly northward. This motion is not continuous over time, being mainly allowed by the fault slidings that occur during major earthquakes along the boundaries of the Adriatic plate.

'Each strong shock triggers the motion of the just decoupled Adriatic sector, which then propagates through the plate with rates controlled by the plate's properties,' says Professor Mantovani. 'This process tends to involve more and more northern zones along the lateral borders of the Adriatic plate, up to reach the northern front of the plate in the Eastern Alps. This hypothesis is compatible with the distribution of major earthquakes that occurred along the Adriatic boundaries in the last four centuries.'

The above interpretation may provide a tool to locate zones where ongoing stresses, induced by the driving forces and past seismicity in tectonically connected zones, are closest to the strength of the crust. This approach has allowed the University of Siena team to recognise the Central-Northern Apennines as a priority zone, where some years later in 2016, strong earthquakes took place.

Informing Prevention Policies

'The most important problem concerning earthquake mitigation in Italy is the fact that a large proportion of the buildings were built without any anti-seismic criteria,' says Professor Mantovani. 'Thus, the restoration of such a vast building heritage would require a very long prevention project. This problem could be addressed by the recognition of the zones most prone to next strong earthquakes, where prevention could be prioritised in the short-term.'

His team's work aims to help local authorities to achieve this goal, by recognising patterns of seismic activity driven by ongoing tectonic processes. Such information could be essential in mitigating the effects of next major seismic disasters.

Meet the researcher

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Before his retirement in 2015, Professor Enzo Mantovani held the post of Professor in Solid Earth Geophysics at the University of Siena, Italy. His previous positions include research fellowships at the University of Siena and the UCLA University of Los Angeles, USA. He has devoted his decades-long career to understanding the geological evolution of the Mediterranean region, with over 100 articles published in peer-reviewed journals. Professor Mantovani's research has included setting up seismic stations across Italy, reconstructing the tectonic history of the Mediterranean, and studying the link between tectonics and earthquakes. His work on seismic risk assessment has been used to manage resources for disaster prevention in Tuscany.

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DSFTA
DIPARTIMENTO DI SCIENZE FISICHE, DELLA TERRA E DELL'AMBIENTE

PREDICTING DISASTERS USING GLOBAL WATER INTELLIGENCE

Accurate knowledge of the water cycle is essential for predicting disasters such as floods and droughts. However, it's not easy to obtain good information from traditional weather and water forecasts. The Group on Earth Observations Global Water Sustainability initiative (GEOGloWS) provides hydrologic forecasts through an accessible web service to assist local water users. Partnering with water scientists worldwide, Professor Jim Nelson of Brigham Young University worked with the European Centre for Medium-Range Weather Forecasts to develop a global streamflow service. This service provides local communities with actionable water intelligence, enabling them to focus on solutions to water-related problems.

A Global Water Forecasting Project

Water is the world's most precious natural resource. A limited supply of freshwater supports the global food chain, sustains human life and powers industry. At a time of worldwide population growth and increasing water stress due to climate change, effective management of this critical resource is key to ensuring food security, avoiding conflict and promoting sustainable development.

Managing the world's water supply requires accurate forecasts that warn of devastating events such as droughts and floods. Predicting these disasters with sufficient lead time requires accurate river flows and depth measurements. However, many people who are vulnerable to water insecurity, or hazards such as flooding, live in countries with limited water monitoring infrastructure or the modelling capability necessary to produce good data. In many developing countries, this lack of data means that floods and droughts are difficult to predict, making their impacts far more devastating.

In these areas, water modelling can be an essential tool for forecasting water-related disasters. When local river gauge data is unavailable, models can use global datasets, such as observations made by satellites, to forecast water flows worldwide.

However, while developed countries have access to sophisticated river flow models, developing countries can be at a disadvantage. Models are expensive to create, can require specialised equipment or skills, and are difficult to program. In addition, models that predict river flow for the entire globe often lack enough detail to produce usable information on a local scale.

Previous solutions to these problems have involved donor countries funding hardware, software and specific technical training to develop and run local forecasting systems with the power to provide information that is useful in decision-making. However, as maintenance costs continue after the project funding ends, projects like these are not always sustainable in the long term.

The Group on Earth Observations GEOGloWS initiative is dedicated to tackling these challenges. Along with GEOGloWS's international team of water experts, Professor Jim Nelson at Brigham Young University has led the creation and testing of a transformative global system for delivering actionable streamflow information. Water management agencies in developing countries can access the global forecasts for free. The information is useful as is, but can also be used

to implement national systems or strengthen locally generated modelling data.

Because the system is maintained and operated as a cloud service, vulnerability to computer and software updates, or limited local capacity, can be mitigated. This also overcomes the high cost of maintenance or improvement, because each local user immediately benefits from upgrades and improvements made to the global data service.

The GEOGloWS ECMWF Streamflow Service aims to provide the necessary information to decision-makers who respond to droughts and floods. This has the potential to save lives and infrastructure and increase food security. It provides forecasts in areas that lack water observation data, providing local organisations with crucial information to help reduce water-related vulnerabilities.

Developing a Global Prediction System

Numerical models of the global land surface can be used to predict important water processes such as evaporation, soil moisture levels, the amount of snow on the ground – and crucially, water flow in rivers. However, developing a global modelling system with enough detail to produce sound local forecasts is no easy task.

Professor Nelson and his colleagues addressed this problem by partnering with the European Centre for Medium-Range Weather Forecasts (ECMWF), one of the world's leaders in meteorological forecasting, to map the water flow predicted by their global model to watershed catchments, and then routing these flows through a fine-scaled stream network. In this way, the GEOGloWS streamflow services use trusted available global data to produce detailed local forecasts.

The new model is beneficial in areas where observations are scarce, such as transboundary waters – aquifers, rivers, and lake basins shared by two or more countries. It can be challenging to produce forecasts locally in these regions due to the need for data sharing and coordination between countries.

For this reason, the researchers tested their new forecasting system on two huge transboundary river basins: the Ganges, Brahmaputra, and Meghna rivers in South Asia and the Mekong River in Southeast Asia. Both river basins are densely populated and suffer heavy rainfall from yearly monsoons, making them prone to flooding.

The team produced river flows for the two basins using the new system. They compared the simulations to local measurements of river flow to test the accuracy of their predictions. The GEOGloWS global model downscaled to local streams could predict water flows with enough detail to produce actionable hydrologic information.

To ensure the new system continues to improve, the researchers also developed an application called the Historical Validation Tool. The tool is used to monitor the performance of GEOGloWS by comparing the river flow predictions to observations. If it detects a bias in the model at that location – meaning the model always overestimates or underestimates flow in predictable amounts – the model can predict the errors in future forecasts and correct them.

A Truly Accessible Service

The GEOGloWS ECMWF Streamflow Service produces useable river flow predictions on a local scale, using freely accessible global datasets. However, accurate forecasts can't be helpful unless the results are readily available and clearly presented.

Large-scale models produce a vast amount of data, so sharing and presenting the forecasts is a challenge in itself. In addition, the groups interested in water data – including scientists, emergency responders, decision-makers, and the general public – have a diverse set of needs, making the communication of results a significant challenge.

The GEOGloWS ECMWF Streamflow Service uses cloud computing to run the forecasts, meaning that local forecasting agencies don't need expensive computing hardware. 'GEOGloWS centralises the cyberinfrastructure, human capacity, and other components of hydrologic modelling using the best forecasts and expertise available,' explains Professor Nelson.

Previously, every local agency wishing to produce water forecasts would have had to download huge volumes of input data, such as terrain information, land-use data, and weather data. They would also have to provide computers,

The GEOGloWS ECMWF Streamflow Hydroviewer App.

software, and experts to produce the forecasts. 'Having to replicate this resource everywhere is expensive in terms of the cyberinfrastructure and human capacity required,' says Professor Nelson.

In contrast, users of GEOGloWS can retrieve the forecasts through web services, meaning they are available to anyone with a computer and an internet connection. Data on a river-by-river basis can be accessed and used in simple web applications. Users can see maps and graphs showing predicted river flow volumes or use them to create derivative information as needed. They can also obtain historical simulation data on each river, which acts as a surrogate to observed data that provides information about what are low, normal, and high flows. 'Our approach represents a paradigm shift from the provision of complex weather forecasts to be transformed into local hydrological information, towards the provision of hydrological forecasts,' says Professor Nelson.

The Historical Validation Tool, facilitates adding local river flow measurements to the forecast system to produce greater confidence and potential improvements to the forecasts. Forecasting organisations can also create customised tools that use the forecasted data to help solve specific problems. One such customisation made by the International Centre for Integrated Mountain Development (ICIMOD) is the Bangladesh Transboundary Streamflow Prediction Tool. This tool provides crucial forecasts for Bangladesh's Flood Forecasting and Warning Centre, because approximately 92% of the watershed lies outside of its boundaries. This information is critical in places where little if any information is shared across boundaries.

Even when forecasts are provided, expert knowledge will still be necessary to interpret model results. Local organisations need to understand the model assumptions, limitations, and uncertainty, and decisions surrounding forecasted events remain the responsibility of local communities. But with water forecasts readily available, disaster agencies can focus more of their time and resources on some of the most pressing water-related issues society faces. 'Local organisations can focus on the decisions made from hydrologic information rather on the development of the actionable hydrologic information,' adds Professor Nelson.

A Global Effort

River flooding is one of the most common and most expensive natural disasters around the globe. Early warning systems are a crucial strategy in reducing environmental hazards such as floods and droughts, but accurate forecasts aren't always available locally. The GEOGloWS project provides water forecasts to regions where measurements are scarce, bringing global water management capabilities to local decision-makers. Distribution of water information, such as flow forecasts, through easy-to-use web services, removes the burden and expense of carrying out modelling locally, improving the transfer of technology to the places that need it most.

The forecasts will also benefit the global economy by informing the insurance industry about water-related risks. 'GEOGloWS benefits the global economy by also providing water intelligence to sectors such as the insurance and reinsurance industry, and many others that need to make high-risk investment decisions,' explains Professor Nelson.

GEOGloWS is the work of a truly international team of experts and demonstrates the power of collective action to solve global challenges. The success of the GEOGloWS project hinges on fruitful collaborations between water scientists and local stakeholders. 'One of the most important achievements of the project is the mobilisation of a wide international group of experts to assemble this service,' says Professor Nelson. Collaborations with forecasting agencies have been crucial in ensuring the service can be implemented locally. 'We have definitely been encouraged lately by powerful stories of the possibilities GEOGloWS is achieving to try and do more to extend its reach,' he continues.

Fuelled by the expertise and reputation of the ECMWF forecasts, the GEOGloWS partnership is continually developing the streamflow services. In the future, the team will continue to extend the global reach, as well as monitoring and improving its performance. Professor Nelson concludes: 'We hope to be able to continue the effort to improve the model accuracy as well as the tools to access the streamflow services while growing the community that supports this important effort.'

Meet the researcher

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Professor Jim Nelson earned his PhD in water resources engineering at Brigham Young University in Utah, where he progressed from Research Assistant, to Research Associate, to Assistant Professor. In 2008, he became a full Professor in the Department of Civil and Environmental Engineering. Over his decades-long career, Professor Nelson has been a pioneer in developing digital modelling and informatics tools to help engineers and forecasters better simulate hydrological processes. His research has resulted in the development of water modelling software used by hundreds of organisations globally. At Brigham Young University, he supervises and teaches numerous undergraduate and graduate students alongside his research activities. Professor Nelson has held editorial positions for scientific journals, as well as prestigious committee positions. He has also been awarded multiple fellowships and awards for his contributions to both teaching, scholarship and technology transfer.

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GEOGloWS APP

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EXPLORING THE EVOLUTION OF SEAFLOOR SAND DUNES

Marine sand is both a vital natural habitat and an essential resource. However, while desert dunes are comparatively easy to observe, their oceanic counterparts are still poorly understood. **Dr Xiaochuan Ma** and his colleagues at the Chinese Academy of Sciences in Qingdao are mapping the shifting sands of the seafloor and measuring their movement. By investigating how seafloor dunes respond to waves, tides, and typhoons, they can help decision-makers protect and manage this critical resource.

Shifting Seafloor Sands

Many of us might take sand for granted, but it plays a significant role in modern life. Sand is used to manufacture concrete and glass for the buildings we live in and the roads we travel on. The tech industry extracts silicon from sand to make computer chips. About 32 to 50 billion tonnes of sand, mostly from the seafloor, are used each year, making sand the most extracted material globally, even exceeding fossil fuels. Marine sand is also a vital natural habitat, with countless species depending upon the sandy seabed.

Seafloor sand is sculpted by ocean currents into dunes and ridges, similar to wind-blown desert dunes on land. These structures can pose a risk to ship navigation, especially in shallow waters. Understanding the dynamics of sand could help policymakers mitigate risks and manage this critical resource.

However, the origin and evolution of seafloor sand formations are still uncertain. In particular, more work is needed to examine the links between sand dunes and tidal flows, ocean surface waves, and extreme events such as typhoons. Understanding the activity of sand under these conditions will help scientists to predict the impacts of climate change on the seabed.

Dr Xiaochuan Ma and his colleagues at the Chinese Academy of Sciences are deploying numerous techniques to address these questions, from sampling and studying seafloor dunes to modelling sand transport. By integrating multiple methods, Dr Ma and his team can uncover the mysterious processes governing the rhythmic forms of these beautiful features.

Measuring Typhoon Impacts

Typhoons are among the most extreme weather events to affect China's coastline and continental shelf. The high wind speeds associated with typhoons can generate giant waves, posing a considerable risk to coastal communities and infrastructure. The effects are also felt offshore: ocean sediments are disturbed by the movement of the water, dispersing seafloor ecosystems.

However, the impacts on the seabed are poorly understood, partly due to the difficulty in gathering data during unpredictable storms. Where measurements are incomplete, mathematical modelling can fill in the gaps. Dr Ma and his colleagues modelled seafloor sediment transport processes during Typhoon Ketsana, the most devastating storm of 2009.

The researchers took sediment samples and produced echosounder maps of the seafloor in the Beibu Gulf, part of the South China Sea, before the typhoon. For three days while the storm passed, they also measured water speed and elevation using an instrument positioned 50 centimetres above the seabed.

Back in the lab, Dr Ma and his colleagues sieved the sediments to measure the size of the sand grains. They processed their grain size and water data using a mathematical model to predict sand transport during the typhoon. Using this model, they could identify when the conditions were suitable for bedload transport, where currents are strong enough to move sediments along the seafloor, or suspension, where sands are lifted into the water column.

The researchers predicted that ocean currents and waves during Typhoon Ketsana could have caused bedload transport, but that speeds were rarely high enough for suspension. The simulated bedload movement during

KEXUE research vessel operated by IOCAS.

the typhoon was about seven times higher than under pre-storm conditions. However, the results of this study are theoretical, as sediment transport was not directly observed during the typhoon.

To obtain more direct measurements, the team have pioneered long-term observations of sedimentary processes during storms. 'In-situ field observation directly provides convincing data and evidence, and is essential to understand the modern behaviours of sediment and small bedforms,' explains Dr Ma.

His team built a multi-sensor measurement platform that can be anchored to the seafloor with heavy lead bricks. The researchers used the platform, moored 440 kilometres south of the Yangtze River mouth in the East China Sea, to conduct a 49-day investigation of sediment flows during Typhoon Chan-hom in 2015. The instruments onboard the platform measured multiple variables, including the water temperature, suspended sediment concentration and ocean currents.

They found that during the storm, water temperature decreased by about 0.8°C and currents reached 1.5 metres per second. The suspended sediment concentrations during Typhoon Chan-hom were 50 times higher than before the storm; most of the sediments came from the re-suspension of seafloor sand. Typhoon Chan-hom, lasting only a few days, was responsible for 89% of the south-westward sediment transport during the whole 49-day study period. Using direct observations, Dr Ma and his colleagues confirmed that typhoons play a significant role in moving seafloor sediments.

Understanding Ocean Dunes

Crescent-shaped dunes, called barchans, are typical of inland deserts, where the wind sculpts their characteristic shape. But barchan dunes also form underwater on sandy continental shelves due to ocean tides, waves and currents. While the formation of desert barchans has been well-researched, few studies have been conducted on their seafloor counterparts.

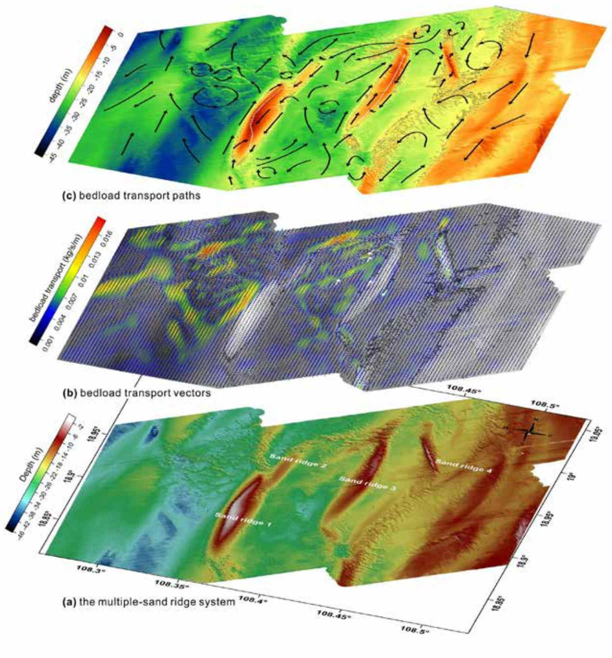
Dr Ma and his colleagues measured the shape and movement of barchans in the Beibu Gulf. In 2007 and 2009, the scientists used an echosounder to map part of the Gulf. They also measured ocean currents and collected sediment samples. When compared, the maps revealed that the individual barchans shifted along the seabed by up to 43 metres in two years.

The researchers studied the shape of the dunes, finding that they were wider and more asymmetric than desert barchans. They also discovered that smaller barchan dunes formed by breaking off from larger ones during typhoons. 'Their morphology is mainly controlled by finite water depth, daily reverse currents, sand supply changes and dune interaction,' explains Dr Ma.

By combining seafloor maps and ocean current measurements with mathematical modelling, the scientists were able to estimate sediment transport directions. The team tested this method on a region of the Beibu Gulf characterised by large sand ridges. They found that small dunes mainly migrated northwards on the west sides of the large ridges and southwards on the east sides, suggesting opposite directions of bedload transport. Transport generally occurred along the ridges rather than across them.

While mathematical modelling and seafloor surveying reveal present sediment transport, scientists can

Sediment sampling on the RV under the moonlight.



Bedload transport pathways in the multi-sand-ridge system in the northwest South China Sea.

analyse the history of dune formation by looking inside the dunes. Dr Ma and his colleagues studied the sediments inside two typical dunes to determine past changes in the tidal environment. The researchers used high-resolution seismic surveys, in which artificially generated shockwaves are reflected or refracted from the different sand layers to build up a picture of the subsurface.

The older, underlying sand layers sloped to the south. In comparison, the newer top layers dipped to the north, indicating a reversal of the sand transport direction. The sediment layers were shortened in the troughs adjacent to the dunes, indicating erosion.

By combining multiple techniques, Dr Ma and his colleagues are building an accurate picture of dune evolution in the Beibu Gulf. 'It is interesting because there are rare records of sediment transport changes in a shelf during small sea level fluctuations,' says Dr Ma.

Internal Solitary Waves

Internal solitary waves, or ISWs, are waves in the interior of the ocean. They form and propagate because the sea is composed of layers with different densities. ISWs often originate in the deep ocean and break when they reach the continental shelf, where the water depth suddenly shallows. Their behaviour could shape the continental slope between the shelf and the deep sea. 'The role that obliquely incident internal waves play in sediment and seabed shaping was elusive before,' says Dr Ma.

To find out how ISWs shape the seabed, his team travelled to the northern South China Sea, where the continental slope is subjected to some of the world's largest ISWs. The researchers deployed temperature and pressure sensors and an acoustic Doppler current profiler, which measures water speeds using sound waves scattered back from particles in the sea. They also mapped the depths of the seafloor, revealing large-scale ripples called sand waves.

The researchers detected strong ISWs and internal ocean tides, which occur as surface tides move ocean water up or down the sloping seafloor. They identified two types of sand waves. Type 1, with crests perpendicular to the ISWs, are most likely formed by wave propagation. Type 2 sand waves only form on steeper slopes, which are most affected by tides. 'This study sheds light on the roles of internal tides and ISWs in shaping the seabed, especially oblique ISWs near the shelf break,' says Dr Ma. A second, later bathymetric survey of the sand waves revealed they are mobile, moving along the seafloor by almost a metre per year.

By combining seafloor surveying, sediment sampling and mathematical modelling, Dr Ma and his colleagues continue to shed light on the hidden shifting sands of the seafloor. Their work could have profound implications for the management of this precious resource. 'Tools including gauge stations, in-situ measurements and acoustic technologies are aiding sand resource management,' says Dr Ma.

In the future, further efforts to understand the physical mechanisms of sand transport depend on more advanced numerical models, along with more measurements. 'More field observations are required, and a dataset about the world's subaqueous sand waves and dunes is urgently needed,' says Dr Ma.

Meet the researcher

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Dr Xiaochuan Ma gained his PhD in Marine Geology from the Chinese Academy of Sciences (CAS), Qingdao. Since 2013, he has worked as a professor in the CAS Key Lab of Marine Geology and Environment. In 2018–2019, he visited the Woods Hole Oceanographic Institution, USA, as a guest investigator. Dr Ma's research focuses on the dynamics of sediment transport from the coastline to the deep ocean, the origins of features such as sand dunes and seamounts, and the effects of storms on the seabed. His work uses a wide array of techniques, from mathematical modelling to conducting research cruises. Dr Ma has published numerous articles in peer-reviewed journals and presented his research at international conferences. At CAS, he supervises postgraduate students and doctoral candidates in addition to his research activities.

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FROM DESTRUCTION TO CREATION: UNDERSTANDING METEORITE IMPACT CRATERS

Ever since the planets first formed, they have been bombarded with space rocks. Asteroid and cometary collisions are so forceful that planetary surfaces fracture and melt beneath them, leaving behind huge craters. These impact events have played an important role in our planet's history, by shaping the geological landscape, producing valuable minerals, and affecting the evolution of life. **Dr Gordon 'Oz' Osinski** from the University of Western Ontario, Canada, aims to understand this fundamental process on Earth, Mars and the Moon – with important implications for space exploration, mining, and for understanding the origins of life.

The Incredible Power of Impacts

So common are asteroids and comets that turning your eyes skywards on any clear and dark night reveals multiples of these 'shooting stars' each hour. Thanks to the protection offered by our planet's atmosphere, most of these space rocks never reach the ground. Instead, they break apart and burn up in an intense display of light and heat, rarely descending further than an altitude of 80 kilometres.

When these rocks are large enough to survive the journey through the atmosphere and reach the planet's surface, they are called 'meteorites'. Fragments of asteroids that are larger than a few tens of metres across can reach the surface at an enormous 20 kilometres per second, while comets of the same size can strike at up to 70 kilometres per second – an incredible 252,000 kilometres per hour. In comparison, a bullet fired from a modern rifle travels at up to 4,300 kilometres per hour.

Even the slowest impacts release around 15 times as much energy as an equivalent mass of TNT upon impact. The results of these impact events are clearly visible on our nearest celestial neighbour, the Moon. Similar craters are observed on all other rocky planets and moons across the Solar System, hinting at the frequency with which impact events have occurred. Earth has not escaped similar bombardments over its 4.5 billion years of existence, but much of the evidence has been lost or concealed by natural processes – such as plate tectonics, erosion, and volcanism.

The impact craters left behind by asteroids and comets that reach Earth's surface range in diameter from tens of metres, to an enormous 250 kilometres – such as the Sudbury impact crater in Ontario. Impacts around this size have the power to cause mass extinctions, such as the Chicxulub impact in Mexico, which is believed to have caused the extinction on non-avian dinosaurs 66 million years ago.

Impact melt rocks at the Mistastin Lake impact structure, Labrador, Canada.

It may be hard to imagine that events so powerful could result in anything other than destruction. But even mass extinctions can provide opportunities for life to evolve in new directions. Without the Chicxulub impact, mammals would not have become the dominant animals on Earth – and humans wouldn't exist today. And while large impacts may extinguish

Dr Osinski conducting fieldwork above the clouds on the south coast of Devon Island, Nunavut, Canada.

life, they could also form the cradle of life on barren planets – by delivering the building blocks and creating the right environmental conditions for early forms of life to emerge. Thus, impact craters could hold clues to understanding the origins of life, and may help the ongoing search for extraterrestrial life on other planetary bodies such as Mars.

Impact craters also have more immediate benefits to society. Many of the valuable resources extracted through mining are created during an impact event and deposited in and around impact craters. For instance, the Sudbury impact crater is rich in important metals, including nickel, copper, palladium, gold and platinum, and the Sudbury area hosts a major mining community as a result. Investigating impact cratering on Earth and other planets thus has applications in resource mining.

Dr Gordon 'Oz' Osinski, Professor in the Department of Earth Sciences and Director of the Institute for Earth and Space Exploration at the University of Western Ontario, has spent his career researching the beneficial effects of impact cratering. Leading an international team of researchers, Dr Osinski has conducted extensive fieldwork and laboratory studies of meteorite impacts – including collecting data on all 200 of Earth's known impact craters through his Impact Earth initiative.

His work encompasses three major processes and products of impact events: to understand how rocks are metamorphosed and melted during impact events; how materials from impacts are ejected; and how the 'hydrothermal' – or hot water – environments within impact craters develop and evolve.

Creation of a Crater

The formation of a crater during an impact event can be divided into three main stages. First, the asteroid or comet contacts and compresses the ground around the impact point. Second, material is displaced downward and outward by shockwaves and tension-release waves from the point of impact. Some of the material is ejected from the growing so-called transient crater, forming the characteristic bowl shape. Lastly, the crater undergoes modification, with melted and broken up rock flowing and settling both inside the crater and outside the crater rim. Dr Osinski has been studying both the formation of craters and the emplacement of impact ejecta.

'Simple' craters retain their bowl shape during the final modification stage. Depending on the size of the asteroid or comet, 'complex' craters can form, comprising a central peak and a crater rim that are heavily deformed and fractured. Very large complex impact craters sometimes exhibit one or more centrally uplifted rings, giving the crater the appearance of having two or more concentric peaks.

'There remains no consensus as to how the peak-ring morphology forms, with some proposing it forms from the outwards collapse of a central peak, and others that this morphology is the result of the increased melt volumes as crater diameter increases, which results in melting of the peak,' explains Dr Osinski. 'This has resulted in uncertainty regarding the original morphology and structure of the largest impact structures on Earth: Chicxulub, Sudbury, and Vredefort.'

Dr Osinski and his colleagues have been contributing to our understanding by comparing impact structures on the Earth, Moon, and Mars. This allows them to differentiate local and site-specific effects from more general features of impact craters. His team has also been developing techniques and technologies for robotic and human operations on the surface of the Moon and Mars, which are also applicable to terrestrial mining operations.

Initially, Dr Osinski focused on craters between 2 to 40 kilometres in diameter. His team subsequently expanded this research to include large impact craters, with the aim of better understanding the original structure of the Sudbury impact crater and thus supporting targeted mining efforts. At around 250 kilometres across, the Sudbury crater is one of the largest found on Earth.

Shocked and Melted Rocks

The incredible temperatures and pressures generated during a meteorite impact melts rocks near the point of impact. Other existing rocks undergo

A shatter cone – formed through shock metamorphism.

Sudbury Breccia – a rock produced via melting during the Sudbury impact event.

'shock metamorphism' to become new kinds of rock without a great degree of melting. Impact melt rocks in some regions, such as the Sudbury crater in Ontario, contain economically important ore deposits that support a thriving mining industry.

Dr Osinski and his colleagues have helped to shape our understanding of these processes. Their fieldwork and powerful microscopic analysis of the rocks around several craters transformed our understanding of how 'carbonate' rocks and minerals – such as limestone or dolomite – respond to impact events. It was originally believed that these rocks do not melt during impact events, but rather disintegrate into carbon dioxide and other greenhouse gases – with implications for the planet's climate post-impact.

However, the team demonstrated that carbonates do undergo melting during impact. 'This work has important implications for assessing the environmental effects of impacts, such as the Chicxulub impact 66 million years ago that is blamed for the extinction of the dinosaurs and 60% of all species on Earth,' says Dr Osinski.

'Igneous' rocks, such as granite or obsidian – formed from molten rock that has cooled and solidified – are created through natural processes within the Earth's crust and through volcanism on the surface. Igneous rocks also form during meteorite impacts. Though formed through different processes, these rocks share similar characteristics, such as flow textures and cooling cracks, making their origin tricky to determine.

Dr Osinski synthesised information and methods for determining igneous rock origins using samples. However, he notes that samples are not always available, for example during exploration of other planets and moons. Remote sensing technologies may one day offer solutions to problem.

The Cradle of Life

In some of his recent research, Dr Osinski led a team of researchers in investigating the possibility that impact craters may have been the origin of life on Earth. It has long been believed that meteorite impacts would have presented a barrier to the emergence of early life, but Dr Osinski has turned that idea on its head. He posits that after the initial destruction, meteorite impacts can create a hospitable oasis for early life to form.

It is believed that early life formed in hot, wet environments. Impact events can generate these conditions by creating hydrothermal vents through cracks and fissures in the Earth's crust, both on land and under the sea. Add this to the minerals, clays, and other chemical ingredients that are generated or delivered during impact – and the recipe for life may be created.

Impact events were far more frequent during the first 500 million years of the Solar System than they are now, lending weight to this hypothesis. Unfortunately, after billions of years of erosion, volcanism, and plate tectonics, we'll never really know where or when life originated on Earth. But perhaps the finding could direct our search on other planets.

Impact craters on Mars – not subjected to the same processes that destroy the evidence on Earth – may help planetary scientists eventually solve the puzzle. If they know what to look for. 'It's a good place to start to explore the role of meteorite impacts in the origin of life, as long as they look out for the habitats, nutrients, and building blocks for life that we outlined in our study,' says Dr Osinski.

For now, the hunt for the origin of life continues. Dr Osinski's research on the beneficial effects of impact craters on Earth and beyond could one day contribute to the discovery of a generation. In a recent paper, he concludes, 'Would it not be poetic that impacts, long seen as harbingers of death, turn out to have in fact been the cradle of life?'

Meet the researcher

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Having studied Geology during his undergraduate degree at the University of St. Andrews, Scotland, Dr Gordon 'Oz' Osinski relocated to Canada, earning his PhD from the University of New Brunswick. He currently holds the position of Professor in the Department of Earth Sciences and is Director of the Institute for Earth and Space Exploration at the University of Western Ontario. He is also Director of the Canadian Lunar Research Network and the founder and Chair of the Planetary Sciences Division of the Geological Association of Canada. Dr Osinski is a member of several advisory committees, including the Space Advisory Board of the Government of Canada. He uses fieldwork, advanced laboratory analysis, modelling, remote sensing, and other techniques to investigate meteorite impact craters on the Earth, Moon and Mars. Dr Osinski's work has achieved international acclaim. He has published over 200 papers in peer-reviewed journals and has given over 100 conference presentations.

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Western

MEASURING METEORITES TO REVEAL THE ORIGINS OF THE EARTH

The planet we call home has a 4.5-billion-year history, but humans have only been around for a tiny fraction of this time. To discover what happened before life arose on Earth, and even before Earth's formation, scientists can study objects sent from space – from icy comets and rocky asteroids to tiny particles of interstellar dust. Early in Earth's history, primordial gases became trapped deep in the planet's interior. By determining how they were trapped and where they might be stored, **Dr Manfred Vogt** and his research group at the Ruprecht-Karls-University of Heidelberg are shedding new light on Earth's origins.

Early Stages of Earth's Formation

In the beginning, there was the solar nebula: a swirling disk of gas and dust left over from the formation of the Sun. About 4.5 billion years ago, this mass of space debris began to clump together as particles collided under gravity. For the first few tens of millions of years, the early Earth's gravitational pull continued to collect material from the inner solar system. An insulating atmosphere of steam formed above an ocean of molten magma.

Early in the Earth's history, gases from the Sun became trapped in the Earth's mantle. Scientists can obtain signals from the ancient Sun by analysing the properties of neon atoms from volcanoes, where material from deep within Earth's mantle upwells to the surface. Neon atoms from the ancient Sun contain – on average – a slightly different number of neutrons in their atomic nuclei, compared to those from different sources, giving them a characteristic solar isotope signature.

About fifty million years after Earth's formation started, it collided with another planet-sized object. This catastrophic impact created a ring of material around the Earth, which eventually became the Moon. The young Earth lost a significant part of its atmosphere in the collision.

After the impact, most of Earth's remaining mass was added by bombardments of meteorites from the asteroid belt and beyond. These new meteorites came from further out in the Solar System and were distinct in being richer in volatile substances compared to objects closer to the Sun. The Earth's atmosphere today contains neon without a 'solar' signature, but rather a 'planetary' signature from these later meteorite impacts.

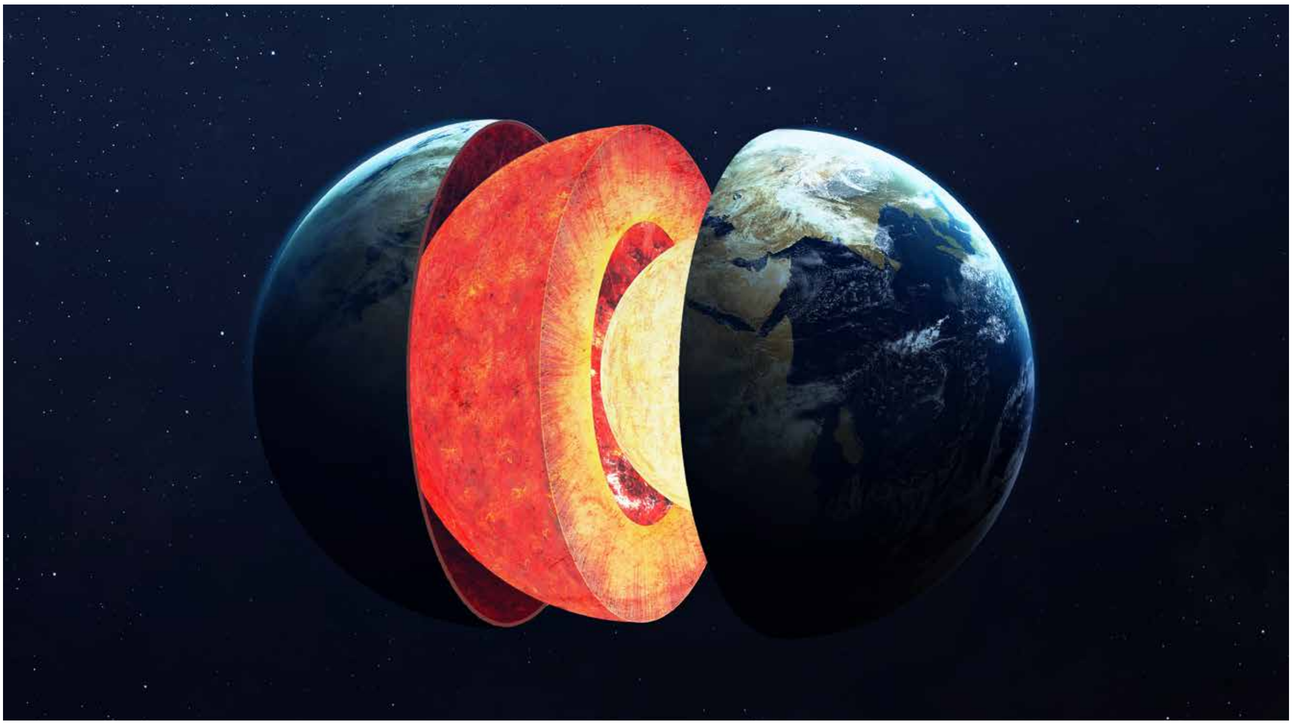
Questions remain about how primordial solar gases were incorporated into the Earth's mantle and where exactly they are stored today. Dr Manfred Vogt and his colleagues at the Heidelberg University are addressing these questions by studying the gases in cosmic dust and metallic meteorites.

By combining these measurements with sophisticated mathematical models, they can shed new light on the formation of our planet.

Origins of Solar Gases on Earth

The primordial neon in the mantle must have been incorporated in the early stages of the Earth's formation, but its exact origin is unclear. Two competing models have been proposed to explain the abundance of neon atoms with a solar signature in the mantle. The first is that the young Earth could have pulled in gases from the solar nebula, which then dissolved in its magma ocean.

‘I have measured and established the first solid proof that the core of a planetary body, resembled by the iron meteorite Washington County, can host solar signature noble gases – helium and neon – in its interior.’



Alternatively, the debris and dust that formed the Earth could have brought components from the solar wind. Implanted neon from the solar wind could have been carried on the surfaces of the particles.

Until recently, scientists doubted that the second process could have brought enough solar neon to explain the amount in the mantle today. However, Dr Vogt and his colleagues have shown that tiny interstellar dust particles alone could have carried enough solar neon to explain the mantle's composition today.

The team used neon isotope data from cosmic dust – tiny particles from space that have fallen to the Earth's surface. Particles in space carry solar neon on their surfaces, so the smaller particles, with their high surface area to volume ratio, can carry the most neon. Smaller particles falling to the Earth today are also crucial for studying this solar neon component, as larger ones (over a few tenths of a millimetre) heat up too much on entry and deliver their gases straight to the atmosphere.

The scientists found that if the solid particles that formed the early Earth comprised even a small fraction of solar-wind-irradiated dust, this could have been responsible for delivering all of the solar neon found in Earth's mantle today. ‘The solar wind implantation process potentially causes unexpectedly high concentrations of solar-composition-neon in irradiated planetary dust particles,’ explains Dr Vogt. ‘Implanted solar wind in cosmic dust, alone, might have contributed sufficient solar neon to explain Earth's solar mantle signatures.’

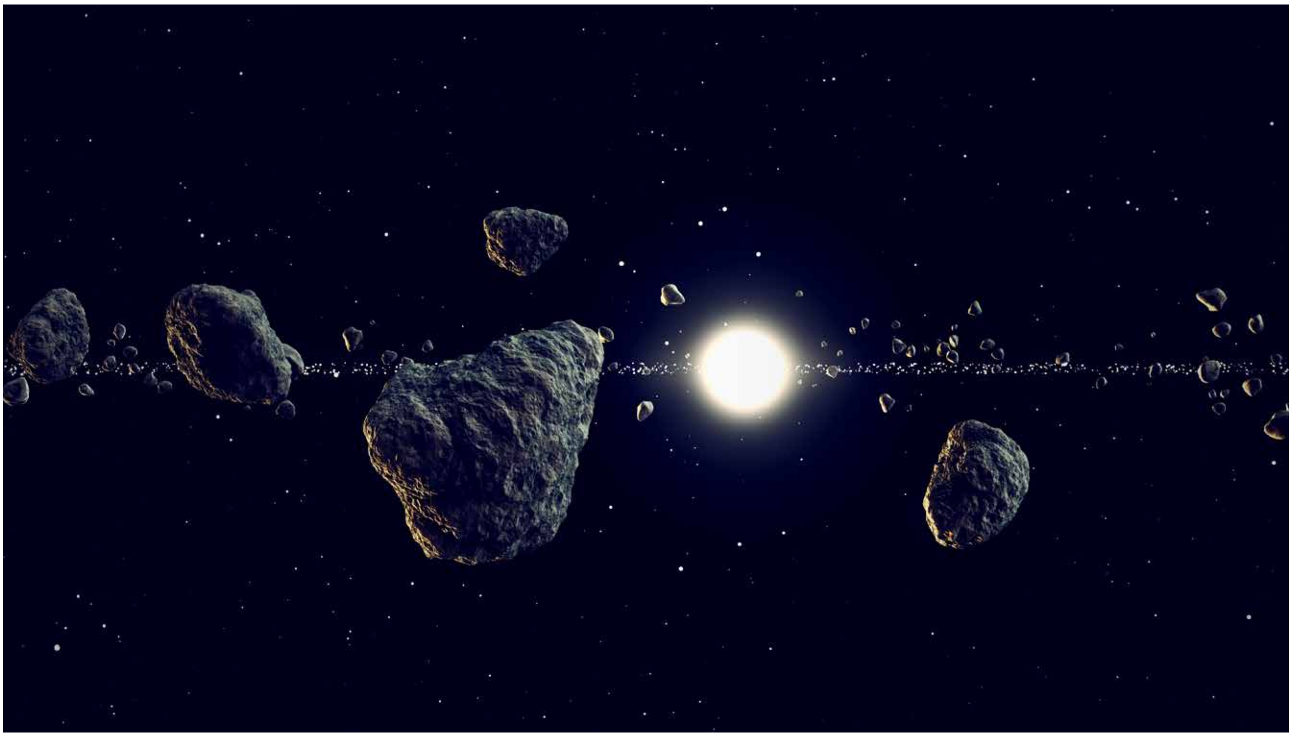
These minuscule particles would have been enriched in other volatile compounds, in addition to solar neon. ‘Small dust particles with high abundances of volatile species, which might also include the ingredients of life, probably played a significant role during the terrestrial formation,’ says Dr Vogt.

Their calculations took into account the Earth's early accretionary stage, the Moon-forming impact, and the subsequent meteorite bombardment. ‘Post-lunar delivery of neon by late accretion explains the different neon composition of Earth's atmosphere compared to Earth's mantle,’ says Dr Vogt. Using a range of possible compositions for the late-arriving meteorites after the moon impact, the team estimates that possibly around 2% or less of Earth's mass could have been added by this late bombardment.

Extracting Gas from an Iron Meteorite

As mentioned, we know from observations of upwelling mantle material from volcanoes that solar signatures are present in the Earth's mantle. Primordial neon and other gases could be stored throughout the deep mantle, or in isolated layers at certain depths. Speculatively, these primordial elements could even be stored in the Earth's core – the hot, dense centre of our planet, made almost entirely of iron and nickel.

However, we can't directly measure the composition of the core. ‘Up to now, only theoretical models and hypotheses suggest a source of solar signatures



in Earth's core,' says Dr Vogt. One way to find out whether these primordial gases could be present in the core is to study meteorites. Metallic iron meteorites are a good analogue for Earth's core because they were formed in a similar way. These meteorites are fragments of the cores of small celestial bodies, known as planetesimals, and they were formed by the separation of lighter rock-forming minerals and heavier metals during planetesimal formation.

Recently, Dr Vogt and his team have been investigating a metallic iron meteorite known as the Washington County meteorite, to begin to understand whether signals from the young Sun might be preserved in planetary cores, including Earth's core. Upon heating samples of the meteorite at various temperatures between 600°C and 1800°C, the researchers analysed the different gas elements that were released. Amongst these gases were helium and neon, both of which revealed a strong primordial solar isotope signature.

The team also discovered that these gases mainly escaped when the metals in the meteorite reached their melting temperatures. These solar gases were found throughout the meteorite, indicating they were incorporated during its formation. Dr Vogt's research suggests that fragments of a planetary core could have incorporated solar gases during the early stages of its growth.

'I have measured and established the first solid proof that the core of a planetary body, resembled by the iron meteorite Washington County, can host solar signature noble gases – helium and neon – in its interior,' he says.

During Earth's formation, solar gases may have been incorporated into the Earth's core from the metallic cores of small planetesimals. Fragments like the Washington County meteorite could have contributed material to Earth's core early in its development. 'The meteorite demonstrates the feasibility of Earth's core to have incorporated light solar noble gases,' says Dr Vogt.

Shedding New Light on Planet Formation

By investigating neon and helium isotopes, Dr Vogt's research has explained why neon in the atmosphere looks different to neon in the mantle, and how primordial solar gases could have been incorporated into the early Earth. They have also verified that the primordial neon in lava from hotspot volcanoes could have come all the way from Earth's core.

The research group plans to extend their work to studying other meteorites, and their work is already underway. 'I intend to shed new light on yet unconstrained processes of planetary body formation (that is, iron meteorite parent bodies), their formation regions and material exchange in the early solar system,' says Dr Vogt. To learn more about the formation of planets in the early solar system, his team will focus on the composition of solar gases and other volatile substances.

These primordial elements can provide invaluable information about the Earth's 4.5-billion-year history. To understand what came before the Earth as we know it today, Dr Vogt and his colleagues will continue to study clues in objects that tell of an earlier time. Decoding the messages within meteorites and tiny particles of cosmic dust will yield intriguing insights into our solar system's origins and the Earth we inhabit today.

Meet the researcher

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Dr Manfred Vogt earned his PhD in cosmochemistry at the Ruprecht-Karls-University of Heidelberg in Germany in 2018. After a year at the Karlsruhe Institute of Technology (KIT) working on nuclear waste disposal, he returned to Heidelberg in 2020, where he currently works as an Academic Associate in the Institute of Earth Sciences. Dr Vogt studies the composition of meteorites and cosmic dust to advance scientific understanding of Earth's early formation and evolution. He has published several articles in peer-reviewed journals and presented his research at international scientific conferences. Dr Vogt's research has contributed to our understanding of how the Earth formed and how primordial signatures in interplanetary dust particles and large body collisions can explain the current composition of Earth's interior and shaped the atmosphere.

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EXPLORING WINDS IN THE POLAR THERMOSPHERE

Beginning 80 kilometres above Earth's surface, and extending to the edge of the atmosphere, the thermosphere occupies a large proportion of Earth's upper atmosphere. So far, studies of this expansive region have largely focused on how the air it contains flows over global scales. Now, **Dr Ying Zou** at the University of Alabama in Huntsville has explored how the thermosphere is also significantly influenced by 'mesoscale' interactions with Earth's magnetosphere, creating flows spanning just hundreds of kilometres. Her team's work could greatly improve our knowledge of how the upper atmosphere behaves.

Earth's Thermosphere

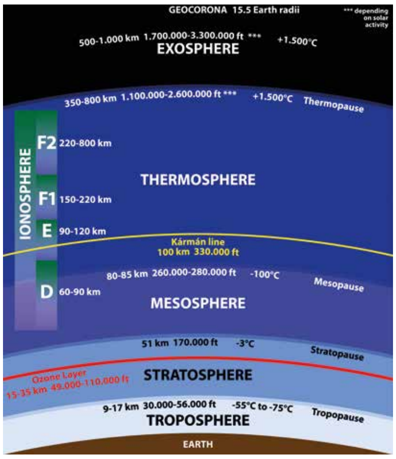
Within the Earth's thermosphere, atoms and molecules are subjected to extremely different conditions to those closer to the surface. Here, ionisation and heating are triggered as particles interact with the Sun's powerful radiation, creating plasmas with exceedingly high temperatures. In addition, the region is strongly influenced by Earth's magnetosphere – the region surrounding its atmosphere whose properties are governed by the shape and strength of its magnetic field and the flow of the solar wind.

'The thermosphere can be highly variable, since the sun and the magnetosphere deposit large amounts of energy on a wide range of temporal and spatial scales into this layer,' explains Dr Ying Zou, researcher at the University of Alabama in Huntsville. 'The science community is now actively examining some fundamental properties of the thermosphere, including its density, temperature, and velocity.'

One major challenge to these studies is the wide range of scales at which processes can occur – both in space and time. While some energy depositions can occur on scales comparable to the Earth itself, other 'mesoscale' processes can measure just hundreds of kilometres across – the size of some small countries. Moreover, processes can either unfold over timescales of several hours, or just a few minutes.

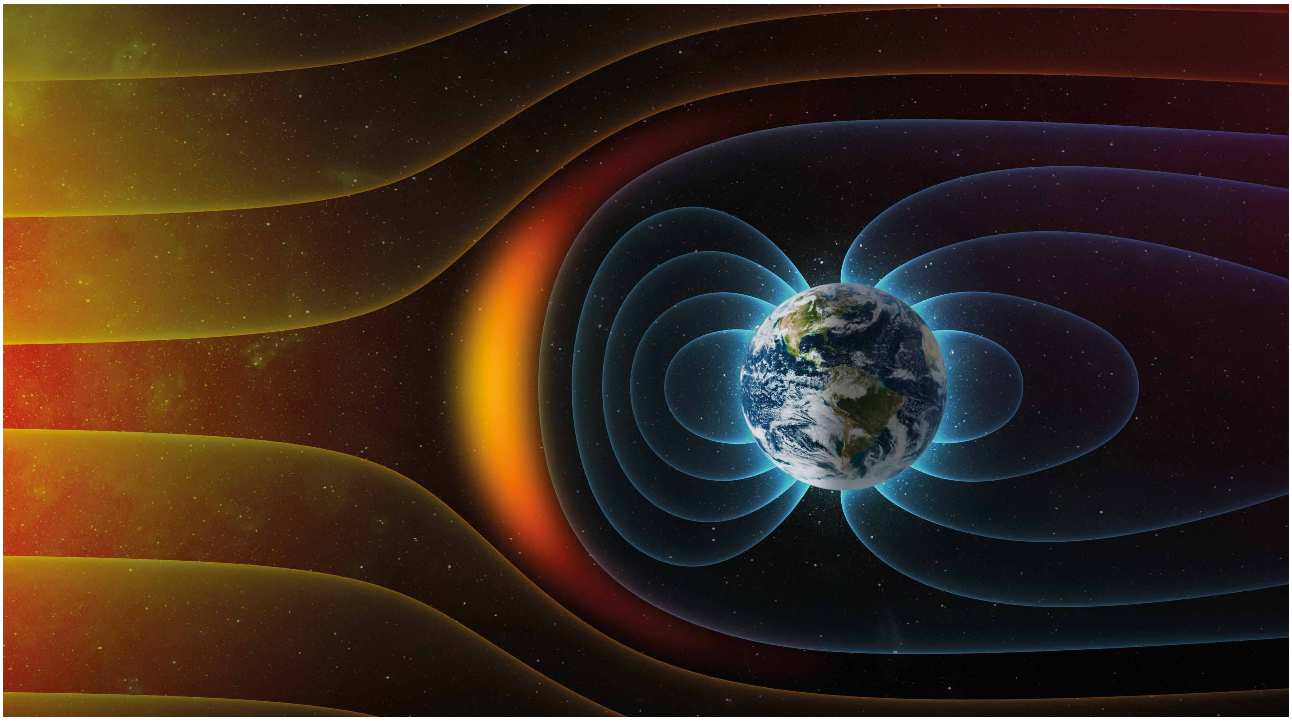
The nature of these depositions is particularly important to consider during geomagnetic 'storms' and 'substorms'. Storms are major disturbances that occur when there is a very efficient exchange of energy from the solar wind into the magnetosphere. They inject energy into the thermosphere across a broad range of latitudes and last for several days, creating the well-known natural light displays known as the aurora borealis in the northern hemisphere, and aurora australis in the south.

Substorms are also disruptions in the Earth's magnetosphere, but they



are much briefer and release less energy than storms. Both storms and substorms cause extra drag on satellites in low-earth orbit, modify the path of radio signals, disrupt navigation systems, and create harmful geomagnetic induced currents in the power grid and pipelines.

Such storms and substorms can lead to features including fleeting surges and streams of particles, as well as longer-lived arcs of auroras. However, one particular aspect of these features has remained notably unexplored until now.



Considering Global Circulations

So far, studies of winds in the thermosphere have been dominated by the exploration of global-scale circulations. Researchers have drawn their conclusions using satellite and ground-based observations of how these large-scale air flows are altered during different levels of geomagnetic activity, revealing characteristic patterns in their intensification. However, Dr Zou argues that this picture does not tell the whole story. Rather, it downplays the full influence of the magnetosphere as it interacts with the thermosphere, generating far more localised winds at high latitudes.

As Dr Zou explains, this oversight means that previous studies have left a significant gap in our knowledge of the thermosphere. 'Traditionally, it has been assumed that to drive the thermosphere in motion, forcing or energy originated from outer space must be long lasting, considering the large inertial of the thermosphere,' she says. 'In other words, if the forcing is transient, the thermosphere would exhibit little change. My research suggests that the assumption fails around aurora borealis.'

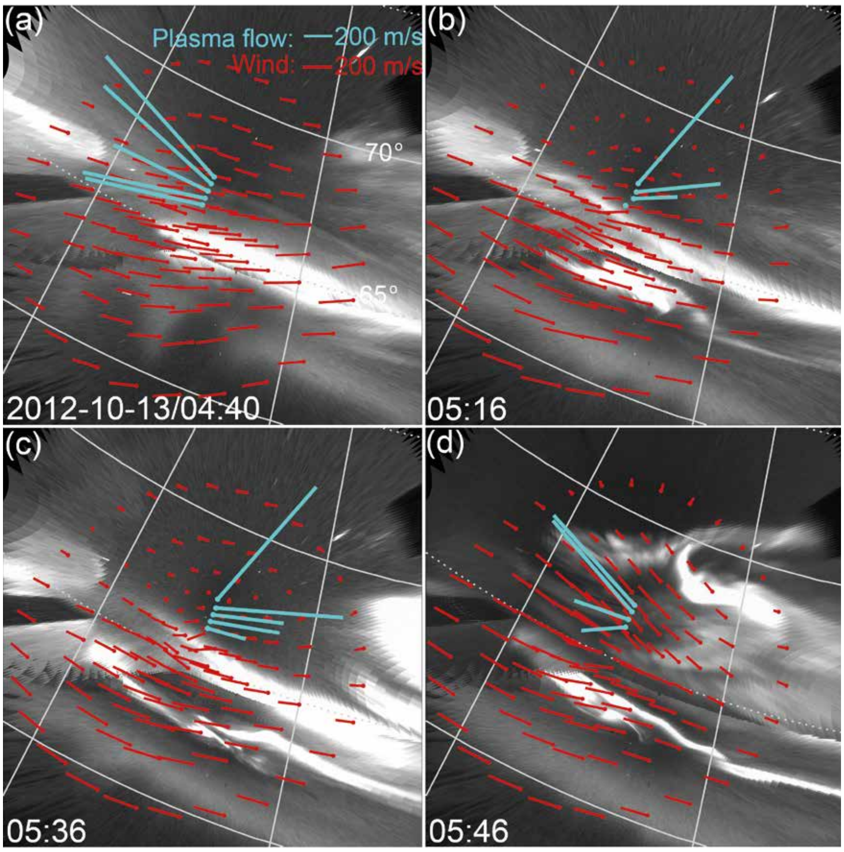
With no measures in place to account for the smaller, more fleeting motions of the aurora on top of the global-scale features it is embedded in, previous studies have produced sketches of air flow that are over-simplified. However, these shortcomings are by no means insurmountable. Using the latest monitoring tools and analytical techniques, Dr Zou and her colleagues could draw out a roadmap towards a better understanding of the interaction between thermosphere and magnetosphere.

Setting Out New Goals

Winds in the thermosphere are crucial in several aspects – all of which can benefit from a thorough analysis of the mesoscale processes found in the aurora. 'Firstly, the winds transport atoms and molecules from one place to another,' Dr Zou explains. 'This means that given a disturbance in air at one certain location, air circulation can cause it to spread, occasionally all the way to the opposite hemisphere.' Therefore, her team's findings would provide critical insights into how mesoscale processes affect the transport throughout the entire thermosphere, beyond simpler, more uniform processes.

'Secondly, the velocity affects how frequently thermospheric particles collide with charged particles from the ionosphere, and therefore how much heat is created due to frictional heating,' Dr Zou continues. 'Generally speaking, a blowing thermosphere will produce less heat than a stagnant one.' While temperatures in the thermosphere can reach up to 1,700°C, they are known to fluctuate widely with the Sun's activity, which varies the amount of energy transferred into the magnetosphere. Therefore, the team's studies could explain more accurately how these variations will unfold.

Having identified each of these aspects, Dr Zou and her colleagues next set out several objectives to determine how mesoscale winds are associated with different types of features in the aurora, and how their occurrence and properties can change. The first of these objectives involved measuring how mesoscale winds are distributed around longer-lived auroral arcs on hour-long timescales, while the second considered how winds evolve and distribute around more transient arcs. Finally, the team's third objective involved measuring how mesoscale winds vary with the activity of the Sun, and Earth's magnetosphere.



Monitoring from Ground and Space

Dr Zou's team has a wide range of instruments at their disposal to achieve each of these goals. The first of these is a chain of ground-based Fabry-Perot interferometers named Scanning Doppler Imagers (SDIs), which are positioned over the skies of Alaska. By continually monitoring thermospheric wind speeds in this region, these interferometers can produce mosaics of wind disturbances induced by the aurora at varying times. Secondly, THEMIS All-Sky Imagers are a constellation of NASA cameras, which monitor how auroral features intensify during substorms. With imaging areas spanning thousands of kilometres, these cameras can readily capture mesoscale features in their entirety as they occur.

Finally, the Poker Flat Incoherent Scatter Radar facility, also in Alaska, sends radio signals into the atmosphere, enabling researchers to monitor the energy input originating from the magnetosphere. In their latest research, Dr Zou and her colleagues have combined over a decade of data gathered using these instruments, and analysed them using cutting-edge statistical techniques. Through this approach, the researchers were able to address each of their goals, without the need to gather any new data. Their results have revealed unprecedented insights into some of the most mysterious characteristics of Earth's upper atmosphere.

Revealing Mesoscale Winds

As Dr Zou describes, the researchers have now clearly demonstrated how the thermosphere's behaviour is influenced by mesoscale processes. 'When auroras occur, the thermosphere responsively adjusts,' she says. 'Within 20 minutes, the thermosphere velocity field can exhibit spatial structures that mimic the forms and evolution of the auroras. Such results suggest that one should not treat the thermosphere as a slowly-varying and spatially smooth fluid. Instead, the thermosphere is dynamic and structured.'

This crucial result has led the team to make key discoveries in their following projects. Firstly, they have shown that substorms can significantly alter wind circulation in the polar thermosphere, altering flow speeds by as much as 200 metres per second. Secondly, they have provided new insights into the formation of a wide ribbon of hot plasma found in the thermosphere, which flows as rapidly as 6 kilometres per second. Named STEVE, this feature was first spotted in a citizen science project in 2016, and has widely mystified researchers since.

Together, these results provide corrections to a variety of long-standing misconceptions, which assume that winds in the thermosphere are only relevant on global scales. By considering how mesoscale winds are also driven by magnetospheric interactions with widely differing sizes and strengths, researchers could gain a far better understanding of the thermosphere as a whole.

A New Understanding of the Thermosphere

As well as improving our understanding of a large proportion of Earth's upper atmosphere, the findings of Dr Zou and her colleagues could shed new light on the surroundings of the many satellites that occupy the thermosphere. These include the International Space Station (ISS), as well as many other spacecraft in low-Earth orbit, which provide crucial infrastructures for global communications systems. Therefore, the team's results could lead to better predictions of the environments surrounding these satellites, and how their operation could be affected.

Through further research, Dr Zou's team now hopes their groundbreaking work will soon lead to models that accurately incorporate the mesoscale interactions between thermosphere and magnetosphere for the first time – potentially enabling greater predictions of how the Earth's atmosphere behaves as a whole.

Meet the researcher

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Dr Ying Zou completed her PhD in Space Physics at the University of California, Los Angeles in 2015. She has since occupied research positions at UCLA and Boston University, before taking her current role as Assistant Professor at University of Alabama in Huntsville in 2019. Her research interests are focused on processes that occur in Earth's magnetosphere, ionosphere, and upper atmosphere, and how they depend on the solar wind, which she observes using a variety of cutting-edge ground- and space-based instruments. Dr Zou has also been the recipient of several prestigious awards and fellowships, including the Jacob Bjerknes Award for academic excellence, and the NASA Living With a Star Jack Eddy Postdoctoral Fellowship

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FUNDING

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THE UNIVERSITY OF
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EXPLORING THE VIBRANT DYNAMICS OF NEAR-EARTH SPACE

The region of space in which Earth's magnetic field interacts with flowing charged particles is home to a rich array of physical processes – but studying them is no easy task. Through a career spanning over 50 years, **Dr Gerhard Haerendel** at the Max Planck Institute for extraterrestrial physics has carried out world-leading research into these processes. His discoveries have now led to ground-breaking insights in the field of plasma physics – including explanations of striking arcs in the aurora, the discovery of characteristic prominences on the Sun's surface, and analysis of artificial comets seeded directly into space.

Near-Earth Space

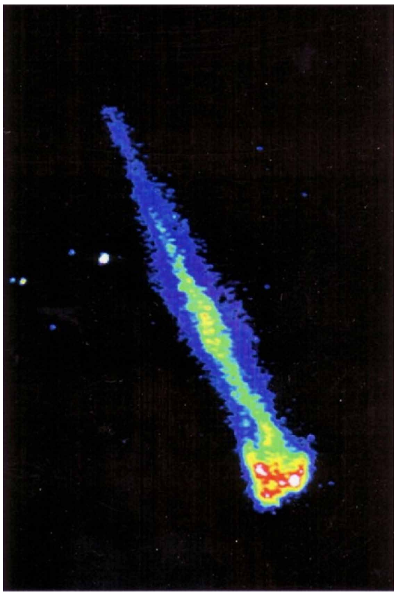
To the naked eye, the region of space just above Earth's atmosphere may appear to be empty and static. In reality, however, this region is an ever-changing landscape of dynamic interactions between charged particles, which are dominated by the influence of Earth's magnetic field. At its lower end, the region of space where these processes occur is bordered by the ionosphere: the part of Earth's atmosphere that contains particles ionised by the Sun's radiation. At its upper end, it is responsible for deflecting streams of charged particles originating from the Sun – named the solar wind – protecting Earth's surface from this damaging radiation.

Interspersed throughout near-Earth space is a thin plasma composed of negatively charged electrons, and positively charged ions. As it moves, this fluid generates its own magnetic field, which itself interacts with Earth's magnetic field, as well as those in the ionosphere. This interplay between charges and fields creates a deeply complex web of interactions which, for researchers, is notoriously difficult to study. In order to disentangle these dynamics, researchers have developed a wide array of sophisticated techniques over past decades.

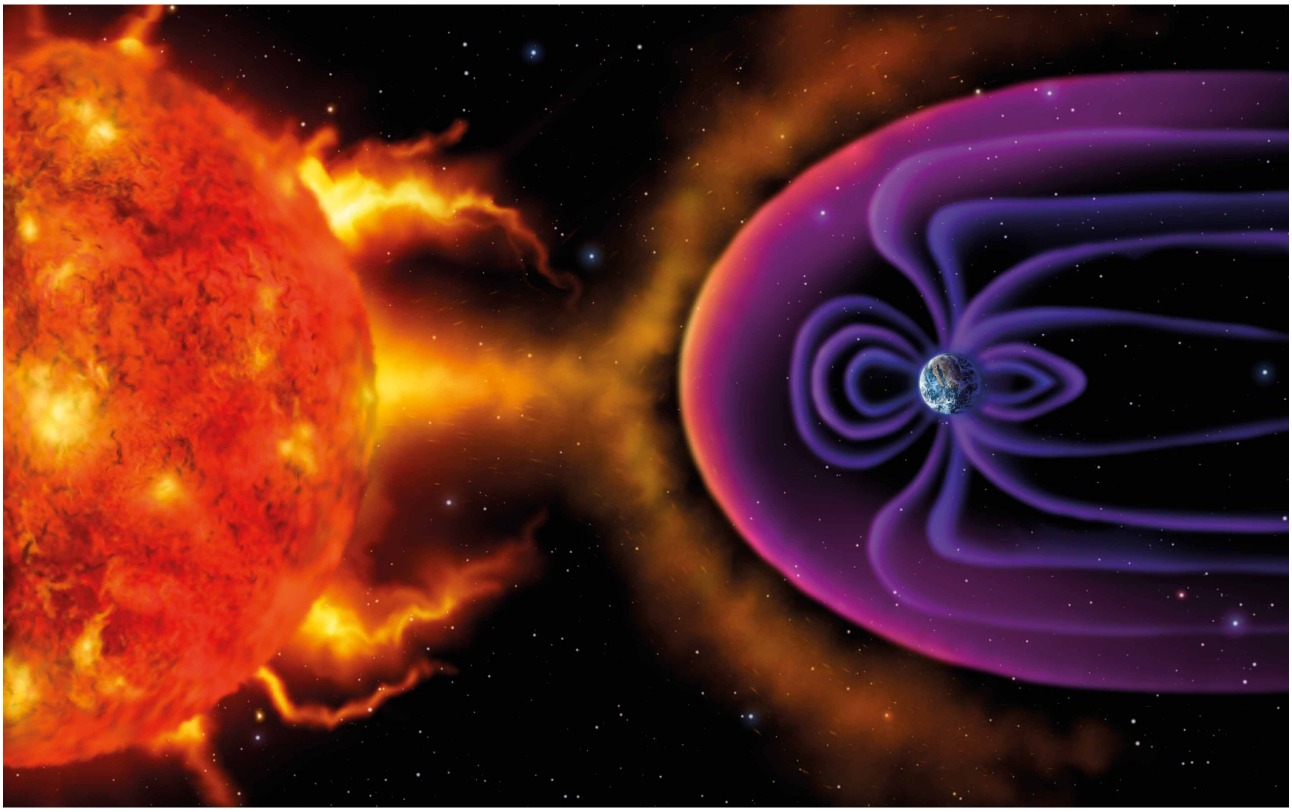
Seeding Clouds in Space

When Dr Gerhard Haerendel first started out in his career, simulation-based techniques were not nearly powerful enough to capture these processes. In order to understand them, researchers instead attempted to study them through elaborate experiments in space. In 1969, Dr Haerendel became the head of one such group at the MPI for extraterrestrial physics, which fired rockets, and later satellites, directly into near-Earth space. At their destinations, these vessels released, or 'seeded' clouds of barium directly into the surrounding natural plasma.

'For 25 years I was involved in experiments with sounding rockets and later satellites for the purpose of seeding artificially produced plasmas in space and study their dynamics and interactions with the natural plasma environment,' explains Dr Haerendel.



Once seeded, the neutral atoms in the clouds were ionised by the Sun's radiation, causing them to emit photons with frequencies characteristic to barium. By picking up these signals using sensors on the ground, Dr Haerendel and his colleagues could study how their seeded cloud evolved over time, and how it interacted with its surrounding environment. By the early 1980s, these experiments had provided researchers with a far greater understanding of the processes that



play out above Earth's atmosphere. Overall, his team's efforts culminated in a monumental experiment, which has never been attempted since: placing artificial comets directly into space.

Creating Artificial Comets

Comets are small, icy bodies, which are perhaps best characterised by their two striking tails. Flowing out from a single 'head', one of these tails is made of ice and dust particles, while the other is made of plasma. Furthermore, both tails always point away from the Sun, due to the combined influence of the solar wind, and pressure imparted by the Sun's radiation. Between December 1984 and July 1985, Dr Haerendel's team used NASA's AMPTE satellites to provide unprecedented insights into how comets' tails form, and how they interact with plasma in the solar wind.

To do this, the researchers released two canisters of barium from the satellite, and then exploded them simultaneously. This produced a rapidly expanding cloud, which engulfed the German spacecraft built by Max Planck Institute in just a fraction of a second.

Dr Haerendel and his colleagues then saw that that the barium gas was swept away as it was ionised by the Sun's ultraviolet radiation, forming a visible tail, distinct from the head, which travelled at speeds of tens of kilometres per second.

To analyse this behaviour, the physicists measured the density and motions of ions and electrons in different parts of the evolving cloud. This allowed them to explore fundamental characteristics of the interaction between the cloud, and plasma in the solar wind. They concluded that their artificial comet's behaviour was comparable to Earth's 'bow shock' – an obstacle to the solar wind, which forms as the magnetosphere interacts with the solar wind. Overall, this ground-breaking experiment provided critical new information about the interactions taking place in near-Earth space. In the coming decades, theoretical techniques would also improve significantly, and would soon become a key element of Dr Haerendel's research.

Arcs in the Aurora

Above the Earth's poles, the inward-curving shape of its magnetic field enables the solar wind to interact with the ionosphere. The results of these interactions are the colourful swirls of light that can be seen in polar skies, known as the aurora. One particularly striking feature of the aurora is the emergence of widely extending luminous arcs generated by the impact of energetic electrons – whose source has long remained a mystery. Leading on from experiments in which his team directly seeded barium clouds into these arcs, Dr Haerendel discovered that they are a result of 'fracturing' magnetic fields in the ionosphere.

This theory states that under growing shear forces exerted by the upper magnetosphere, opposite-facing frictional forces in the ionosphere cause stress to build in its magnetic field, which can be released suddenly. This occurs as fractures appear in the field, where electrical currents, trapped in 2D 'sheets', develop field-aligned voltages. Here, auroral arcs will form as the plasma and field undergo rapid stress

Dr Haerendel on his 80th birthday with Dr Reinhard Genzel

releasing motions. For the first time, this discovery allowed Dr Haerendel's team to characterise the physical properties of these structures by parameters including their widths, as well as their time-varying motions.

Reconnections Between Field Lines

In parallel research, Dr Haerendel and his team studied how magnetic fields in near-Earth space can undergo 'reconnection' – a process in which field line shapes are suddenly rearranged due to external forces. Just as processes like tearing or joining paper involve far more energy than simply bending it, this process can oversee the dramatic release of magnetic energy, in the form of kinetic and thermal energy. In the environment of near-Earth space, this process can have profound effects on the behaviours of plasmas and magnetic fields, but its influence still needs further exploration.

Dr Haerendel has recognised that within an area of low plasma density, situated at a few thousand kilometres above the Earth's surface, fractures in the magnetic field are enabled by field-aligned voltages, which are responsible for the acceleration of particles in the aurora. The fracturing causes the magnetic fields in this region to become temporarily disconnected from fields anchored in the ionosphere and replaced by new connections. A dramatic release of energy is involved in this process, which becomes invested in the acceleration.

Related Dynamics on the Solar Surface

Dr Haerendel's research has not been limited to near-Earth space. Elsewhere, he has explored how similar principles can be applied to magnetic fields close to the Sun. In particular, he was the first to explain the cause of downflowing plasma in 'prominences'. First observed by instruments aboard the Hinode satellite in 2008, these structures form mysteriously thin, vertically oriented threads above the Sun's surface, with steady down-flowing velocities of 20 kilometres per second.

Through his analysis, Dr Haerendel determined that these flows are made up of plasma squeezing through vertical field lines under the influence of gravity, dragging magnetic fields with them. Eventually, these fields disconnect from that of the prominence as a whole, and reconnect with others – eventually forming smaller packets of plasma. Such behaviour is remarkably similar to how water breaks up into droplets when flowing over a mountain ridge.

Alongside this work, Dr Haerendel has studied magnetic reconnection associated with more familiar phenomena, known to astronomers as solar flares, which are closely related to dramatic eruptions of plasma from the Sun's surface. Through this analysis, he reconsidered previous theories of the process to account for reconnection in the Sun's magnetic field, which is continually being sheared due to subsurface motions. These calculations enabled Dr Haerendel to develop a new model that modifies, for the first time, the brightness, sizes, and flow speeds of ribbon-like features in the flares on account of field-parallel acceleration processes.

Suddenly Stopping Plasma

Back close to Earth, Dr Haerendel has considered the complex physics underlying flows in the aurora, as they interact with the field of plasma in the magnetosphere's 'tail'. Facing away from the Sun, this feature arises since the solar wind compresses Earth's magnetic field on its daytime side, allowing it to extend far out into space on the night-time side – in a remarkably similar process to that observed in Dr Haerendel's earlier comet seeding experiments. Within the strongly stretched field of the magnetic tail, large amounts of plasma – and subsequently, a large reservoir of energy – can be stored.

Through theoretical considerations, supported by independent lab-based experiments, Dr Haerendel became the first to show how a 'stop layer' forms at the interface between plasmas arriving from reconnection in the tail and the magnetic field, acting like an abrupt wall. From these results, he has shown how this mechanism causes the momentum and energy of plasma in the tail to be coupled directly to fields in the outer magnetosphere and from there to the ionosphere – in a direct reversal of the magnetic reconnection process.

A Successful Career of Research

While the interactions of multiple systems of plasma and their associated magnetic fields are notoriously difficult to model, Dr Haerendel's ground-breaking research has significantly advanced researchers' comprehension of the physical processes involved. By building on the new physical insights that he has pioneered throughout his career, one may hope to understand these processes in even more detail in the future. Aside from areas ranging from the vibrant behaviours of the aurora, to the ever-changing dynamics playing out on the Sun's surface, his insights may have numerous applications within other astrophysical situations.

Meet the researcher

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Dr Haerendel has over 50 years of experience in space research, since he began his PhD studies in Physics at the University of Munich. After his graduation in 1963, he worked at the Max Planck Institute for extraterrestrial physics, where he became Director of the Institute in 1972. Here, he was responsible for a series of plasma cloud experiments, which led to ground-breaking results in the fields of plasma and magnetospheric physics. Dr Haerendel held this position until retiring in 2000, and has since taken on numerous different roles – including the founding dean of the School of Engineering and Science at Jacobs University in Bremen, as well as being the co-founder of the first astronomical observatory on the island of Crete. Over the course of his successful career, he has been Vice President of the International Academy of Astronautics, President of the Committee on Space Research (COSPAR) and Chairman of the European Space Science Committee (ESSC).

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REVEALING THE TRIGGER FOR MARTIAN AVALANCHES

For years, scientists have been puzzled by the appearance of dark streaks appearing on Martian hillsides. The linear features look like water flows – and if water is present, they could be harbouring life on Mars. However, the freezing conditions on Mars mean that liquid water flows are unlikely. Previous theories suggest the flows could be dust avalanches, but this doesn't explain why they only appear in the Martian summer. **Dr Anthony Toigo** and his colleagues at Johns Hopkins University Applied Physics Laboratory, NASA Goddard Space Flight Center, and the University of Colorado – Boulder, have modelled weather conditions near the Martian surface and recreated the Martian atmosphere in a laboratory. By doing so, they could examine how Martian dust and surface soils respond to the changing seasons on the red planet.

Mysterious Dark Streaks on Mars

Every year, in the Martian summer, dark streaks begin to appear on the steepest hillsides, such as valley walls and the rims of ancient meteor craters. The lines are visible in images taken by Mars orbiters, and scientists refer to them as 'recurring slope lineae', or RSLs. The streaks grow slowly throughout the summer and then disappear when the Martian weather gets colder.

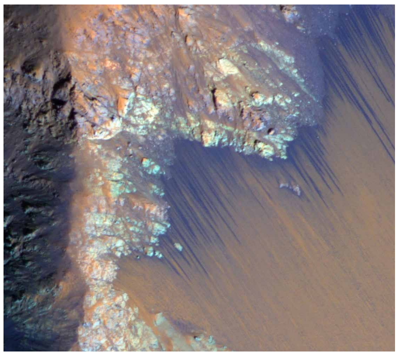
Scientists initially assumed that these RSLs were wet, as they look like flows of water. As liquid water is essential for life, the flows could be sites for ancient or even current biological activity on Mars. If the sites were home to alien life forms on Mars, they would be a top priority in efforts to protect and preserve the planet's environment.

Liquid-carved features on the surface of Mars indicate that ancient rivers once flowed on the red planet. However, scientists generally agree that for about the last 3.5 billion years, temperatures on Mars have been too cold for pure water to exist as a liquid. Water could only flow in the form of very salty brine, as salt dissolved in water lowers its freezing temperature.

Any water in the RSLs could come from either frozen or liquid aquifers underground. However, the dark streaks sometimes appear on isolated peaks and ridges, which are unlikely to store underground water. Alternatively, water vapour from the atmosphere could be absorbed by the Martian soil. Still, it has previously been unclear how atmospheric water vapour could trigger seasonal avalanches.

If water on the Martian hillsides comes from atmospheric vapour, the sites would be unlikely to contain life. Understanding whether water could trigger these flows and where it could come from is an essential first step in determining whether these sites could harbour life.

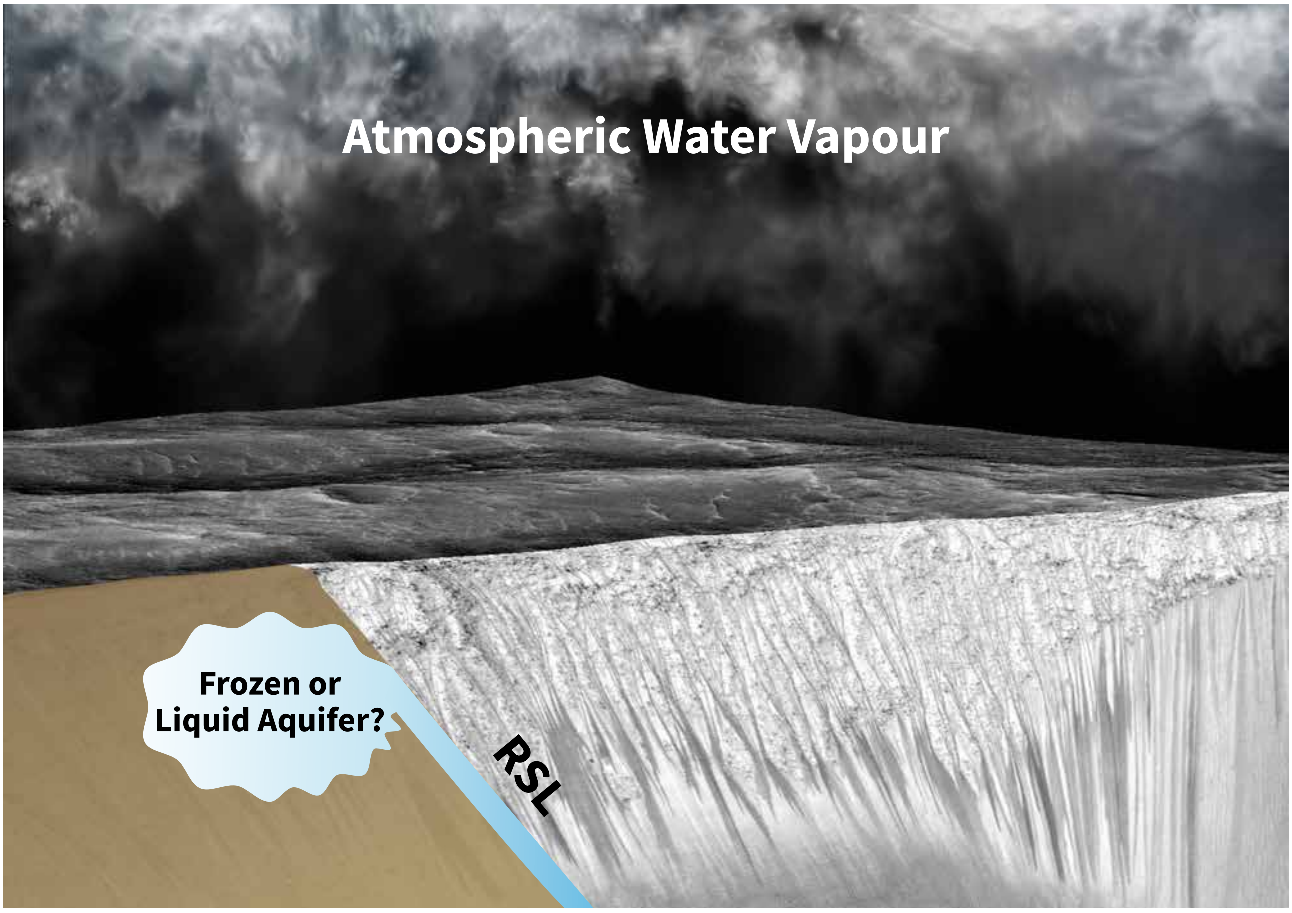
Dr Anthony Toigo at the Johns Hopkins University Applied Physics Laboratory has devoted years to investigating the causes of Martian RSLs. His team's latest work aimed to determine whether RSLs could be caused by water vapour absorbed from the Martian atmosphere rather than liquid water flows. If the streaks could form without liquid water, scientists may have to look elsewhere for life on Mars.



CREDIT: Lunar and Planetary Laboratory/NASA

Simulating the Martian Atmosphere

At Hale Crater on Mars, the site of an ancient meteorite impact, dark streaks form every year. The flows start growing in early spring on the steep slopes of



the crater walls and fade away in the Martian winter. To understand whether atmospheric water vapour could be causing the streaks, Dr Toigo and his team set out to understand the temperature and humidity conditions at the site.

Spacecraft orbiting around Mars, such as the Mars Reconnaissance Orbiter, pass by Hale Crater at approximately the same time every Martian day and measure atmospheric conditions, but Dr Toigo's group wanted to understand how atmospheric conditions changed throughout the whole day. Furthermore, the orbiters cannot detect humidity in the lower layers of the atmosphere nearest the surface of Mars.

To fill the gap between observations, they used mathematical models to predict how temperature and humidity would change throughout the Martian day. They forecasted the daily temperature and humidity cycles at the crater in the summer months, when the flows appear, and the winter months, when they are absent. Their results show that temperatures at the crater are very cold; even during the summer, they typically remain below freezing.
Once they had estimated the Martian conditions, the team replicated the Martian atmosphere in the lab. This was the first time that daily-varying environmental conditions at Martian avalanche locations were simulated on Earth. Firstly, the researchers tested whether the streaks could be brine flows triggered by a process called deliquescence. In this process, salts in the Martian soil would absorb enough atmospheric water vapour to dissolve in the absorbed water, forming a concentrated salt solution.

Next, the group studied a type of salt found in the Martian soil, called calcium perchlorate, subjecting it to Martian temperature and humidity conditions in their lab. To do this, they encased the salts in a cell with controlled temperature and humidity, cooling the samples using liquid nitrogen and humidifying it with water vapour. They then directed a laser at the samples and measured how they scattered the laser light, to find out how much absorbed water or ice they contained.

In both the summer and winter experiments, the conditions were sufficiently cool and humid for water to be absorbed by the salt overnight. However, the salts did not take in enough water to form a liquid brine. Therefore, Dr Toigo and his colleagues deduced that the flows on Mars could not be brine flows created by water absorption from the atmosphere into the soil.

However, they noticed an interesting difference between the two sets of experiments. The salt absorbed water overnight and released it back to the atmosphere during the day, but only lost all of its water in Martian summer conditions, when the dark flows form. In contrast, in the Martian winter conditions, even in the warmest time of day, the salt did not completely dry out. 'When the RSLs are seasonally active, the ground is drying,' says Dr Toigo.

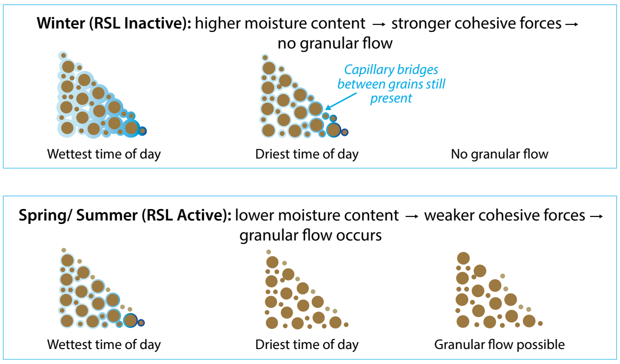
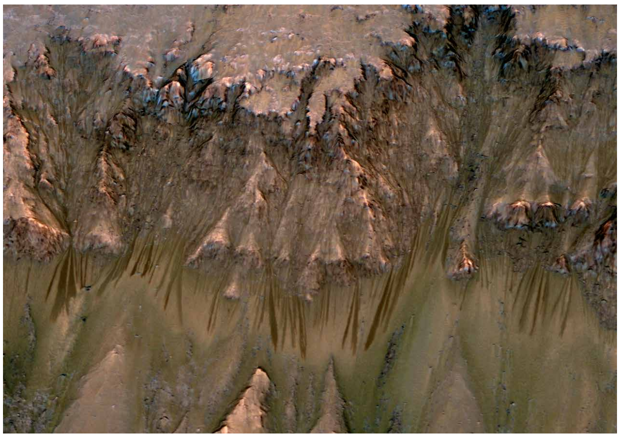


Illustration showing the trigger mechanism for RSLs



CREDIT: NASA/JPL-Caltech/University of Arizona

The researchers formed a new hypothesis for how atmospheric water vapour could trigger flows on the crater walls in the summer, without the need for liquid brine. Instead of a fluid flow, the dark streaks could be dry avalanches of dust caused by salts in the Martian soil drying out in the summer.

The Trigger for Martian Avalanches

The warm, dry conditions at Hale Crater in the late spring and summer could cause the salts in the soil to completely dry out during the warmest part of the day. When the soil dries out, the cohesive forces between the grains, which usually hold them together, weaken. The Martian soil becomes less sticky and more prone to sliding downhill. 'When the soil seasonally starts drying, it becomes more loose and more likely to collapse, like a dry landslide,' explains Dr Toigo.

When this happens, the bright-coloured dust and sand slide down steep slopes such as the walls of Hale Crater. 'This collapse would expose darker material underneath, appearing as the discolouration seen in the images taken by spacecraft,' adds Dr Toigo.

More dust from the atmosphere is deposited on the slopes in the winter, and the temperature never becomes warm enough to dry it out. The soil grains have a high moisture content all day, and the cohesive forces between the grains prevent them from flowing downhill.

The streaks could plausibly be caused by dry dust avalanches, as they occur on slopes steep enough for dry material to flow. Some scientists had previously suggested that they could be dry flows caused by wind disturbing the dust or gas flowing under the soil, but these theories can't explain why the flows only appeared in the warm months. The absorption and release of atmospheric water by salts in the ground are possible under Martian conditions and explain the flows' seasonality.

If yearly dust fall provides the material for the flows, they could be very thin – possibly only a fraction of a millimetre in depth. Dr Toigo's model suggests that the subsurface could be dehydrated up to a depth of about six centimetres. However, if the surface dust is much brighter than the rocky ground underneath, even a tiny, thin flow could easily be observed from space.

Is Mars Currently Habitable?

Dr Toigo's team found that the dark streaks on Martian hillsides could be dry dust avalanches, where surface grains are normally held together by the absorption of atmospheric water vapour at night by salts in the soil, and then become looser by a drying of the ground during the warmest parts of the day. The theory explains why the flows are only observed in the summer, as the salts can only completely dry out in the summer, and then the dust is loosest and avalanches can be most easily started.

It remains unknown why the flows are common on some slopes, such as Hale Crater, but not others. However, if the atmospheric vapour theory is correct, the variation could be explained by locally varying temperatures or salt concentrations in the soil.

The atmospheric vapour theory has important implications for the search for life on Mars. 'If RSLs can form from the seasonal absorption of water vapour in the air instead of from underground reservoirs of water, then areas where RSLs are found would not be locations of likely biological activity,' explains Dr Toigo.

The findings could have implications for the protection status of the flows. If they do not contain liquid water and are unlikely to be habitable, they could be suitable sites for future exploration by landing probes. However, anyone on a mission to find life on Mars might be disappointed. 'The search for life on Mars would best be conducted elsewhere,' concludes Dr Toigo.

Meet the researcher

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Dr Anthony Toigo obtained his PhD in planetary science at the California Institute of Technology, where his research focused on atmospheric processes on Mars. After graduating in 2001, he continued to study the Martian atmosphere as a Research Associate at Cornell University, New York, and subsequently as an International Scholar at Kobe University, Japan. In 2009, Dr Toigo moved to the Johns Hopkins University Applied Physics Laboratory, where he currently develops software and conducts research analysing spacecraft observations and computer models. Dr Toigo has dedicated his career to understanding planetary atmospheres, and his work has furthered our understanding of the Martian atmosphere and climate, Martian dust storms, and the atmosphere on Pluto. Alongside his academic research, he contributed to verifying landing and operating conditions for several Mars spacecraft. Dr Toigo has been awarded multiple prestigious grants and awards for his contributions to planetary science.

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Mars Reconnaissance Orbiter (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM)

- http://crism.jhuapl.edu
- NASA instrument built and operated by the Johns Hopkins University Applied Physics Laboratory onboard NASA mission

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UNCOVERING THE TRIGGER FOR MARS' GLOBAL DUST STORMS

Enshrouding the Martian surface with thick clouds of dust, the Red Planet's unique global dust storms have long mystified astronomers and planetary scientists. **James Shirley**, at NASA's Jet Propulsion Laboratory, has shown through his research that the occurrence of these global storms is strongly linked to the changes in Mars' motion about the gravitational centre of the solar system. Already boasting strong observational evidence, his results could not only improve our understanding of the Mars atmosphere – they may also lead to a better understanding of turbulent weather patterns on Earth.

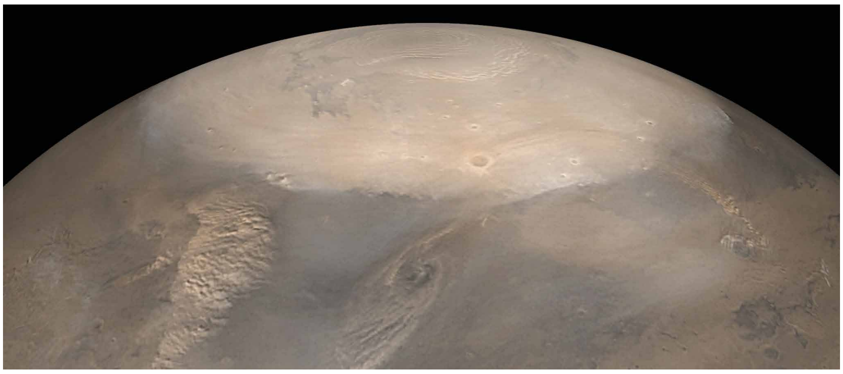

Figure 1. Regional dust storms sweep eastward (from left to right) around Mars' growing northern polar cap region during the southern summer dust storm season. CREDIT: NASA PIA 10787.

Dust Storms

Every summer in Mars' southern hemisphere, large dust storms are stirred up from the planet's surface, producing striking clouds which can be clearly seen, both in satellite images, and in telescopic images obtained on Earth. The strong seasonal pattern in the timing of these storms is due to the elliptical shape of Mars' orbit, varying its distance from the Sun.

Mars reaches its closest point to the Sun during the late spring season of its southern hemisphere. This results in higher temperatures, and increasing surface winds, allowing dust to be kicked off the surface more readily. Yet every few years, this process appears to go into overdrive: in 2018, Mars experienced a dust storm so ferocious that it enshrouded the entire planet. For several weeks, the dust cloud was so thick that many of the known features and landmarks on the planet's surface were completely obscured. These dramatic events have now captured the public imagination, producing the terrifying clouds that first stranded Mark Watney in Ridley Scott's *The Martian.*

The mystery as to why these global storms appear in some years, but not in most others, has puzzled astronomers and planetary scientists for decades. According to Shirley, however, the timing of the global storms can now be explained by a novel mechanism known as *orbit-spin coupling*.

Dragged Along By the Sun

When we think of the Solar System, we typically imagine the Sun in a fixed position at its centre, unaffected by the gravitational pull of its vastly smaller orbiting planets. However, this picture isn't entirely accurate. In reality, the Sun noticeably shifts away from the gravitational centre of the Solar System due to the influence of the heavy gas giants, particularly Jupiter and Saturn. The motions of these bodies cause the Sun to orbit around a centre of mass which can be hundreds of thousands of kilometres away from its own centre – this 'barycentric revolution' is not unlike the motion of a pair of dancers spinning while holding hands, as shown by Figure 2.

The smaller inner planets, including Earth and Mars, are dragged along in this dance by their gravitational attraction to the Sun. One result is to significantly alter the 'orbital angular momentum' (OAM) of Earth and Mars. The OAM is the product of the planets' masses, velocities, and orbital distances from the centre of the solar system. Its magnitude can be thought of as the amount of momentum that would need to be removed in order to somehow stop their orbital motions in their tracks.

Depending on the relative positions of the giant planets, which throw the Sun out to varying distances from the Solar System's centre, Earth and Mars can either lose or gain OAM, while the total angular momentum of the solar system remains constant. Figure 3 shows the changes in the angular momentum of Mars between the years 2006 and 2020, alongside the solar energy received by Mars.

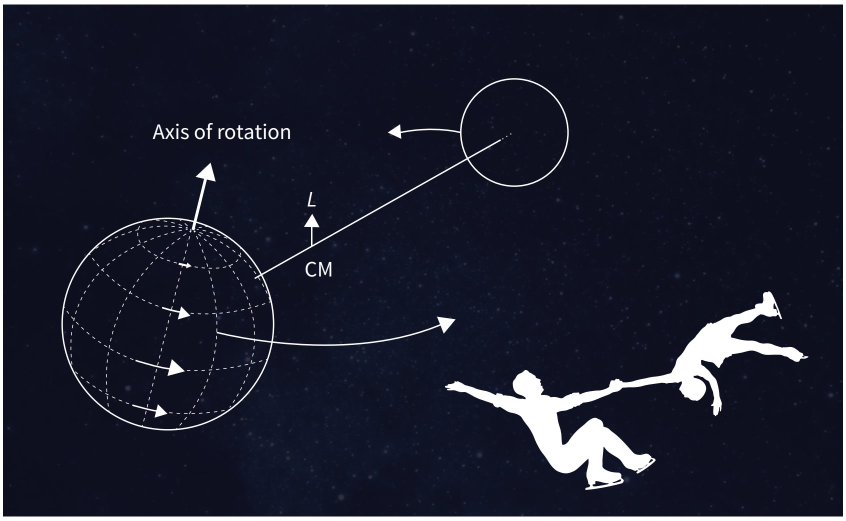

Figure 2. Two bodies orbit a shared centre of mass.

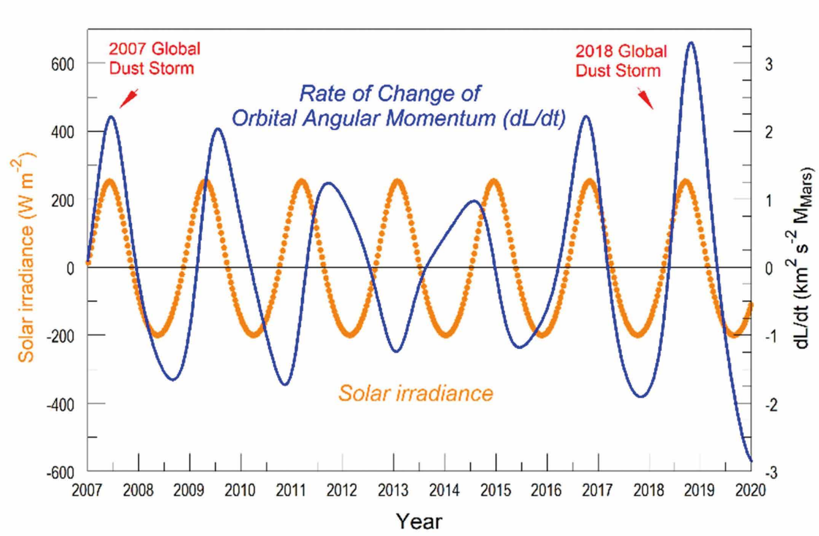

Figure 3. The curve in blue illustrates times when Mars is gaining and losing orbital angular momentum. Orange symbols indicate the period of the Mars year.

The orbital momentum of Mars is millions of times larger than the angular momentum associated with its spin. The angular momentum of the atmospheric circulation, by comparison, is an additional ten million times smaller still.

Until now, the ongoing changes in OAM have been largely ignored, both by astronomers and by atmospheric scientists – since, under existing theories, they don't appear to have any significant influence on important factors such as the planetary surface temperature. In contrast, Shirley's work demonstrates that OAM changes are key to understanding why global dust storms arise on Mars in certain years, but not others. The underlying mechanism is simple in concept: A tiny fraction of the OAM is transferred, more or less continuously, to (and from) the planetary rotation, as the OAM changes with time (Figure 3). The planetary atmosphere participates in the transfer of momentum between the two.

Nature of the Coupling

While scientists have long suspected that a connection might exist between orbital motions and rotational motions, no theory existed to explain how that connection might be accomplished. Through his earlier research, Shirley was the first to derive an equation describing how the orbital momentum could be 'coupled' to the vector describing the rate at which Mars spins on its axis – which is tilted at an angle relative to its orbital plane.

Shirley's orbit-spin coupling equation yields an acceleration field that is illustrated in Figure 4. The arrow symbols on the figure give the directions and relative sizes of the horizontal forces that result from the coupling. This fixed pattern of forces takes the appearance of a beach ball, with the forces acting in directions which appear at first glance to bear no relation to Mars' rotation or orbital motion. We have to imagine the planet spinning through, or beneath, this pattern of forces, as it rotates in a counter-clockwise direction around the north pole, shown near the top of the figure.

The large-scale pattern of the forces on the planet provides a twisting effect, or torque, about an axis lying within the equatorial plane of the body, as indicated by the cartoon shown at the lower right in Figure 4.

In Figure 3, we see that the curve giving the changes of Mars' OAM often passes through zero. When this happens, the force vectors shown in Figure 4 diminish and disappear, to re-emerge thereafter pointing in opposite directions. Orbit-spin coupling thus produces a *reversing torque* that varies in a complex manner with time. This turns out to play an important role in the triggering of global dust storms.

As they act on the Martian atmosphere, the predicted forces must accelerate its air to widely varying degrees. Prior to Shirley's investiagtions, the atmospheric motions produced by orbit-spin coupling had never been considered – but this was soon about to change.

Effects on the Large-scale Circulation

As with the Earth, the circulation of the atmosphere on Mars is primarily driven by energy arriving from the Sun.

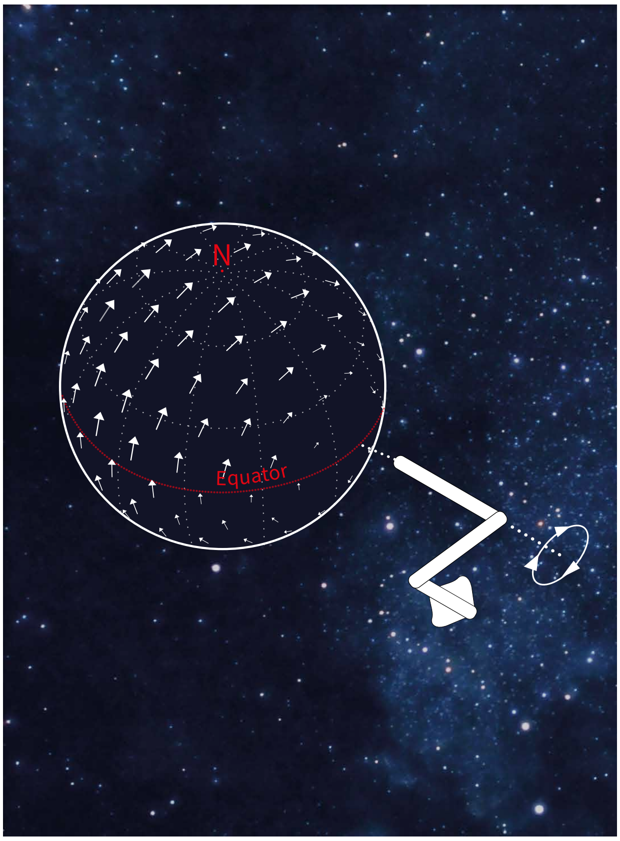

Figure 4. The pattern of horizontal forces produced on a planetary surface by the coupling of the orbital and rotational motions. The turning tendency, or torque, produced by the forces shown is indicated by the bicycle pedal assembly shown as a cartoon at the lower right.

Several well-known effects control the large-scale pattern of the circulation. For instance, as air is heated at the planet's equator, it rises to high altitudes, and moves to higher latitudes in the upper atmosphere. After the air cools, it then drops back down to the surface, and moves back to the equator across Mars' surface, producing two separate circulation loops known as Hadley cells. Another important control is provided by the well-known Coriolis force, which causes high-pressure systems to circulate in a clockwise direction in the northern hemisphere, and counter-clockwise in the south – with important consequences for global weather patterns. The atmospheric motions induced by orbit-spin coupling are superimposed on these larger patterns.

Shirley's work with atmospheric circulation computer models shows that as Mars spins beneath the approximately fixed beach ball pattern of forces (Figure 4), the atmosphere above individual points on its surface will be pushed around, and pressure systems will be pushed out of shape, by continually varying forces throughout the day. While the added atmospheric forcing due to the coupling could be pushing weather systems northwards in the morning, the push could weaken and stop by the afternoon; before strengthening in the opposite direction, and pushing the weather southward in the evening.

These effects might not be be particularly important, under typical circumstances. However, the situation changes entirely if the time when Mars is gaining OAM most rapidly happens to coincide with the dust storm season – the time when the planet reaches its closest point to the Sun. If these two events happen within a few months of each other, computer models show that exceptionally strong motions within the atmosphere may kick dust off the Martian surface even more vigorously than normal. Figure 3 illustrates this correspondence for the two most recent Martian global dust storms, which occurred in 2007 and in 2018. At these times, Mars was rapidly gaining OAM, at the expense of other planets.

Shirley's studies of atmospheric general circulation models confirm this relationship. When Mars is gaining OAM from the Sun, the global wind patterns favourable for dust storm occurrence can be strengthened by 20% or more. Atmospheric computer models *lacking* the orbit-spin coupling accelerations, by comparison, show no such variability.

How Strong is the Evidence?

Scientists generally require strong statistical evidence before lending credence to new ideas. Several scientific papers published since 2015 have reported statistically significant relationships and patterns linking changes in Mars' OAM with dust storms. The next step in proving a new hypothesis involves detailed numerical calculations and modelling studies, which can demonstrate that the theoretical mechanism is strong enough to produce important effects. This milestone was passed in Shirley's 2017 paper, which presented the orbit-spin coupling equation for the first time.

Computer modelling with atmospheric general circulation models, while expensive, allows more powerful testing to be done. Two recent studies revealed that models including orbit-spin coupling could produce conditions favorable for dust storm occurrence *in the years in which such storms actually occurred.* They could also reproduce the century-long historic record of Mars years with and without global dust storms, with an accuracy approaching 80%. No other model has approached this success rate, either for Mars, or for the Earth. All of the global dust storms of the historic record have occurred either when the magnitude of the torque was peaking, or when the torques were changing most rapidly, as in 2018.

The orbit-spin coupling hypothesis was employed to successfully forecast the 2018 global dust storm on Mars, in a series of scientific papers beginning in 2015. Even more convincingly, the predicted circulation changes were confirmed through direct observations of the Mars atmosphere by spacecraft in the earliest days of the 2018 storm. Shirley's models predicted that the spinning-up of the atmosphere in that season would lift dust tens of kilometres higher into the atmosphere than would be the case for typical summer storms.

The expected powering-up of the large scale circulation was actually observed, between June 4 and June 9.

As the high-altitude dust fell and spread out, it was then carried large distances by high-altitude winds, enshrouding the entire planet within just a few days. The orbit-spin coupling hypothesis thus successfully explained both the mechanism for strong dust lifting and the patterns seen in the timing of global dust storm occurrence.

Forecasting Future Events

The orbit-spin coupling approach has enabled Shirley and his co-workers to forecast when future global storms are likely to occur. He expects that the next such storm will most likely occur in 2026, following a relatively quiet period of Martian weather.

Ultimately, his research strongly indicates that existing atmospheric general circulation models must be updated to account for this new effect, which has long escaped the attention of climate modelers. Orbit-spin coupling has already significantly improved our understanding of how the Martian atmosphere behaves; its forecasts may even help future settlers of the Red Planet to avoid the fate that befell Mark Watney.

Studying Our Home Planet

While it is fascinating to study atmospheric behaviours on Mars, Jim Shirley's work is ultimately directed towards a more important goal: improving atmospheric general circulation models for Earth. Currently, even the most advanced models cannot forecast the intricate variability in Earth's weather patterns beyond around two weeks in advance, leaving communities with little time to prepare for damaging storms.

While Earth's atmosphere and surface are more complex, with features not found on Mars, such as oceans and forests, producing complex alterations in its atmospheric circulation, Shirley is convinced that the influence of orbit-spin coupling still plays a fundamental role.

By accounting for how changes in Earth's orbital angular momentum induce continually varying levels of atmospheric forcing, researchers could conceivably make far better predictions of when and where the most damaging weather events could occur. In a changing climate, such predictions could prove critical for saving lives in natural disasters, and for protecting the economic wellbeing of many millions of people around the world.

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DEVELOPING A GUIDEBOOK TO SEARCH FOR LIFE BEYOND EARTH

Are we alone in the universe? Searching for life beyond our Solar System is one of the most ambitious efforts humans have ever undertaken. Because we do not have the ability to travel to distant exoplanets, scientists must rely on indirect clues that could help us find extraterrestrial life. **Dr Edward Schwieterman** and his colleagues at the University of California, Riverside, have been developing advanced methods to determine the habitability of planets and detect the elusive signs of life from afar.

Where is Everyone?

Beyond our protective atmospheric blanket, space is a vast and harsh frontier. Is our world – with its mild temperatures, breathable air, and abundant life – unique in the universe? Searching for other habitable environments and extraterrestrial life is a deeply compelling scientific objective. Answering this question with certainty would fundamentally reshape our understanding of our place in the cosmos.

Humanity has made significant strides towards finding an answer during the last four decades. We have progressed from not knowing whether planets existed outside our own planetary system, to identifying over 4300 planets orbiting other stars – so-called 'exoplanets'. This number is increasing almost daily, with new discoveries facilitated by observatories such as NASA's space telescope TESS. TESS and the Kepler mission before it identify exoplanets by the characteristic dimming effect they have on a host star's light as they cross in front of it. Some of these exoplanets are small, rocky planets like Earth, and may possess conditions conducive to the presence of life.

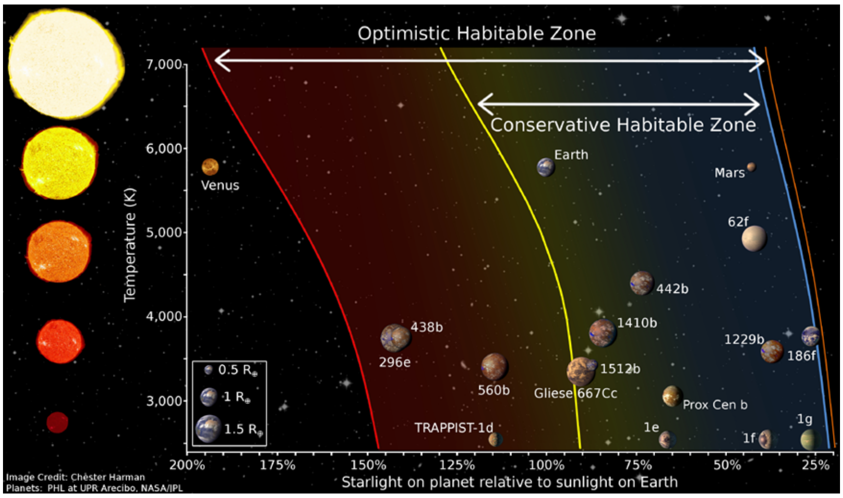
These discoveries offer unprecedented opportunities to search for extraterrestrial life. However, we are exceedingly unlikely to be able to reach these distant planets in the foreseeable future. As such, it is imperative to develop technologies that can identify life unambiguously across the immense gulf of interstellar space.

We are currently transitioning from simply detecting exoplanets towards detailed investigations of their atmospheres and surfaces. Writing the guide to finding life among our Sun's neighbouring stars is Dr Edward Schwieterman and his colleagues in the Department of Earth and Planetary Sciences at the University of California, Riverside. Dr Schwieterman's research group uses a range of experimental and modelling techniques to determine the potential habitability of planets and plausible signatures of life.

Seeking a Habitable Zone

Having discovered thousands of exoplanets, the next stage in the search for extraterrestrial life is to identify those with potentially habitable environments. Above all else, this means liquid water – believed to be a key requirement for life. The conventional 'habitable zone' is the range of distances around a star in which liquid water can exist. If an exoplanet is too close to a star, surface water will evaporate, and if it is too far from the star, surface water will freeze.

Atmospheric greenhouse gases, such as carbon dioxide, play a role in stabilising planetary surface temperatures from the hotter inner edge (where the star's light is brightest and warmest) to the cooler outer edge (where less star light reaches). However, advanced Earth-like life, such as animal life, is unlikely to be able to survive throughout the whole range of the habitable zone. 'To sustain liquid water at the outer edge of the conventional habitable zone, a planet would need more than ten thousand times the carbon dioxide in Earth's atmosphere today,' explains Dr



Schwieterman. 'That's far beyond the levels known to be toxic to human and animal life on Earth.'

Additionally, most of the exoplanets discovered so far orbit around stars that are quite different from our own Sun. Smaller, cooler, red stars constitute over 70% of the stars in our Milky Way galaxy. These red dwarf stars are believed to promote the accumulation of toxic gases, such as carbon monoxide, in planets' atmospheres. Dr Schwieterman and his research team developed an advanced model that incorporated these factors, to produce an illustrative 'Habitable Zone for Complex Life', with a far more restricted range than the conventional habitable zone. Outside of this range, within the limits of the conventional habitable zone, the only life that could exist is likely to be microbial.

However, the template of life on Earth is not necessarily inclusive of all evolutionary pathways that could exist throughout the universe. As-yet unknown compensatory mechanisms may allow advanced life to exist in the extreme conditions found on other planets. Although our definition of life is limited by our understanding, our search efforts are aided by the laws of physics and chemistry, which are the same throughout the universe. Finding even microbial life on an exoplanet would be an extraordinary discovery.

Seeking a Habitable Planet

Being within the Habitable Zone does not necessarily guarantee that an individual planet is habitable. The next problem is how we would affirmatively detect habitability and life on a distant exoplanet. Clues about the conditions on planetary surfaces can be gained through imaging techniques. However, even the best images of distant exoplanets have all the information collapsed into a single point of light.

Images of Earth taken by the space probe Voyager 1 provide a representative example. Taken from approximately 6 billion kilometres away, the Earth appeared – as described by popular science communicator Carl Sagan – as a 'mote of dust suspended in a sunbeam.' By comparison, the nearest exoplanets are over 40 trillion kilometres from us. But these tiny 'motes of dust' can still provide useful clues into the exoplanet's conditions. For example, this light can be split into its component wavelengths, revealing the fingerprints of individual molecules that constitute the atmosphere, such as oxygen and carbon dioxide. In addition, a characteristic 'glint' can signal the presence of liquid such as water on the planet's surface.

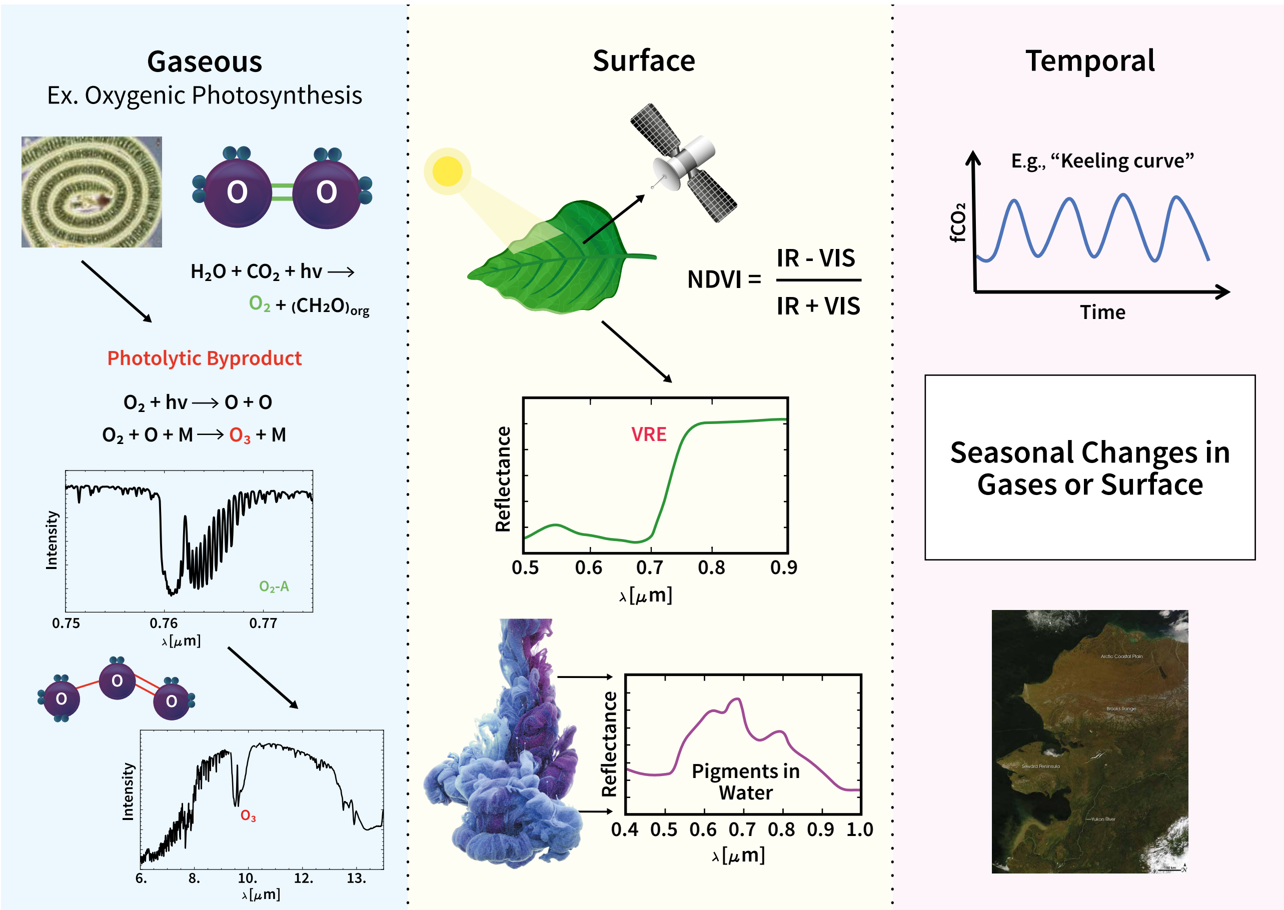
The intensity and colour of the light reflected by the planet can also help scientists determine the surface composition of the world. Finding signatures suggesting both surface water and atmospheric carbon dioxide could suggest that the planet's surface maintains hospitable conditions.

Seeking a Sign of Life

The next step in the search is to find positive indicators of life – called 'biosignatures'. Biosignatures are substances, objects or patterns that are produced by life and can be separated from potential non-living sources. They can be separated into surface, atmospheric or gaseous, and temporal signatures.

Oxygen is often considered a gaseous biosignature because plants, algae and other microbes produce enormous amounts of it, replenishing the oxygen lost to geological processes. However, non-living processes can also be a primary source of oxygen for planets orbiting other stars, potentially leading to 'false positives' for extraterrestrial life. Therefore, interpreting the presence of oxygen as a biosignature depends largely on the environmental context. Dr Schwieterman suggests that multiple gaseous biosignatures could provide more compelling evidence of a legitimate biosignature, particularly if these gases are in a 'chemical disequilibrium', and would otherwise react without a constant source.

Breaking the signals of light reflected by the planet's surface into component wavelengths, indicative of the absorption and reflection properties of a planetary surface, can help scientists find surface biosignatures. For example, plants on Earth absorb most red and blue light, and reflect green (hence their green appearance), along with infrared light. Absorbing red light and reflecting invisible infrared light gives rise to the 'vegetation red-edge effect' – the characteristic sudden increase in reflected light near the infrared range. This phenomenon is used to map vegetation over the Earth's surface, and could be used to detect plant-like life on exoplanets.



Temporal biosignatures are time-dependent cycles in gaseous or surface biosignatures. We observe this in the seasonal changes on Earth. For example, vegetation growth in the spring and summer causes a decrease in the concentration of atmospheric carbon dioxide in the Northern Hemisphere, which then increases again as plants die back during the autumn and winter.

The signs of life on exoplanets may not be an exact replica of what we observe on Earth, though it is the only example we have available of a habitable and inhabited world. By digging deep into our planet’s history, Dr Schwieterman has gained a glimpse into multitudes of possible life-bearing conditions that could help us link our observations of exoplanets with possible biosignatures. ‘Over billions of years of persistent habitability, the prevailing chemical state our planet’s atmosphere and surface has undergone extraordinary shifts including from an anoxic, hazy, orange world three billion years ago to the oxygen-rich pale blue dot we take for granted today,’ he explains.

Dr Schwieterman and his colleagues describe a ‘Purple Earth’ from billions of years ago, before the development of photosynthesis observed in modern plants. Some microbes from this period used a different compound called retinal – similar to the compound found in the retina of the human eye – which reflects red and blue light, hence its purple appearance. A ‘green-edge effect’ could be a possible biosignature for exoplanetary life that uses his compound to collect light energy.

There’s Still No Place Like Home

The challenge remains to identify irrefutable biosignatures to aid our search for extraterrestrial life. ‘Practically, prospective exoplanet biosignatures will be only tentative signs of life with other possible explanations,’ says Dr Schwieterman. ‘However, we can systematically gain confidence by obtaining more and more information about the target planet and its properties, and thereby slowly rule out all explanations other than life. Finding life elsewhere will require patience.’ One possible shortcut to this process would be to find evidence of ‘technosignatures’ – unambiguous signals of an advanced or technological civilisation, sought by projects such as ‘Search for Extraterrestrial Intelligence’ (SETI).

We are perhaps far more likely to find evidence of microbial extraterrestrial life. Dr Schwieterman’s research has helped to inform the development of new techniques for the search for biosignatures, and his suggestions – such as the inclusion of ultraviolet detectors on future telescopes to better detect ozone – could prove invaluable.

With much work still to do in the search, we may be waiting a while to get an answer to the age-old question. In the meantime, Dr Schwieterman leaves us with a thought: ‘I think showing how rare and special our planet is only enhances the case for protecting it; as far as we know, Earth is the only planet in the universe that can sustain human life.’

Meet the researcher

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Dr Edward W. Schwieterman currently holds the position of Assistant Professor of Astrobiology in the Department of Earth and Planetary Sciences at the University of California, Riverside. He previously earned his PhD in Astronomy and Astrobiology at the University of Washington, before continuing his postdoctoral research at UC Riverside and the Georgia Institute of Technology. Dr Schwieterman's main research interests include observing Earth as an exoplanet and modelling the chemistry and spectral appearance of terrestrial planet atmospheres. His research includes exploring the nuances of planetary habitability and identifying and assessing remotely detectable biosignatures. Dr Schwieterman's work has contributed to the study and design of next generation space-based telescopes, such as NASA's Large UV/Optical/IR Surveyor (LUVOIR) and Habitable Exoplanet Observatory (HabEx) mission concepts and improvements to computational models of atmospheric chemistry. In addition to his research, Dr Schwieterman aims to inspire and train the next generation of planetary scientists and astrobiologists through a range of courses, workshops, and presentations.

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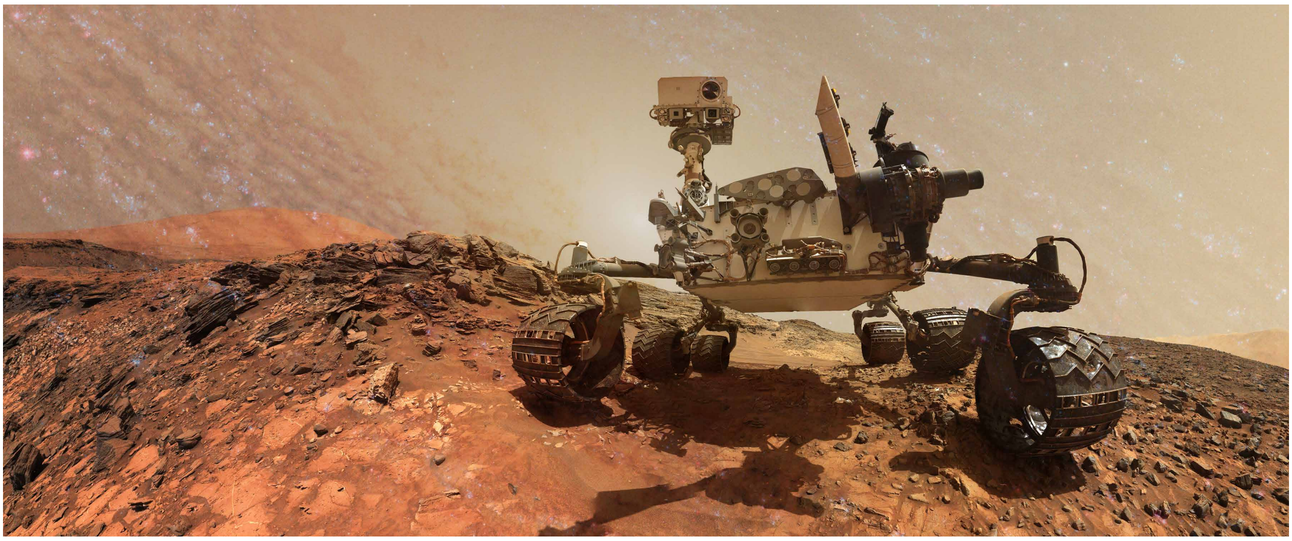
WHY SPACE EXPLORATION NEEDS SCIENCE COMMUNICATION

Article written by Sam Jarman



For many a space enthusiast, the week leading up to July 14th, 2015 is hard to forget. Over the course of a few days, measurements gathered by NASA's *New Horizons* probe gradually transformed our best view of Pluto to date from an off-white blur, into crystal clear images with resolvable features as football pitches. It was a clear demonstration that we, as humans, are capable of exploring the furthest reaches of the Solar System; a concept which, in itself, might seem like enough to capture the public imagination. Personally, I don't think this is true.

Before missions like *New Horizons* can ever achieve such success, they must first face a daunting array of challenges. Alongside the seamless integration of many different branches of astronomy, physics, engineering, and computer science, space exploration requires decades of hard-fought negotiations for funding, expansive collaborations between worldwide institutions, and countless hours of work from some of the world's brightest minds. Inevitably, such Herculean efforts come with hefty price tags, which are often funded by taxpayers.

Added to this, space exploration doesn't appear to have any immediately obvious applications to our minds or bodies, or to the technologies that influence our everyday lives. This sets it apart from many other fields of research that are widely reported in the media, whose direct applications are the very ways in which they garner support from research communities and the public. Without the advantage of such immediate benefits, it could potentially become incredibly difficult for researchers to justify the immense costs associated with exploring the Solar System.

In reality, the benefits that space exploration offers to the wider world are immeasurable. Its findings feed into other branches of research, from human physiology to materials physics – many of which have far more tangible influences on our everyday lives. In addition, space exploration has a long history of significantly improving opportunities for women and minorities in research – perhaps no better symbolised than through NASA's recent decision to name its Washington DC headquarters after its first black female engineer, Mary W. Jackson.

More existentially, the desire to learn more about our universe is hard-baked into our evolution. Perhaps through the same innate drive that pushed our distant ancestors to question whether the berries over the next hill are tastier, we strive to push the boundaries of our knowledge of the Solar System ever further, in a quintessential expression of what it means to be human. In the long term, the discoveries we make now may one day lead us to inhabit worlds beyond Earth: potentially securing our long-term survival as a species.

If the findings of space exploration were kept within the confines of the scientific community and away from the public eye, researchers would not only risk letting all of these fundamentally important aspects fall by the wayside; they would also endanger the field as a

whole. Yet we only need to look back at the many decades of success enjoyed by space exploration to see that this clearly hasn't happened. So how has our exploration of the Solar System continued to thrive for all this time?

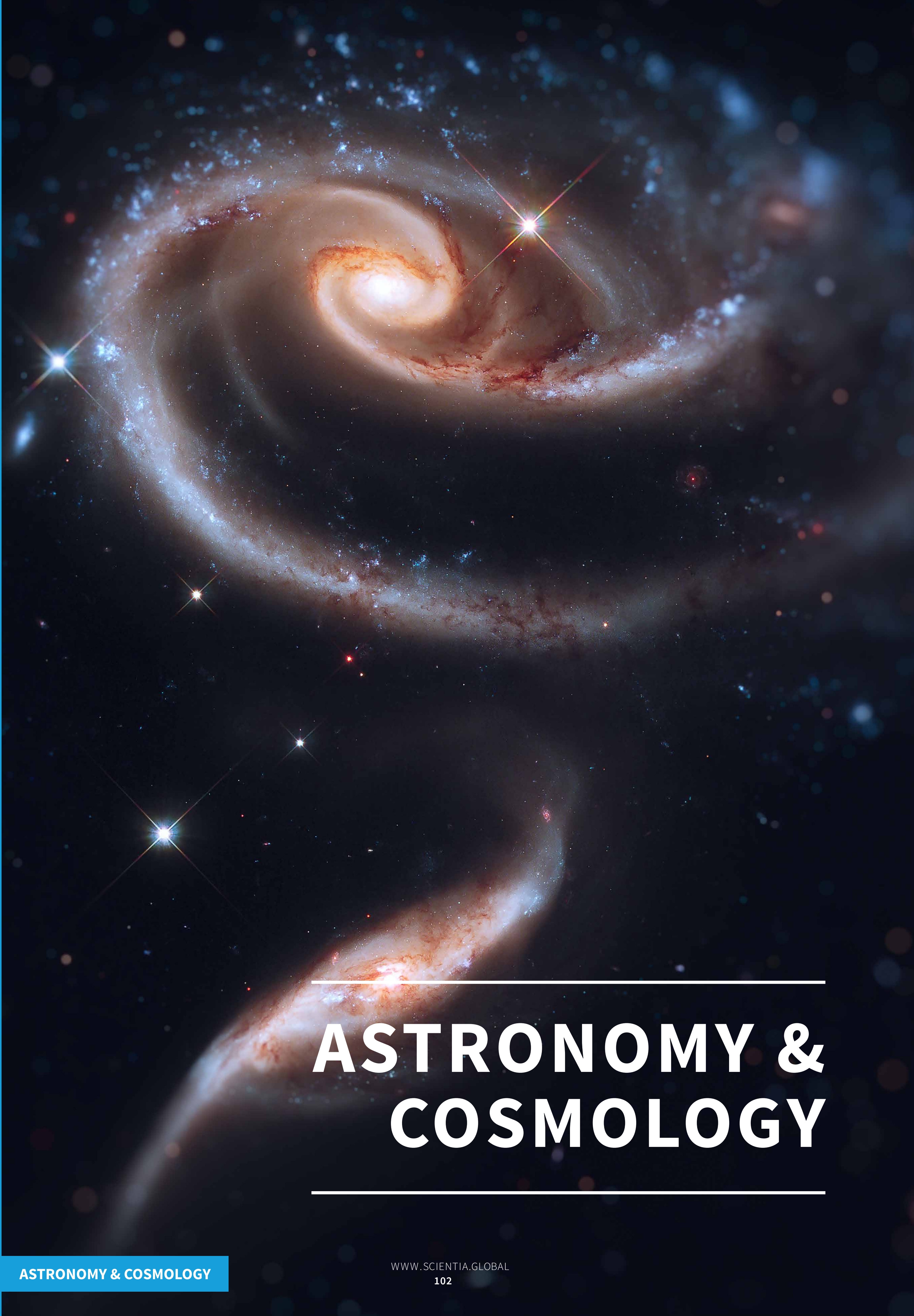
Without taking any credit away from the many researchers who have dedicated much of their lives to their important work, I think that the efforts of scientists and the media to communicate the findings of space exploration to the public have been one of the most important routes to its success. Over many years of both manned and unmanned missions, from the landing of Apollo 11, to the launch of Mars 2020's Perseverance rover, science communication has remained a centrally important aspect of many missions to date.

Since the newspaper articles and TV reports which covered the Apollo missions, space exploration programs have come a long way in their science communication efforts. From livestreams featuring interviews with researchers, which allow viewers to pitch in with their own questions; to Twitter accounts that give the rovers *Curiosity* and *Perseverance* their own personalities, many researchers are now engaging a wide scope of public audiences as part of their core efforts. Missions including *New Horizons* have even incorporated high-resolution optical telescopes which are not critical to their science goals, but can capture beautiful images that make for world-class public engagement.

Science communication has also taken significant strides outside the official efforts of space missions themselves. Through access to press releases and online journals, and the ability to easily interact with researchers, journalists from a wide range of publications are now able to engage a large sector of the public through a diverse range of different ways, including the in-depth articles you can read in Scientia.

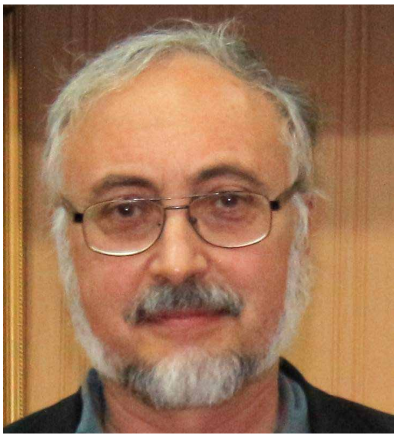
The results of these numerous communication efforts now mean that the wider public is not only highly engaged with space exploration; they are also largely supportive of its efforts – even though its immediate findings do not appear immediately relevant to our everyday lives. This unwavering support is critical in ensuring that researchers around the world can secure the funding they need to continue their important efforts, without running up against unnecessary barriers. Such a resounding success has been made possible because science communication has become a deeply ingrained aspect of many current space missions, thanks to decades of innovative efforts from scientists and the media alike.

In the coming years, space exploration is now promising to become ever more advanced, and will be sure to present scientific and technical challenges more vexing than any we have faced before. However, as long as the research efforts they involve are carried out in close step with efforts to communicate their findings to the public, we can ensure that our exploration of the Solar System will continue to thrive well into the future.



ASTRONOMY & COSMOLOGY

THE AFRICAN ASTRONOMICAL SOCIETY



Launched in 2019, the African Astronomical Society (AfAS) is a diverse and inclusive Pan-African society of professional and amateur astronomers, which aims to create a globally competitive astronomy community in Africa. The mission of AfAS is to be the voice of astronomy on the continent and to address the challenges faced by Africa through the promotion and advancement of astronomy. In this exclusive interview, we speak with the Society's president, **Dr Jamal Mimouni**, who discusses astronomical achievements in Africa and how AfAS supports and advances astronomy research and education across the entire continent.

Please start by sharing some inspiring examples of recent astronomical achievements in Africa.

Very good. Let me dwell on three examples. The first one will lead us to Senegal where a team of some 30 young Senegalese, some with physics backgrounds and others from the amateur community, are undertaking regular occultation campaigns with help from NASA. One project they are working on is the Arrokoth campaign to find a suitable Kuiper belt object for the New Horizons spacecraft to fly by.

On the night of September 23, 2020, they were able to successfully observe the occultation of the Polymel asteroid of an 11th magnitude star, which lasted less than two seconds. This should help the LUCY probe mission to the Trojan asteroids, which will be flown over six of them, including Polymel, in 2027. This is a success story in the sense that it helps train young science students, paving the way for professional careers in astronomy or space science, as well as producing science of direct use.

My second example will bring us to Morocco in North Africa, where the Oukaimeden Observatory is situated near Marrakech. In synergy with researchers at the Department of Astronomy at Cadi Ayyad University, this observatory is producing great science as well as training local students to become professional astronomers. There is a dynamic and ambitious program of installing optical facilities enticing various international partners thanks to the pure sky of the High Atlas Mountains where this high-perched observatory is situated.

The Oukaimeden Observatory distinguished itself by participating in the discovery of the 'seven sisters' planetary system of the TRAPPIST-1 star in 2016 – seven rocky planets resembling our Earth and situated a stone's throw away (well, 40 light years, which is a trifle of a distance compared to the huge expanse of space), and offering a glimpse to the stupendous variety of planetary systems that probably fill our Galaxy.

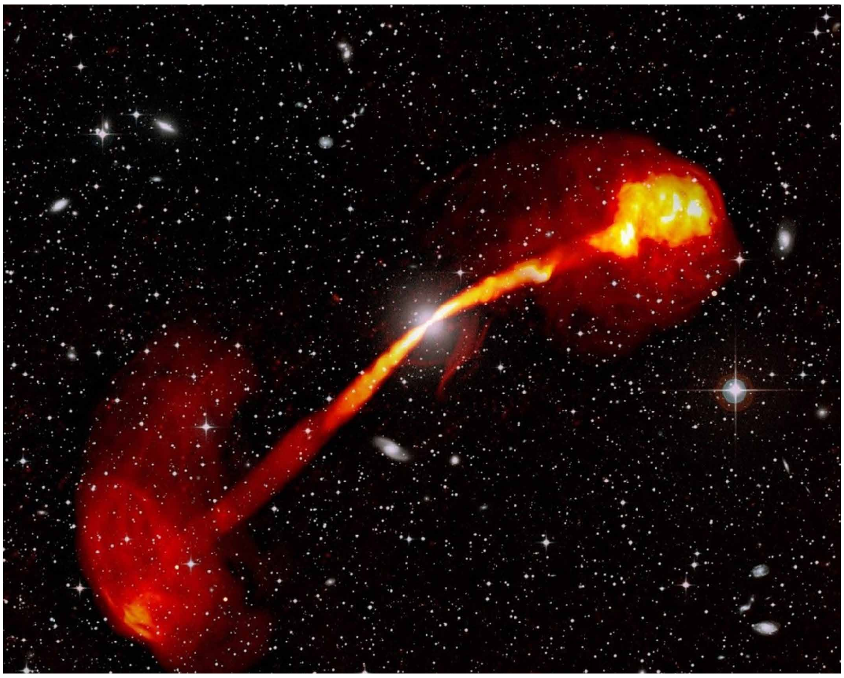
Finally, I shouldn't leave the list of examples without mentioning South Africa, which is a heavyweight actor on the astronomical world scene. There lies a superb optical facility on the Sutherland plateau dominated by SALT, the largest optical telescope in the world, and the future Square Kilometer Array (SKA) – a multi-billion-dollar international project which South Africa was selected to be home

Thirty young Senegalese were trained in manipulating telescopes and doing observations in preparation of the campaign.

The Oukaimeden Observatory near Marrakech.

for. In the meantime, the MeerKAT telescope array in the Karoo desert and a precursor of the SKA, is delivering world-class science. One can admire from a recently released picture of unmatched resolution, the intricate details of powerful radio emissions from an enormous rotating black hole in the elliptical galaxy IC 4296. It displays a combination of cosmic features never

'The key objective of AfAS is to cultivate and encourage collaboration among countries in Africa as well as collaborations between Africa and the rest of the world in scientific, educational, and outreach astronomical activities.'



Jets from the black hole in IC4296 jets as seen from the MeerKAT radiotelescope in South Africa.

seen before, providing a window into the inner mechanisms within giant radio galaxies.

What is your own area of expertise, and why did you pursue a career in this field?

Well, it all started from a real passion for the sky, and in particular the science of the stars. I have been fascinated from a tender age by those little dots in the sky even before I knew how to write any equation. But the physics of stars, the burning nuclear phases going on within them, and their prodigious diversity, which can be related to their colour and spectrum, captivated me.

Later, I started as a student in theoretical physics in Algeria, graduating with a BSc in 1977 from Algiers University. I then focused on particle physics when doing my PhD at the University of Pennsylvania, and finally turned to astroparticle physics and cosmology in my professional life.

For the past two decades, I have also been very involved in setting up the basis of astrophysics in my country, as the head of Astrophysics Studies in the physics department of my university – the first and only such program in Algeria. I am also involved with the National Aurès Observatory project, which will be the first such astronomy facility in Algeria since the independence of my country.

But I have also devoted an increasing amount of effort and time to the connection of science and society, and in particular the cultural dimension of scientific debate in the Arab-Muslim world. I have developed a keen interest in the philosophy of contemporary science, as well as spreading scientific culture in the developing world. As such, I have been involved in public debates and have lectured to various audiences all over the world.

On the 'ground', I have acted for decades as an adviser and resource person to amateur astronomy associations in Algeria, as I am also the founder and head of the well-known Sirius Astronomy Association. My peregrinations throughout Africa for lecturing and outreach made me well-known enough that the African astronomical community has thought of electing me as the first President of AfAS in March 2019.

Congratulations on being elected as the first President of AfAS. Please explain how this wonderful Society facilitates collaboration between astronomy professionals both within Africa and beyond.

The key objective of AfAS is to cultivate and encourage collaboration among countries in Africa as well as collaborations between Africa and the rest of the world in scientific, educational, and outreach astronomical activities. AfAS is also dedicated to making every attempt to support collaboration, rather than competition, with other relevant initiatives on the continent by bringing together complementary resources, networks, and expertise.

AfAS itself also has agreements with other organisations, such as the International Astronomical Union Office for Astronomy for Development with which we have recently signed a Memorandum of Understanding, which is aimed primarily at strengthening development through astronomy throughout the African continent. We are also working towards various flagship projects that aim to create networks for optical and radio astronomy, outreach and education, as well as High-Performance Computing.

Our annual conference attracts hundreds of participants from across Africa and different parts of the world and promotes discussions on collaboration so that the community can be better organised for astronomy research, education, outreach, and development on the continent. AfAS also organises various workshops, webinars, and special sessions at other

A group picture of delegates from all over Africa and the diaspora, at the launch of AfAS in Cape Town in 2019.

meetings and conferences throughout the year to develop relationships with our community and strategic partners from relevant organisations.

In what other ways does AfAS aim to advance astronomy research?

AfAS has developed a Science Strategy that aims to create an interlinked and world-class African astronomy community that contributes to the advancement of human knowledge. Through this, we hope to advance astronomy through the development of strategies, facilitation of interdisciplinary collaborations, encouragement of cross-border engagements, and stimulation of human capital development.

We have recently embarked on a project to create a science portal to develop and disseminate open-source resources that will benefit astronomy. This will also involve databases of astronomy expertise, active research areas, infrastructures across Africa and African diaspora. We are also conducting a survey of astronomy on the continent to help us identify 'focus areas' of research groups in Africa and resources available (and required) in different locations. This will play a role in encouraging African countries to have appropriately aligned strategies.

AfAS is committed to increasing the number of African astronomers, as well as the number of astronomers working in Africa. Therefore, we aim to advance astronomy research and secure its future by investing in early-career research through our Seed Research Grant, which supports research projects in astronomy (including Astrophysics and Space Science) conducted by postgraduate students and early-career researchers based in Africa.

Our future goal is to be further involved in infrastructure support, such as the development of intelligent telescope networks, High-Performance Computing for astronomy and interdisciplinary research, site testing of optical telescopes, radio astronomy and dish conversion, the African Very Large Baseline Interferometer Network, the African Millimetre Telescope and the Event Horizon Telescope.

How does the Society plan to improve STEM education in schools across the continent?

AfAS has established Outreach and Education committees with a philosophy to be at the service of the astronomy community in Africa and to encourage the appreciation of the significance of astronomy for society, with a particular focus on the future generation.

We want to use astronomy to inspire young people to pursue STEM studies and careers. We are already doing this by setting up programs and undertaking well-targeted actions in this area. Our goal is to increase science and astronomy literacy across Africa and enhance the presence of astronomy by creating and curating reliable and accessible resource material on astronomy for the general public, school students, and teachers.

We will also work to facilitate partnerships with national institutions to help establish astronomy research programmes in more tertiary institutions in Africa and develop materials for schools and the public, which use astronomy to promote careers in STEM.

Tell us about some of your other public outreach efforts.

The Outreach Committee is the key element in the actions undertaken by AfAS to promote astronomy and spread astronomical knowledge, even though it is primarily a professional astronomy association.

Such outreach enables the public to see the inner-workings of scientific research and the grandiose cosmic picture it brings, while also challenging irrational thinking, which is an impediment to social development. We are working to

‘We want to use astronomy to inspire young people to pursue STEM studies and careers.’

establish and coordinate a network of astronomy outreach professionals across Africa, building on what is already in place. We already have a number of working groups that focus on various key areas of interest. Each of these groups has a definite focus, with members with expertise as well as passion in those areas. These groups will provide valuable service to the community and will be expanded as needed.

For example, the Affordable Mobile Planetaria group is tasked with developing, testing and authenticating various prototypes for affordable mobile planetaria that are suitable for amateur astronomy associations, schools and colleges, and science organisations at a fraction of the cost of what is available on the shelf from commercial companies.

The Amateur Radio Telescopes group aims to develop a suite of radio telescope designs appropriate for amateur astronomers, schools and universities, facilitate a network of interested partners, and develop a program for construction and usage of these telescopes. This work is motivated by the presence of the Square Kilometre Array (SKA) megaproject in Africa.

Currently, we are also looking at more emphasised promotion of astronomy in countries where its presence is minimal. We also support the continuing and exemplary work of amateur astronomy associations, and assist the formation new associations, with an emphasis again on regions where astronomy is not yet well developed.

Finally, tell us a bit about the African Network of Women in Astronomy (AfNWA), and its role in increasing female participation in the astronomy community.

AfNWA is a bold initiative aimed at connecting women working in astronomy and related fields in Africa. It was established in September 2020 as one of the committees under AfAS. Its aim is to empower women in sciences, especially in astronomy-related research areas.

Indeed, according to the latest report of the UNESCO, the number of female researchers in astronomy is on average less than 30%. With AfNWA we would like to guarantee future participation of girls and women at all levels in astronomy and science developments in Africa. Our main objectives are improving the status of women in science in Africa, and using astronomy to inspire more girls to pursue STEM careers.

www.africanastronomicalsociety.org

AfAS
African Astronomical Society

THE CROC PROJECT: UNDERSTANDING REIONISATION IN THE EARLY UNIVERSE

Hundreds of millions of years after the Big Bang, charged, 'ionised' particles not seen since the earliest ages of the universe began to re-emerge. Named 'reionisation', this event was crucially important in the history of our universe – but because it occurred so far back in the past, telescope observations can only offer astronomers limited clues about how it unfolded. In his research, **Dr Nick Gnedin** at the Fermi National Accelerator Laboratory uses advanced computer simulations to study reionisation. His team's project, named 'Cosmic Reionization On Computers', or CROC, now offers a key resource to researchers studying this distant period.

From the Big Bang to Reionisation

In the earliest years following the Big Bang, temperatures throughout the universe were so hot that protons and electrons could only exist 'apart from each other' in a dense, opaque plasma – continually scattering off one another whenever they met. After around 400,000 years since the Big Bang, conditions became cool enough for these particles to combine into neutral hydrogen atoms, in an event which cosmologists now call 'recombination'.

For another 500 million years afterwards, almost all matter in the universe existed in this form. Since hydrogen atoms only emit light extremely rarely, the universe was almost entirely devoid of light at this time, and entered a period named the 'dark ages'. However, this situation would not last.

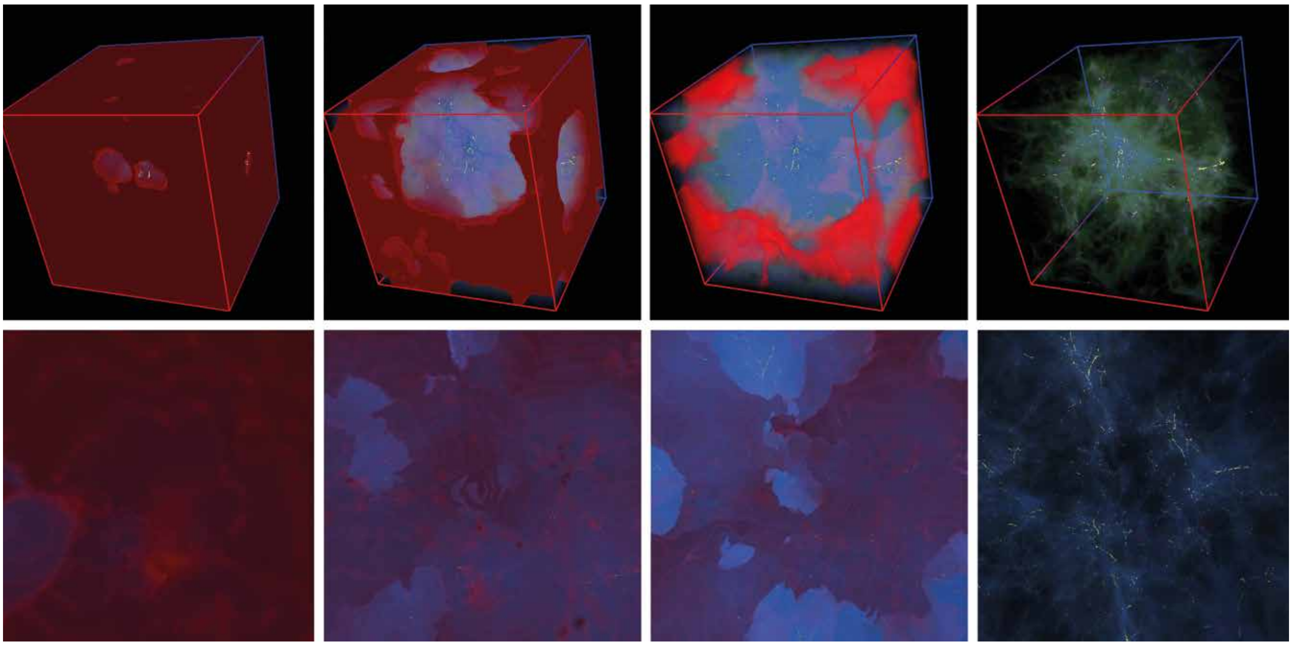
Under their mutual gravitational attraction, hydrogen atoms eventually clustered together to form dense clouds: structures that would eventually become the first stars and galaxies. As these newly-formed bodies radiated energy in the form of photons, hydrogen atoms were again stripped of their electrons, forming ionised plasmas once again. This period was named 'reionisation', and was a crucial turning point in the history of the universe.

Even today, however, cosmologists don't fully understand how the event unfolded. Since the earliest galaxies lie many billions of lightyears away from us, even the most advanced telescopes available today cannot study them in sufficient detail to answer many pressing questions.

Discrediting Theories of Backreaction

At the onset of reionisation, the most immediate effect was for ionised gas to be expelled from newly formed galaxies. In the year 2000, a new theory emerged which proposed that this expulsion must have fundamentally altered the course of star formation across the universe.

This theory of 'backreaction' gained traction over the following years, but wasn't without controversy. Among its opponents were cosmologists who argued that the influence of gas expulsion couldn't have been strong enough to alter star formation in such a significant way. Without any way to acquire telescope images with suitably high resolutions to capture such early star formation, the debate came to a standstill.



Stills from animations showing volume rendering of neutral hydrogen density (opaque fog), dense ionised hydrogen (blue), plus galaxies (yellow dots)

In a 2014 study, Dr Nick Gnedin and his colleagues at the Fermi National Accelerator Laboratory took a new approach: putting the theory to the test using the newly designed 'Cosmic Reionization On Computers' (CROC) project. Instead of relying on observations, their technique recreated the conditions of the early universe entirely virtually.

'The project included simulations on Mira supercomputer at Argonne National Lab and on Blue Waters at the National Centre for Supercomputing Applications,' Dr Gnedin describes. 'The total scale of the project was one of the largest computational projects in astrophysics, and remains the most accurate and realistic simulations of cosmic reionisation to date.'

With such advanced capabilities, Dr Gnedin's team could use CROC to resolve the long-standing debate over the validity of back-reaction. Their simulations showed that galaxies with gas content that could be affected by photon-induced ionisation contained little star-forming gas in the first place. As a result, reionisation must have had little effect on early star formation within galaxies.

Already, the team had clearly demonstrated the capabilities of their techniques in testing the viability of cosmological theories – yet the advances made through the CROC project were only just beginning.

Outside-in or Inside-out?

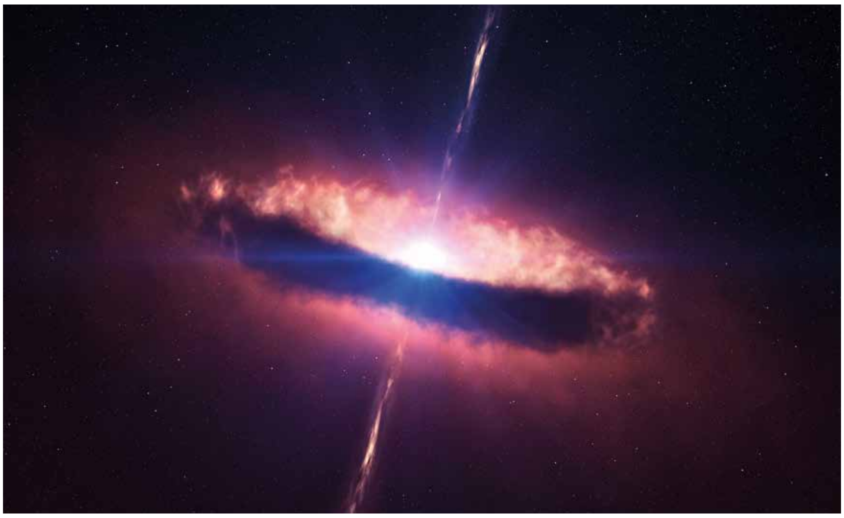
Alongside backreaction, another long-standing debate also emerged in the early 2000s: this time stemming from an uncertainty as to whether reionisation first occurred in regions of high or low density in the early universe. One model argued that since lower density gases contain fewer atoms, fewer photons would have been required to ionise them. Hence, reionisation must have occurred first in these regions.

This idea was called the 'outside-in' theory: since it predicted that denser gases elsewhere in the universe must have been ionised later. In contrast, the 'inside-out' model argued that reionisation must have taken place the other way around. Since light-emitting stars and galaxies must lie in high-density regions, the gas surrounding them must have been ionised first – before the lower density material outside.

Without any possibility of observational proof, any debate between the proponents of both models eventually came to a standstill. That was until 2016, when Dr Gnedin and his colleagues provided a breakthrough. 'For over 10 years there was no consensus among astrophysicists studying reionisation which of the two models is more relevant to reality,' he recounts. 'CROC simulations were instrumental in resolving the dilemma: with high density gas around galaxies and quasars indeed being ionised first, and the low-density gas second.'

Resolving the Debate

At first glance, this conclusion may appear to validate the inside-out model over the outside-in. However, the full picture is more complex: at the time of reionisation, hydrogen atoms had had little time to gravitationally accumulate, meaning that fully-formed galaxies were exceedingly rare. Instead, gas was often sculpted into long, thin filaments, which were not quite dense enough to collapse into galaxies. CROCS simulations have now shown how these filaments created a third type of gas with an intermediate density, which ionised after both high- and low-density gases.



'Our main conclusion was that both models are mostly right, and also a bit wrong,' explains Dr Gnedin. 'They are right in describing a particular stage of reionisation: it starts as inside-out and ends as outside-in. Yet neither of them describes the full process, which can only be captured in complex simulations on the largest existing supercomputers.' In uniting the mathematics of both theories, CROCS simulations again led to an answer that could not be provided by direct observations – representing a crucial step forward in astronomers' understanding of the early universe.

Looking into Quasars

Some particularly interesting clues about the nature of reionisation can be gleaned from structures named quasars. These extremely bright galactic cores emit vast amounts of radiation across the electromagnetic spectrum: directing it out along the rotation axes of the supermassive black holes at their centres. If this radiation happens to point towards Earth, astronomers can use it to learn more about the space between us and its origin, by measuring the wavelengths of light that have not been absorbed during its voyage. In this case, Dr Gnedin and his colleagues discovered that this non-absorption of light from quasars must be due to galaxies that cross our line of sight.

Previously, telescope observations have shown that the more distant the quasar, the more of its radiation must be absorbed by the cosmic gas filling the space. 'The phenomenon is related to reionisation,' explains Dr Gnedin. 'The further we look into space, the further we look back in time: and hence, the most distant quasars probe the time of reionisation. Because the universe was more opaque back then, more of the quasar light has been absorbed, and less is able to reach us.'

Yet this doesn't explain the full picture: in the sightlines of more distant quasars, astronomers can also observe regions far brighter than their surroundings, named 'transmission spikes'.

Identifying Transmission Spike Sources

In a 2019 study, Dr Gnedin's team used simulations from CROC to determine how the number of observed transmission spikes relates to quasar distances – enabling them to study the origins of these spikes in more detail. By accounting for the interplay between radiation, and the fluid motions of charged plasma, they discovered that these brighter regions are generated by the galactic neighbours of quasars. 'For the quasar light to pass through a highly opaque universe, it needs help of nearby galaxies to produce more ionising radiation,' Dr Gnedin explains. 'This over-ionises the gas around them, thus making that gas more transparent.'

As a result, the brightness of a transmission spike must relate to both the density of gas in these galaxies, and the fraction of their gas that can become ionised. Unfortunately, present-day telescopes don't have high enough resolutions to confirm this prediction through direct observations – but Dr Gnedin's team hopes that this will soon change. As astronomers hope to interpret potentially vast amounts of future data, the team's simulation results will likely be critical to understanding the physical processes involved.

Continuing with Better Telescopes

The next decade promises to be an exciting time for astronomers and cosmologists. As technological advances enable engineers to build near-perfect arrays of mirrors on far larger scales, reflecting telescopes both on land and in space will soon be able to collect far more light than their predecessors. This will enable them to produce images with unprecedented resolutions – helping researchers to gather images of far more distant structures than ever achieved previously.

'The next generation of optical telescopes – including the Giant Magellan telescope, the Thirty Meter telescope, the European Extremely Large Telescope, and the James Webb Space Telescope, will multiply the existing samples of distant galaxies 10 to 100-fold. That means there is going to be an immense amount of observational data just in a few years,' Dr Gnedin concludes.

By adapting CROC's simulation parameters to better match these observations, Dr Gnedin and his team will provide an invaluable resource for researchers aiming to verify and discredit certain theories about the nature of reionisation. Ultimately, these efforts will help astronomers and cosmologists to gain a better understanding of how the universe as we know it today came to be.

Meet the researcher

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Dr Nick Gnedin completed his PhD in Astrophysics at Princeton University in 1994. Following positions as a postdoctoral researcher at both MIT and the University of California, Berkeley, he joined the faculty at the University of Colorado, Boulder, in 1998. Since 2005, he has been a Senior Scientist at the Particle Physics Division of the Fermi National Accelerator Laboratory, while also working part-time at the University of Chicago, where he teaches astronomy. Dr Gnedin's research interests lie in high-performance computing for studying the formation of cosmic structures, as well as the nature of dark matter and dark energy.

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FUNDING

DOE, Innovative and Novel Computational Impact on Theory and Experiment
(INCITE) program

NASA, Astrophysics Theory Program (ATP)
NSF, Extragalactic Astronomy and Cosmology program NSF, Petascale Computing Resource Allocations (PRAC) program

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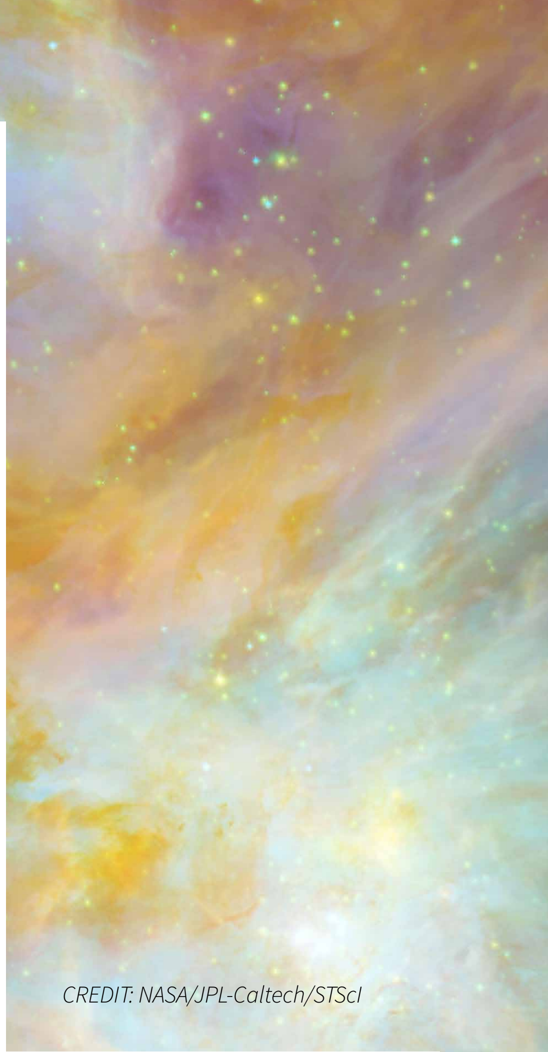
THE SPITZER SPACE TELESCOPE: EXPLORING THE INFRARED UNIVERSE

From 2003 until 2020, NASA's Spitzer Space Telescope provided an unprecedented view of our universe in infrared. One of the most important instruments aboard the telescope was the Infrared Array Camera (IRAC), which was designed and operated by a team led by Dr Giovanni Fazio at the Center for Astrophysics | Harvard & Smithsonian. Across its 16-year run, the camera gave crucial insights into processes ranging from galaxy formation in the ancient universe, to emissions from supermassive black holes. The discoveries enabled by **Dr Fazio** and his colleagues could soon be instrumental in aiding observations from even more advanced telescopes.



CREDIT: NASA/JPL-Caltech/STScI

Infrared Radiation

Every part of the electromagnetic spectrum – from radio waves to visible light to x-rays – can tell astronomers something different about our universe. However, perhaps the most interesting part to study is the infrared range.

Lying next to the visible part of the spectrum, infrared waves have longer wavelengths than red light. Although they cannot be seen with human eyes, they can often be observed using optical telescopes. However, infrared radiation also contains an abundance of information that cannot be gathered through visible observations alone.

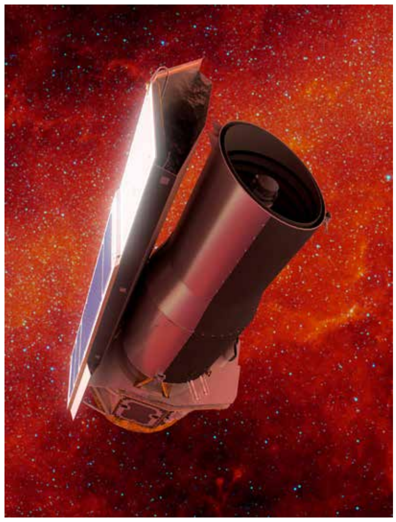
All the same, infrared observations face a major challenge: as the waves pass through Earth's atmosphere, they are strongly absorbed by water vapour, making them incredibly difficult to observe from the ground. Fortunately, there is one clear solution to this problem.

Launching the Spitzer Space Telescope

In 2003, NASA's Spitzer Space Telescope was launched from Cape Canaveral in Florida, and sent into orbit around the Sun – trailing slightly behind the Earth but gradually drifting away from it. From this prime position, the telescope could easily study infrared radiation originating from sources many billions of lightyears away, completely free from the influence of Earth's atmosphere.

In addition, the spacecraft was equipped with a supply of ultracold helium. Since the detector itself would normally produce its own infrared radiation due to its heat, it would typically introduce noise to its own observations. However, when cooled to −271°C by the helium, Spitzer became well suited to studying wavelengths across the infrared range.

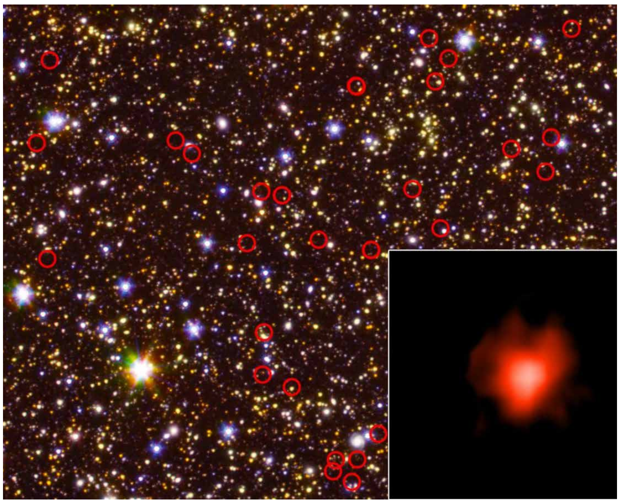
Dubbed 'NASA's Great Observatory for Infrared Astronomy', the Spitzer Space Telescope was principally designed to investigate four major topics: the early universe, giant planets and brown dwarfs, the planet-forming debris disks surrounding newly-formed stars, and the extremely bright regions found at the centres of some galaxies.



The Spitzer Space Telescope. CREDIT: NASA/JPL-Caltech.

To do this, the telescope was fitted with three cutting-edge instruments. The most important of these was an arrangement of four array detectors

Infrared image of the Helix Nebula taken by NASA's Spitzer Space Telescope. CREDIT: NASA/JPL-Caltech.



Deep-field view of the sky dominated by galaxies. Very faint, distant galaxies are circled in red. CREDIT: NASA/JPL-Caltech/ESA/Spitzer/P. Oesch/S. De Barros/I.Labbe.

named the Infrared Array Camera (IRAC), whose design and operation had been spearheaded by Dr Giovanni Fazio of the Center for Astrophysics | Harvard & Smithsonian since 1984.

The Infrared Array Camera

At the time of its launch, the IRAC represented a significant leap forward in the capabilities of space-based infrared detectors – boasting high sensitivity, a large field of view, and the ability to produce images in four different infrared wavelengths simultaneously.

For five years after its launch, the instrument operated just as well as Dr Fazio and his colleagues had hoped, with high quality images being produced across the infrared spectrum. As expected, the Spitzer had used up its supply of helium by 2009, and lost its ability to observe longer infrared wavelengths as the spacecraft warmed up.

Fortunately, this didn't stop the IRAC from picking up shorter infrared wavelengths, closer to the visible range. As a result, the detector could continue operating in full capacity in two of its four wavelength bands until 2020, until Spitzer finally retired after a 16-year run.

Over that time, the IRAC captured striking infrared images of a wide variety of astronomical structures, and led to several important discoveries about their formation and evolution. Dr Fazio was involved in two particularly important branches of this research: exploring the formation and evolution of galaxies in the early universe, and the characteristic emissions from material found at the centre of our own galaxy.

Observing Ancient Galaxies

For much of its first few hundreds of millions of years, the universe was a largely dark, uneventful place, full of hydrogen atoms in their neutral, unionised form. Yet as matter was drawn together under its own gravity, it eventually came to form stars. The intense radiation from these stars stripped the electrons from neutral hydrogen atoms to form hydrogen ions, initiating a new era called 'reionisation'. Around this time, matter was also coalescing on larger scales to form the first galaxies.

Because of the limited speed of light, the wavelengths emitted by the most distant galaxies we can observe began their journeys many billions of years ago, just as the reionisation era was getting underway. As a result, they can provide astronomers with a clear window into this long-distant period in the history of the universe.

Prior to Spitzer, there was much debate among astronomers as to how early on in the reionisation era that galaxy formation first began. Through infrared observations made by the IRAC, as well as visible and ultraviolet observations from the Hubble Space Telescope, significant strides have been made towards solving this intriguing mystery.

Rethinking Reionisation

In a study published in 2016, measurements taken by both Spitzer and Hubble were used to investigate a galaxy named GN-z11. Positioned more than 13 billion lightyears away from us, this galaxy is one of the oldest known to astronomers – forming around 400 million years after the Big Bang.

Previously, calculations had predicted that reionisation in the early universe must have peaked roughly 550 million years after the Big Bang. Intriguingly, however, these new observations from the IRAC and Hubble showed that GN-z11 had a similar brightness to galaxies observed around the time of this peak, despite being 150 million years older.

Infrared image of the core of the Milky Way taken by NASA's Spitzer Space Telescope. CREDIT: NASA/JPL-Caltech.

This result suggested that the build-up of galaxies could have been well underway shortly after the beginning of reionisation – far earlier in the universe's history than many astronomers previously thought. If correct, this would suggest the need for a fundamental re-think of how stars and galaxies first formed.

Ultimately, Dr Fazio and his colleagues hope that the IRAC's observations will now fuel future interest in this mystery. Today, new generations of upcoming space telescopes have built on the capabilities of their predecessors, and could soon lead to discoveries of large numbers of similarly ancient galaxies – potentially transforming our understanding of how they formed and evolved.

Analysing Sagittarius A*

While most black holes form as massive stars collapse in dramatic supernova explosions, the supermassive black holes found in the centres of many galaxies are far larger still – reaching billions of times the mass of our Sun. At the centre of our own Milky Way galaxy, around 27,000 lightyears away, lies the supermassive black hole Sagittarius A*. Typically, any material surrounding such an enormous body will possess vast amounts of energy, causing it to glow brightly. Unusually, however, Sagittarius A* is extremely dim – emitting roughly 100 million times less radiation than its maximum possible limit.

With a high density of nearby stars creating a bright background to the black hole, astronomers have long seen Sagittarius A* as a compelling and challenging target for observation. In a 2014 study, Dr Fazio's team used IRAC measurements to study a disk of gas orbiting and falling into the black hole. Such material caused Sagittarius A* to fluctuate in brightness at infrared wavelengths at a rate of about four times in 24 hours. These continuous observations were about twice as long as the fluctuations measured in any previous infrared observations, opening up new possibilities for future studies.

Variability Across the Spectrum

Infrared is far from the only type of radiation emitted by material falling into supermassive black holes. In addition, waves from across the electromagnetic spectrum can be found – from radio waves to x-rays. Building on their observations of the gas cloud orbiting Sagittarius A*, Dr Fazio's team combined Spitzer's data with x-ray measurements taken by several other space telescopes to explore the variability of different wavelengths in more depth. In their 2021 study – one of the last to use data gathered by the IRAC – the researchers discovered that x-rays flares emitted by the black hole on short timescales were less variable than its infrared wavelengths.

After analysing the results with advanced mathematical models, the researchers concluded that this difference arose because the processes responsible for infrared and x-ray wavelengths are intrinsically linked. As fluctuating infrared wavelengths interact with electrons within the infalling material, scattering effects related to quantum mechanics will produce distinctive fluctuating x-rays, after a certain time delay.

This discovery was an important step forward in our understanding of the enigmatic conditions surrounding the heaviest single bodies in the universe. However, Dr Fazio and his colleagues hope that the many lines of research initiated by the IRAC's observations are only just beginning.

Informing Future Observations

Throughout its lengthy and highly productive lifetime, the IRAC has led astronomers to draw highly advanced insights into primordial galaxies, supermassive black holes, and a variety of other areas. Now, these researchers are eagerly hoping to continue exploring the infrared universe through a successor to Spitzer: the James Webb Space Telescope, which is scheduled for launch in late-2021.

Encompassing many of the latest advances in technology, the telescope will allow them to characterise the physical properties of these features far more easily. By building on the discoveries of Dr Fazio and his team, their efforts could finally answer some of the most pressing questions about the nature of our universe.

Meet the researcher

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Dr Fazio completed his PhD in Physics at the Massachusetts Institute of Technology (MIT) in 1959. He then moved to the Smithsonian Astrophysical Observatory and the Harvard College Observatory in 1962, and went on to initiate programs including the large balloon-borne telescopes for infrared astronomical observations in the 1970s. Along with his central involvement in the first infrared telescope to fly aboard the Space Shuttle, he also became Principal Investigator for the Infrared Array Camera aboard the Spitzer Space Telescope in 1984, which was launched in 2003, and operated until 2020. Following a highly successful career spanning more than sixty years, Dr Fazio is now a Senior Physicist at the Center for Astrophysics | Harvard & Smithsonian, where his main research interests include development of infrared instrumentation, and observations including ancient galaxies, black holes, and star formation through the use of infrared array cameras.

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IRAC INFRARED ARRAY CAMERA SPITZER SPACE TELESCOPE

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

SIMULATING FLOWS BETWEEN CLUSTERED GALAXIES

The spaces in between galaxies may be unimaginably vast, but within galactic clusters, they are far from empty. Rather, these expanses are home to a wide range of interplaying, often violent plasma dynamics. In his research, **Dr Tom Jones** at the University of Minnesota plans to use cutting-edge computer techniques to simulate these processes – shedding new light on physical properties that have eluded astronomers so far. His team's research will not only give crucial insights into some of the largest structures in the known universe, but will also capture the public imagination, and inspire a diverse new generation of astronomers.

CREDIT: NASA, ESA, STScI, HFF team

Galaxy Clusters

The sheer sizes of galaxies are far too vast for our minds to grasp. Our Milky Way alone contains hundreds of billions of stars, and spans 185,000 lightyears in diameter. However, even galaxies are not the largest known structures in the universe.

Around 10 billion years ago, several billion years after they first formed, large groups of galaxies began to cluster together – pulled in to each other by their mutual gravitational attraction. Today, these colossal structures can contain between hundreds and thousands of galaxies. Our own galaxy, for example, forms a small part of the Virgo supercluster – one of roughly 10 million clusters scattered across the known universe.

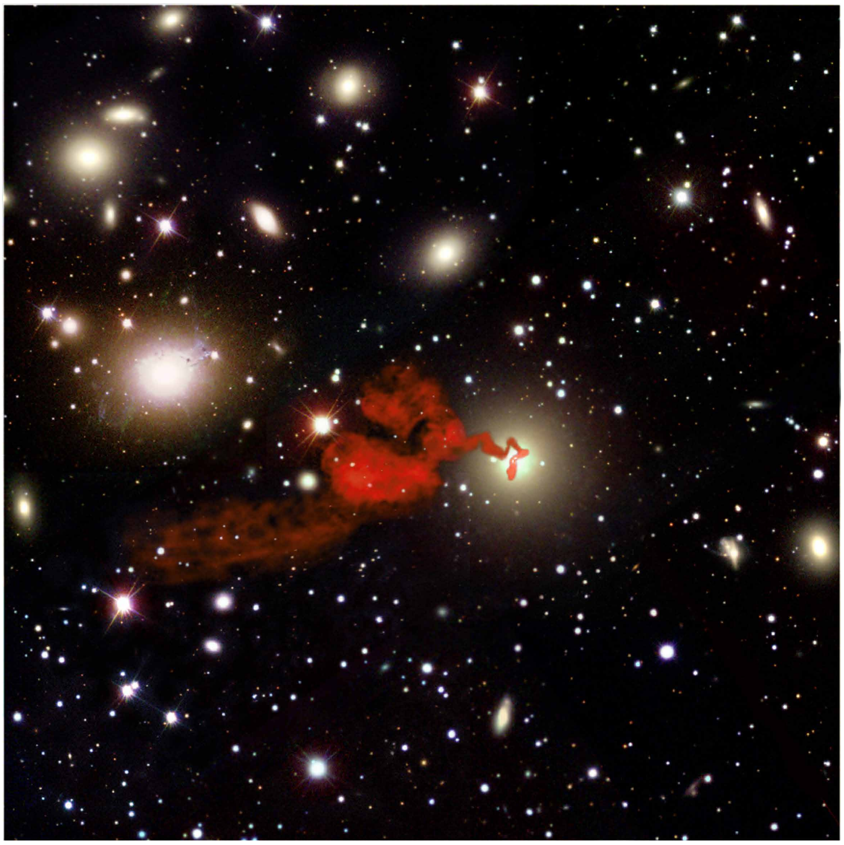
In the expansive regions between clustered galaxies, there exist stretches of superheated plasma named the 'intracluster medium' (ICM), which is heavily influenced by gravitational interactions between galaxies and broadly distributed but invisible 'dark matter', whose gravity is so-far, the only known link to other matter. As clusters form, vast amounts of energy are released into the ICM, forcing its plasma to flow in strange and often unpredictable ways. Dr Tom Jones at the University of Minnesota aims to study this diverse range of physical processes – though not by observing them directly, as most astronomers are used to.

Flows in the Intracluster Medium

Shockwaves are a well-known aspect of fluid dynamics. They are often observed on Earth in the form of pressurised air waves named sonic booms, which form as fast-moving aircraft break the sound barrier. We can also readily feel the effects of disorderly flows of fluid named turbulence – experienced when flying a plane through a storm, or rafting down a fast-moving river. On far larger scales, similar effects can arise in the ICM as surrounding galaxies jostle for space within their clusters.

Following decades of observations of the radiation emitted by ICM plasma, astronomers have discovered that shocks and turbulence can form across a vast range of scales within galactic clusters – producing an abundance of unusual shapes and structures. These include vast, stable jets emanating from the centres of galaxies, which mysteriously bend far out into intergalactic space; tails with distinctive ribs and tethers; and rings surrounding interacting spirals of diffuse material. Yet so far, researchers have met significant challenges in interpreting these observations.

CREDIT: NASA, ESA, Hubble



Optical image from the Sloan Digital Sky Survey of several galaxies in the Perseus Cluster overlaid with the image of the radio jets formed by the massive black hole in one of those galaxies (NGC 1272). These radio jets have been highly deformed as they propagated through the cluster. CREDIT: M.-L. Gendron-Marsolais (ESO), C. L. H. Hull (NAOJ), R. Perley (NRAO); NRAO/AUI/NSF; Sloan Digital Sky Survey.

A Tangle of Cross-talk

The complexity of the problem faced by astronomers stems from the secondary effects of plasma flows in the ICM. As they form, these motions generate both magnetic fields, and streams of high-energy protons, atomic nuclei and electrons, named cosmic rays, which each travel far out into space. In turn, both of these effects can influence the dynamics of other plasma flows in the ICM, altering the characteristics of their own magnetic fields and cosmic rays.

Ultimately, these interactions create an intricate web of cross-talk between different structures, which can be incredibly difficult for astronomers to disentangle using their observations alone. This has created a number of difficult questions regarding the formation and evolution of flows in the ICM, which researchers have mostly been unable to answer. So far, therefore, the processes that came to form the jets, tails, and spirals of the ICM have largely remained a mystery.

Setting Out Key Questions

In their proposal, Dr Jones and his colleagues have distilled the problems surrounding ICM observations into three key questions. Firstly, how can astronomers find and trace the structures produced by shocks and turbulence in the ICM, and physically interpret their observations? Secondly, how can they establish the origins of these flows and their secondary effects, and determine how they are connected to each other? And finally, how can they pin down the physical processes that define the interplays between these flows? Finding answers to each of these questions in turn will prove crucial to understanding the underlying physics of galaxy clusters.

Since astronomers ultimately have no control over what they discover as they scan the sky, relying on observations alone is not always the best way to answer these sorts of questions. Instead, Dr Jones and his team have set out an innovative and wide-reaching proposal for a theoretical research program. Their approach will be based on a cutting-edge, high-performance computer simulation toolkit named WENO-WOMBAT: the culmination of years of previous research by Dr Jones and his colleagues. Through their simulations, they will carry out three complementary efforts to answer each of their initial questions.

Capturing Cluster Evolution

WENO-WOMBAT is capable of simulating two particularly important and challenging aspects of the ICM. One of these is 'magnetohydrodynamics' – which studies the continually changing magnetic fields generated by electrically conducting fluids, including plasma such as the ICM. In addition, the toolkit can recreate the transport of cosmic rays through intergalactic space.

Dr Jones predicts that using the new WENO-WOMBAT toolkit, these simulated effects will successfully capture for the first time the secondary effects of flows in the ICM. Moreover, the high resolution of the toolkit will simulate flow dynamics on scales of less than 1,000 lightyears – around the diameter of a single galaxy – and also the scales on which key ICM properties, such as electric conductivity are established. This will enable the team to account realistically for the motions of each galaxy in a large cluster, as they pull each other through the ICM by mutual gravitational attraction.

In the first of their proposed complementary efforts, the researchers will use these advanced capabilities to simulate the evolution of the occasionally-violent encounters between ICM flows, and radio galaxies embedded in the ICM. These galaxies contain supermassive black holes in

CREDIT: NASA, STScI, CXC, M.Markevitch et al, Magellan, U.Arizona, D.Clowe et al, ESO

CREDIT: NASA, ESA, MJ Jee and H Ford

their centres, which emit vast quantities of radio waves from each of their poles – perpendicular to the galaxy's flat disc. As the techniques and apparatus used by radio astronomers have improved, such galaxies are now being discovered at a growing rate. By better accounting for the energy that they transfer into the ICM, astronomers will be far more well-equipped to determine how different flow structures arise.

Establishing Links

In their second, complementary, proposed effort, Dr Jones and his colleagues will model the physics of 'synchrotron' radiation, which is created when extremely fast-moving electrons are accelerated in spiral paths as they pass through magnetic fields. Since this radiation doesn't depend on the temperature of its source, as is the case for most radiation, it is a powerful probe of intergalactic magnetic fields where plasma is present. Therefore, the researchers hope that the results of their simulations will allow them to determine how strongly this radiation is linked to cosmic ray emissions, as well as dynamics in the ICM.

In their third and final effort, the team will carry out universe-scale magnetohydrodynamics simulations, with the aim of reliably capturing the formation of the ICM structures being studied and their magnetic fields in selected galaxy clusters. This will enable them to better relate the structures observed by astronomers to the dynamical states of individual clusters. It could even allow them to turn back the clock on their evolution, to predict how clusters may have appeared at different stages of the universe's history. Together, the researchers hope that each of these efforts will lead to crucial new insights into several long-standing mysteries surrounding the formation and evolution of galaxy clusters. However, they are just one of two key pillars of the team's proposal.

Commitment to Public Engagement

Beyond their immense value to astronomers, the simulations produced by WENO-WOMBAT will also be visually striking – creating a unique opportunity for the team to engage the public with cutting-edge research in astronomy. Previously, Dr Jones was part of the team behind the citizen science project Radio Galaxy Zoo, through which the public could look through the images gathered by radio telescopes to identify new galaxies. Extending this role, he will now aim to communicate his team's research with the help of the University of Minnesota's Planetarium, and the Bell Museum of Natural History.

Dr Jones and his colleagues hope that a series of live shows at the Planetarium will offer the public a captivating view of the simulations, providing an innovative new way for them to learn about their findings. Combined with further efforts, including public talks and social media outreach, this proposal will give the public unprecedented access to knowledge, and fresh insights into how theoretical physicists carry out their work.

Academic and Public Benefits

As well as public engagement, Dr Jones and his team are also committed to involving graduate and undergraduate students from a diverse range of backgrounds – including groups that are currently under-represented in astronomy research.

Ultimately, their proposal combines public and academic efforts to create opportunities for a new generation of aspiring astronomers, with ground-breaking theoretical techniques that will fill in the gaps left by as-yet unexplained observations. Their plans represent a model approach to how science can be best carried out in the landscape of modern research.

Meet the researcher

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Dr Tom Jones completed his PhD in Physics at the University of Minnesota in 1972. After graduation, he worked as a scientist at University of California, San Diego, followed by the National Radio Astronomy Observatory in West Virginia. In 1978, he returned to the University of Minnesota, where he became a Professor at the School of Physics and Astronomy. His research interests lie in theoretical and computational astrophysics, which involve the study of phenomena including cosmic rays, supernova remnants, active galactic nuclei, and galaxy clusters. In his most recent research, Dr Jones has focused on using numerical simulations to understand how magnetic structures affect flows of plasma and cosmic rays. These efforts have led significant new developments in computer codes for astrophysical simulations.

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FURTHER READING

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