Scientia

NEW HORIZONS IN EARTH SCIENCE AND ASTRONOMY

HIGHLIGHTS:

- Ocean Surface Holds the Key to Understanding Our Climate
- Alfvén Waves: When Earth's Shield Comes under Attack
- Icy Discoveries on Our Innermost Planet
- A Family Affair: Exploring Early Star Formation

EXCLUSIVES:

- The Royal Astronomical Society
- The SETI Institute

Issue: #130

WELCOME...

In these challenging and uncertain times, it is with great pleasure that I introduce this captivating edition of Scientia, which showcases a diverse collection of research, on topics ranging from climate change mitigation to stellar evolution.

The first section of the edition focuses on our changing climate. In the same way that the coronavirus response must be based on sound scientific evidence, solutions to the climate emergency must be rooted in robust research, to ensure maximum success. Here, we celebrate research groups that have contributed to the strong body of scientific evidence on climate change, and those that are developing effective, science-based solutions to mitigate its disastrous effects.

Next, our planetary science section begins by introducing scientists who develop new ways to predict other dangers that we face on Earth – from the threat of anomalous solar activity to major earthquakes. We then venture deeper into the solar system, where researchers are gaining fascinating insights into how the planets evolved, and how their atmospheres can help us understand Earth's changing climate.

In the edition's final section, we explore the mind-blowing fields of astrophysics and cosmology. Here, we meet three research groups who are shedding light on how stars and galaxies form and evolve. Our final article touches on one of the biggest questions in cosmology: are we alone in the universe? In an exclusive interview, Mr Pérez Santiago at the SETI Institute describes his new project, which aims to send music representing humanity into space; what a fantastic way to conclude this remarkable edition of Scientia.

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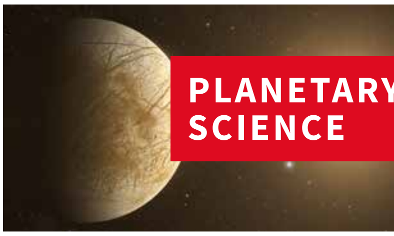

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CLIMATE CHANGE

BATTING CLIMATE CHANGE WITH THE SAME URGENCY AS COVID-19

The COVID-19 pandemic has demonstrated that the global community can effectively work together to tackle a crisis, with governments, corporations and individuals all making dramatic changes to slow the spread of the virus, to save as many lives as possible. As climate change has the potential to wreak even greater devastation within our society, countries must now respond to the climate emergency with similar urgency and on the same scale.

Although two very different challenges, climate change and COVID-19 do not respect national borders, meaning that both emergencies require countries to collaborate intensively to find solutions. The response to each crisis must also be based on the best evidence that science can provide, taking all interrelated factors into account, to ensure the greatest chance of success.

The pandemic is an utter tragedy, but its aftermath will provide governments with a rare opportunity to transform society into one based on clean energy, sustainable development and ecological restoration, to mitigate the impending climate catastrophe. To guarantee maximum effectiveness, such transformations must be based entirely on sound scientific evidence.

In this section of the edition, we celebrate some of the research groups that have been building this strong body of evidence on climate change and its impacts, and those that have developed scientific solutions to undoing the damage already present. Their research, along with that of the thousands of climate scientists across the globe, must now be used to inform plans for global recovery in a post-COVID world.

In the first article of this section, we meet Dr Gabriel Wolken of the University of Alaska Fairbanks and the Alaska Division of Geological & Geophysical Surveys, who has harnessed citizen science to collect data on snowfields in Alaska. As rising global temperatures are altering snowfall and melting patterns, such critical data will enable scientists to understand the broad effects of these changes in mountainous areas, potentially allowing us to mitigate damaging impacts on people and wildlife.

Our next article introduces Dr Meghan Cronin from NOAA Pacific Marine Environmental Laboratory, and Dr Chelle Gentemann from Earth and Space Research in Seattle. Alongside their collaborators, these leading scientists devised a plan for improving weather and climate forecasts through better observations of the heat exchange between the ocean and atmosphere. Such improved predictions of hurricanes, cyclones and extended heavy rainfall are critical for effectively mitigating risk to vulnerable populations.

Also working to improve our ability to predict severe weather events is the Global Satellite Mapping for Precipitation (GSMaP) project, founded by Dr Takuji Kubota at the Japanese Aerospace Exploration Agency (JAXA) and his collaborators, who we meet in the next article. Through a combination of satellite observations and advanced algorithms, the project is now providing highly-resolved data on rainfall across the globe. Such information helps both governments and local communities to make critically important decisions about how best to mitigate the worst effects of extreme rainfall.

In addition to increasing the occurrence of severe rainfall in certain parts of the world, climate change is also making some areas drier, making these regions far more prone to water shortages. Combining computer modelling with satellite data, Professor Leila Farhadi and her team at the George Washington University have created a novel approach to mapping two critical components of Earth's water cycle: evapotranspiration from the landscape and recharge to aquifers. As we show in this section, their work has implications for predicting and responding to water shortages, towards ensuring global water and food security.

Continuing on the theme of satellite monitoring, our next article showcases the capabilities of the TEMPO instrument, built by Ball Aerospace to Smithsonian Astrophysical Observatory specifications and managed by the NASA Langley Research Center. Once launched, this satellite-based spectrometer will provide a wealth of data on pollution and climate variables across North America. As part of a global constellation of satellite air quality missions, TEMPO will soon provide us with the most extensive view of pollution ever achieved, along with its impacts, allowing us to tackle it more effectively than ever before.

Next, we introduce Dr Steven Running and his team at the University of Montana, who have been investigating satellite data from the past few decades to obtain a complete picture of 'net primary productivity' – the amount of carbon dioxide that plants take in during photosynthesis, minus the amount released during respiration. As carbon dioxide is the primary driver of global climate change, having a full understanding of this process is now critical.

Whereas Dr Running focuses on terrestrial plants, our next featured scientist, Dr Michael Behrenfeld at Oregon State University, studies microscopic ocean plants called phytoplankton. Although they only represent about 2% of the total mass of plants on Earth, phytoplankton perform around 50% of global photosynthesis, making them a critical component in the fight against climate change. Dr Behrenfeld and his team are now developing new satellite approaches to create a 3D map of global phytoplankton communities, which will revolutionise our understanding of how these organisms regulate Earth's climate. Their work is also showing how different types of phytoplankton respond to environmental changes, allowing them to potentially act as a climate indicator.

In addition to global heating and climate change, another consequence of rising carbon dioxide levels is ocean acidification, as seawater absorbs atmospheric carbon dioxide and transforms it into carbonic acid. At the Georgia Institute of Technology, Dr Jeannette Yen and her team propose a novel method for monitoring ocean acidification. Their approach, which we describe in the next article of this section, involves a miniscule marine snail, whose unique locomotive behaviour changes in response to rising acidity.

From here, we shift our attention to the devastating impacts of forest wildfires, which have been increasing in severity, frequency and extent due to climate change. Working at the forefront of this field is Dr Bianca Eskelson from the University of British Columbia, who we feature next. Alongside her colleagues at the United States Forest Service, Dr Eskelson utilises vast datasets and investigates conditions before and after wildfires, to quantify their immediate and long-term effects on forest ecosystems. The team's research will prove extremely useful in mitigating or even preventing future fires, as well as informing climate change predictions.

Our final three articles in this section discuss specific solutions to sequestering carbon dioxide from the atmosphere, thus helping to mitigate climate change. As atmospheric carbon is already at a dangerously high level, strategies solely based on reducing emissions will be inadequate in preventing further planetary warning.

First up is Dr Bernd Lennartz at the University of Rostock, who investigates how peatlands respond to changing climate conditions. As peatlands remove 0.37 billion tonnes of carbon dioxide from the atmosphere each year, and contain about 21% of global carbon, his team's research shows that their maintenance and restoration is vital in the fight against climate change.

Next, we explore how rewilding can be a highly effective approach to tackling both the climate and biodiversity emergencies. Here, we feature an opinion piece by the esteemed scientist and science communicator Dr Nathalie Pettorelli of the Zoological Society of London. Dr Pettorelli describes the differences between rewilding and traditional conservation approaches, and explains how well-planned rewilding projects could increase carbon capture and storage capabilities, boost biodiversity, and help protect communities at risk of flooding.

Continuing on the theme of carbon sequestration, our final article in this section takes a different approach. Here, we meet Dr Charles DeLisi of Boston University, who has demonstrated the potential power of genetically engineering plants to remove excess carbon dioxide from the atmosphere. Dr DeLisi's research demonstrates that a multifaceted plan employing many different strategies is necessary to avoid a worldwide climate disaster.

HARNESSING CITIZEN SCIENCE TO COLLECT A BLIZZARD OF DATA

Alongside his collaborators, **Dr Gabriel Wolken** of the University of Alaska Fairbanks and the Alaska Division of Geological & Geophysical Surveys has pioneered citizen science to collect data on snowfields in the largest state of the USA. As rising global temperatures are altering snowfall and melting patterns, such critical data will enable scientists to understand the broad effects of these changes in mountainous areas, potentially allowing us to mitigate damaging impacts on people and wildlife.

Changing Snowscapes

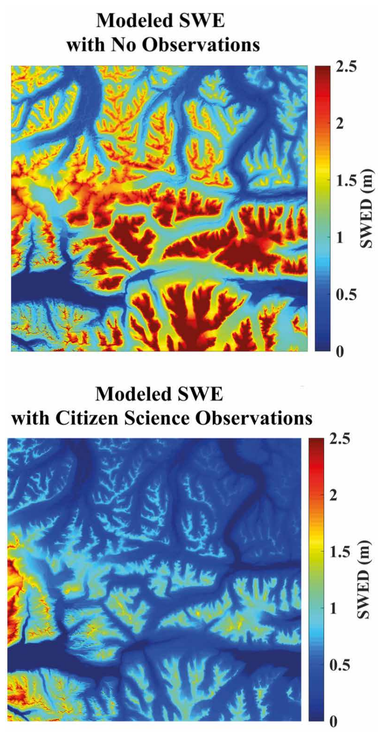
Few things are as beautiful as a towering mountain range, rugged slopes climbing to dizzying heights where snow-capped peaks nestle amongst wind-whipped clouds. Yet one of the key components of this image, snow, is increasingly under threat. Global temperatures are steadily rising due to our greenhouse gas emissions, playing havoc with the regular snowfalls and melting patterns of former times.

These disruptions are a serious concern, as snow is a vital part of the regional ecology in many parts of the world. Deposited in thick sheets during winter, snow gradually melts over the spring and summer and feeds the glaciers, rivers, streams and lakes of the surrounding area. Gradual melting supplements rainfall, providing a consistent source of water for local plants, animals, people, and the resources upon which people depend.

Rising global temperatures bring with them less snow cover, reduced snow depth, and shorter, warmer winters. This means less snow in the mountains and faster melting once spring begins, which leads to a rapid pulse of water careening down the streams and rivers instead of a consistent trickle. In some areas, this makes for long summer months without water – a dangerous situation for wildlife, farmers, fisheries and communities that depend on hydropower.

Despite its importance, understanding the melting process is a challenge for scientists. The melting process is based on a number of interacting variables that are difficult to model. Snow may be deeply packed in one area, exposed to harsh winds and reduced in another, or even hidden in a dark, cool crevasse and preserved in a third. In order to make accurate predictions, allowing policy makers to make effective decisions when it comes to mitigating the impacts of future warming, scientists need accurate data of the entire snowpack in a given region. Satellite imaging, radar returns and measuring differences in local gravity have been used to assess snowpack – all of these methods provide usable data, but each has its own limitations.

One of the most basic ways to measure snow depth is, well, to poke it with a stick and see how deep it is. This direct measurement of the snowpack provides very accurate data, free from the inferences that need to be made when interpreting satellite or fly-by data. However, there are only so many climate scientists, a lot of snow to be measured, and very few reliable roads to get around. 'Monitoring snow in the mountains is very difficult, because



CREDIT: Ryan Crumley

‘Submissions by citizen scientists have dramatically reduced snow distribution model error, which greatly improves our ability to estimate the amount of snow in the areas that are being modelled.’

CREDIT: Joe Klementovich

the amount of snow can change considerably over short distances, while the rough terrain makes access difficult,’ says Dr Gabriel Wolken of the University of Alaska Fairbanks and the Alaska Division of Geological & Geophysical Surveys.

To solve this problem, Dr Wolken and his colleagues turned to crowd-sourced observations and a team of citizen scientists, in a project known as Community Snow Observations, or CSO.

A Snow-Loving Crowd

Alaska is full of towering mountains, snowy fields, and pristine forests. All of these combine to make it a winter paradise, and many Alaskans spend the cold months cruising around on skis or snowmobiles, often venturing out into isolated back-country areas.

These enthusiasts represent a fantastic resource for time-strapped climate researchers – they travel long distances, reach very high elevations and are naturally quite interested in continuing their favourite hobby. This takes them directly into the areas of the snowfields where data is scarce. It is perhaps no surprise that Dr Wolken and his collaborators saw them as natural partners in their research, a body of ‘citizen scientists’ – those who may not have formal training in the field but who are interested in taking part in the research process.

The idea of recruiting local volunteers for this purpose came from an earlier set of measurements performed from an aeroplane. Dr Wolken had asked a number of back-country enthusiasts to cross-check the results they had obtained, and so many skiers and snowmobile drivers spent the day travelling in every direction, measuring snow depth and recording their location using GPS. ‘We ended up getting so many more measurements than we could with just a science team,’ says Dr Wolken. If this was possible in just one day, he and his colleagues reasoned, what could be done with a more permanent and holistic approach? To answer this question, Dr Wolken and his colleagues successfully applied for funding from NASA.

No method is perfect, of course, and citizen science research has some extra difficulties involved. The choice of routes taken and sample locations is naturally up to the volunteers themselves, which means that some locations may be poorly covered. There is also the challenge of training people to take accurate measurements – what seems easy in a YouTube video is a lot harder out on the freezing mountaintop.

To avoid these problems, Dr Wolken and his colleagues decided to develop a simple, rapid method for making observations, as part of their Community Snow Observations program. They focused on snow depth and set out to make the process of reporting data as easy as possible. This was achieved by partnering with the developers of Mountain Hub, a community-focused app which brings live updates from outdoor enthusiasts together into one central location. Available for free on both Apple and Android smartphones, this app provides maps of back-country areas and allows users to upload information about trail conditions. In collaboration with Dr Wolken, the Mountain Hub group included the ability for app users to provide snow depth information.

How does this work? Most back-country snow-goers carry an avalanche probe – a long, foldable pole which allows you find buried people in the loosely-packed snow following an avalanche. The volunteers take three measurements within a one-metre circle, calculate the average, and then enter this information into the Mountain Hub app. The app automatically includes their location and these data are sent in to a central server as soon as a wireless connection is established.

Drifting Back to Reality

This all sounds rather clever, but does it actually work? Yes, and quite well. Initial tests were performed using volunteer measurements from the Thomson Pass region near Valdez, Alaska. The pass is the snowiest area in Alaska, and a popular location for skiers, snowboarders, and back-country enthusiasts. Over the course of 2017, citizen scientists performed a number of depth measurements at widely-scattered locations across the snowfield. They then uploaded the data using the Mountain Hub app.

Dr Wolken and his colleagues then incorporated the snow depth data into a mathematical model to simulate the snowpack. This model uses climate data to create an estimate of the overall depth of snow and the 'snow water equivalence', which is essentially the amount of water you would get if all of the snow melted at once.

As Dr Wolken explains: 'The model performs very poorly in mountainous areas that lack well distributed, continuous observations from weather stations.' This is where the community observations came in useful. By using the collected snow depth values as 'anchor points', the team was able to merge the *calculated* depth values of the model and the actual measured values from the volunteers. This provided a reference point for the computer simulation, dramatically reducing the amount of error in the numbers it spits out. This allows the researchers to make far more accurate predictions about the behaviour of the snowfield than they could without the help of the volunteers.

'Essentially, when a new snow measurement is submitted, the difference between the model-predicted depth and the measured depth is used to steer the model back towards reality,' explains Dr Wolken. 'Submissions by citizen scientists have dramatically reduced snow distribution model error, which greatly improves our ability to estimate the amount of snow in the areas that are being modelled.'

The Future

For their next steps, the researchers hope to recruit even more citizen scientists into the measurement process. The number of new measurements each year is naturally dependent on the number and enthusiasm of the volunteers themselves. However, early signs are promising, as the researchers report that they now have thousands of measurements from across North America.

The Mountain Hub app is used by outdoor-lovers across the globe and so allows snow depths to be registered anywhere in the world. The community has taken up this challenge, and the researchers have reported hundreds of data points coming in from such far-flung locations as Kazakhstan, Iceland, Antarctica, Hawaii and Svalbard near the North Pole.

The next step is to improve the overall community outreach, in particular trying to show volunteers just how their measurements are being used. To do this, Dr Wolken and his colleagues have made their data available to anyone, free of charge. Beyond this, Dr Wolken and his colleagues intend to expand the incentives for the citizen scientists. Although helping the project is voluntary, few people complain when they receive extra recognition or a few goodies. Thus, the scientists have begun to recognise consistent helpers as 'ambassadors', as well as organising free giveaways of snow-related equipment.

The Community Snow Observations program has already shown its worth within just a few years of operating. The additional data gathered by the volunteers allows the researchers to more accurately model the snowpack and its eventual melting. Thanks to the efforts of Dr Wolken and his team, we now have the chance to understand how snow distribution might change with continued changes in climate, and the resulting impacts on hydrological systems, glaciers, ecosystems, and hazards such as avalanches.

Meet the researcher

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Dr Gabriel Wolken was awarded his PhD in Earth and Atmospheric Sciences from the University of Alberta in Canada. He currently holds a joint appointment as the manager of the Climate and Cryosphere Hazards Program at the Alaska Division of Geological & Geophysical Surveys, and a research professor with the Alaska Climate Adaptation Science Center at the University of Alaska Fairbanks. His work revolves around changes in snow and ice, particularly in the high mountains or polar latitudes. Over the course of his career, he has authored numerous papers, reports and data products, and is a regular invited contributor for governmental climate reports.

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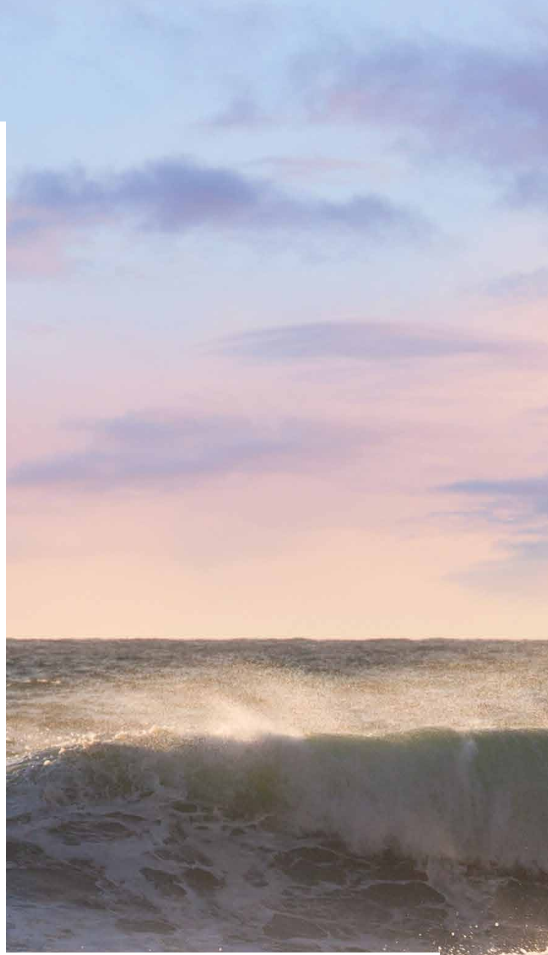
OCEAN SURFACE HOLDS THE KEY TO UNDERSTANDING OUR CLIMATE



Every 10 years, the ocean science community comes together to present a vision for advancing key scientific priorities to maximize societal benefit. In September 2019, leading ocean and climate scientists from around the world presented a plan for improving weather and climate forecasts through better observations of the heat exchange between the ocean and atmosphere. Such improved forecasts will be critical for effectively managing natural resources and mitigating risk to vulnerable populations.

Extreme Weather and Climate Change

Extreme weather events and dramatic shifts in Earth's climate pose a major threat to both human society and all life on Earth. From devastating hurricanes, El Niño, and increasingly frequent droughts and marine heatwaves, to changes in long-term climatic events, major shifts in both weather and climate are the new normal.

Extending the reliability of weather forecasting past two weeks and providing accurate seasonal predictions would allow farmers to protect their crops from drought and heatwaves and help governments limit the damage caused by extreme weather and plan humanitarian responses. The key for extending and improving these weather and climate forecasts lies in the ocean.

The Importance of the Ocean

The oceans influence weather and climate by heating (and cooling) the base of the atmosphere. Because over 70% of the Earth's surface is covered by oceans, and the oceans can store approximately 1000 times more heat than the atmosphere, the ocean acts as a battery for heat, storing energy from the Sun and subsequently releasing it back into the atmosphere.

This heat transfer between the ocean and the atmosphere (or 'heat flux') is fundamentally tied to the hydrological cycle: when the ocean is warmer than the air above it, the sea surface 'sweats', leaving the ocean cooler as moisture is evaporated from its surface. As the buoyant moist air then rises and forms cloud condensate, heat is released, making the air even more buoyant. In this way, ocean heating can form convective cloud systems, precipitation, and drive wind patterns that feed this vertical motion. Like a rock thrown into a pond, the towering clouds leave a wake in the atmosphere.

Shifts in these ocean heating patterns, such as during El Niño events in the equatorial Pacific, can thus affect weather patterns around the globe. Likewise, ocean heat and moisture fluxes are key for driving tropical cyclones and hurricanes, for feeding monsoons and atmospheric rivers, and for anchoring the Jet Streams' storm tracks. If the air-sea heat and moisture fluxes could be better quantified, monitored, and predicted, the ocean's influence on these types of weather and climate phenomena could be better represented in models, improving extended and seasonal forecasts.

Measuring Air-Sea Heat Exchange

Measuring these heat and moisture fluxes, however, is extremely difficult, requiring observations of over eight different essential ocean and climate variables, including: surface air and seawater temperature, surface winds and currents, surface humidity, solar and infrared radiation at the ocean surface, and precipitation. At present, satellite instruments are unable to resolve surface humidity and air temperature with the required accuracy. Likewise, there is only a limited number of platforms in the global oceans that can act as reference points for tuning and testing satellite and numerical model estimates of air-sea exchanges.

Addressing this shortfall is a worldwide team of experts on exchanges at the air-sea interface, led by Dr Meghan Cronin from NOAA Pacific Marine Environmental Laboratory in Seattle, Dr Chelle Gentemann from Earth and

NOAA Ship Reuben Lasker and Saildrone. Photo credit: NOAA Fisheries/Chris Hoefer

Space Research in Seattle, Dr James Edson from the Woods Hole Oceanographic Institution in Woods Hole, and Dr Iwao Ueki from the Japan Agency for Marine-Earth Science and Technology in Yokosuka, Japan.

Every 10 years, since 1999, the ocean community comes together to set recommendations to advance science within the next decade. The strategy papers are then peer-reviewed, ensuring that they represent a community consensus on decadal research directions and are based upon sound science. For OceanObs'19, these strategy papers were published in a special collection, published by the journal of Frontiers in Marine Science. Bringing together oceanographers and ocean information stakeholders from around the world, OceanObs'19, held 16-20 September 2019 in Honolulu, HI USA, was more than twice as large as OceanObs'09, which was more than twice as large as OceanObs'99.

A 10-Year Strategy

At the OceanObs'19 conference, Dr Cronin presented the air-sea flux team's 10-year roadmap for making breakthrough improvements in air-sea heat transfer estimates, as laid out in the team's strategy paper. The team's goal is to create the capability of mapping air-sea heat exchanges every three hours at a resolution of 25 kilometres over the global ice-free oceans with breakthrough accuracy. Their aspirational goal goes further, with proposed hourly maps at 10 kilometres resolution at this impressive level of accuracy. Currently, the target accuracy is only met at less than two dozen reference station moorings and a small number of research vessels that follow best practice, leaving the rest of the global ocean without the critical accuracy and coverage necessary to improve extended weather forecasts.

'We have two big asks,' says Dr Gentemann, 'one calling for improved satellite observations, and one calling for a complementary regionally distributed network of air-sea flux observations.' Together with their collaborators, the researchers suggest that these improvements could increase the accuracy of air-sea flux calculations by an order of magnitude.

Understanding and monitoring the exchange of energy between the atmosphere and ocean across different time and space scales is key to enhancing our knowledge and prediction of extreme weather and global climatic events. Achieving progress in this area requires drastic improvement in the reach and accuracy of air-sea exchange estimates, through an observation system that integrates satellite and in situ measurements, using numerical models.

New and Improved Satellite Observations

To date, there has not been a dedicated satellite mission for measuring ocean surface heat and moisture fluxes, so scientists struggle with two primary issues. First, current sensors were not designed to accurately measure surface air temperature and humidity measurements, and both of these measurements are needed to calculate surface heat and moisture fluxes. Second, scientists must combine data from several satellites that measure a given location at different times of the day, which is a problem because the conditions in many parts of the world can change rapidly.

The GPM Core Observatory satellite orbiting Earth.
CREDIT: NASA

The air-sea flux team's plan calls for new satellite-based measurements that are specifically designed to accurately measure, at the same time and place, air and seawater temperature, humidity, and surface winds. This would be a game-changer for understanding and monitoring, on a global and local basis, how rapidly changing surface fluxes of moisture and heat affect our weather and climate.

In Situ Surface Ocean Observations

Developing, tuning and validating this remote-sensing system requires a complementary in-situ flux observing system. The second recommendation, therefore, is to create a regionally distributed array of in-situ flux observing platforms throughout the global ice-free oceans. The researchers propose that this can be achieved using an array of semi-autonomous surface vehicles and other air-sea flux platforms. Surface drones are propelled by wind or waves, and have electronics powered by the Sun.

With 6–12-month endurance, they can cover thousands of nautical miles and be deployed to regions that have been difficult to send research vessels or deploy moored buoys. With 500 to 1000 platforms, the network could have 1–3 platforms in every 10x10 degree box in the global ocean. 'Because air-sea fluxes are often large in frontal regions, such as the Gulf Stream, in some regions it may make sense to have clusters of drones, rather than a random distribution,' says Dr Cronin. 'The drones could also be re-tasked, as needed, to sample weather events on the fly.'

The team also calls for an expansion of the already established OceanSITES network of deep ocean moored buoys. Acting as reference stations, at present, there are more than 60 institutions in 22 countries contributing to the network of surface and subsurface moorings. These long-term term reference station moorings, operating throughout the oceans, measure a suite of variables at the surface and through the full depth of the ocean, with advanced sensors, many in real time.

The team's 10-year plan calls for the expansion of the OceanSITES surface mooring network into key under-sampled regions of the global ocean. The order of magnitude increase in the number of drones, moorings, ships, and other recording platforms would provide accurate information, under all the varied regimes across the global ocean, to tune and validate satellite calculations of fluxes. In order to achieve the target temporal and spatial resolution, these remotely-sensed and in-situ observations would then be used to by Numerical Weather Prediction models. The team thus included plans for improving the air-sea coupling and marine boundary layer physics in models; algorithm and model development that will depend crucially upon the new in-situ flux observations.

Future Weather and Climate Predictions

It is expected that the improved models, constrained by more accurate remotely sensed moisture and air temperature profiles and complementary in situ observations, would have more true representation of cloud formation processes. This would in turn lead to improved surface estimates of solar and infrared radiation, and air-sea heat fluxes – the mechanism by which the ocean influences the atmosphere.

Measuring air-sea fluxes accurately is a challenge, requiring both high temporal and spatial resolution and a high level of accuracy for a full suite of surface oceanic and meteorological variables. The team's call for international co-operation, collaboration and standardisation of best practices for measurement of air-sea fluxes, will dramatically improve the accuracy of data collected and thus the accuracy of long-term weather forecasts and climate predictions in both the short-term (subseasonal-seasonal) and the long-term (years, decades, and beyond).

With improved knowledge of air-sea fluxes, the ocean's influence on the atmosphere will be better quantified, allowing society to mitigate against the impact of extreme weather events and climatic shifts. This is critically important to all aspects of life on Earth, allowing us to better manage resources as well as supply chains for food, water and energy. A more complete picture of seasonal and interannual weather variation and better climate forecasting will allow us to anticipate and respond appropriately, protecting habitats and ecosystems, and reducing risks to vulnerable people around the world.

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FURTHER READING

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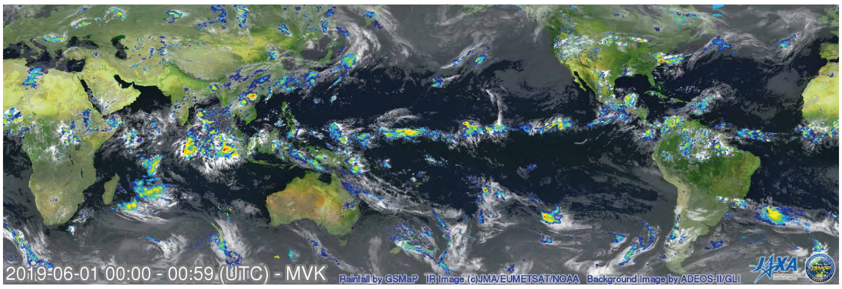
GSMAP: MONITORING RAINFALL FROM SPACE TO PROTECT COMMUNITIES

Of all the Earth's natural processes, rainfall is perhaps the one that has the most significant influence on our everyday lives. Yet as the climate changes, patterns in rainfall are becoming increasingly unpredictable, meaning it is now more critical than ever to monitor precipitation from space. The Global Satellite Mapping for Precipitation (GSMaP) project, founded by researchers from institutions across Japan, is doing just that. Through a combination of orbiting satellites and advanced algorithms, the project is now providing the global region with highly-resolved data on rainfall.



Changing Weather Patterns

Over previous decades, meteorological observations have made it clear that global climate change is having an increasingly severe impact on the weather – raising the frequency of extreme events including droughts and flooding. The effect has already been felt particularly strongly in the Asia-Pacific region, where almost two million people have been killed in weather-related disasters between 1970 and 2011, comprising 75% of all casualties globally. To monitor how weather patterns are changing, and to gain knowledge of how to mitigate their worst effects, it is becoming increasingly important to precisely monitor patterns in rainfall from space.

'Satellite observation is a unique and effective tool to cover a large area in a short time,' says Dr Takuji Kubota, a researcher at the Japanese Aerospace Exploration Agency (JAXA). 'Its advantage is obvious when it observes geophysical parameters that vary both temporally and horizontally, like rainfall.'

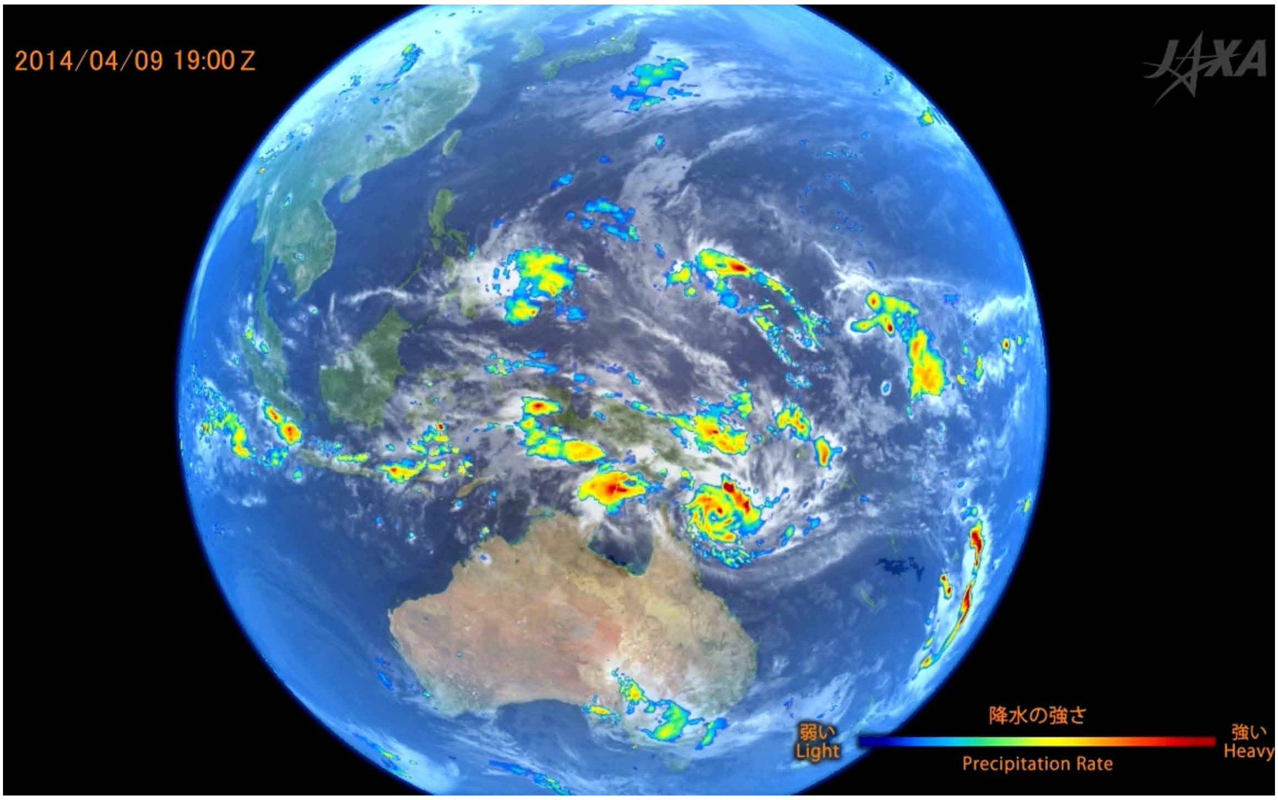
Because weather events are typically highly sporadic, satellites are far better at monitoring them than ground-based techniques. 'Without satellite observations, it is difficult to gain distribution of rainfall over the whole globe,' Dr Kubota continues. 'Rainfall observations by rain gauges and ground rain radars only cover small areas of the global Earth's surface, since regions over land areas where people don't live, and oceans are difficult to access.' Now, Dr Kubota and a group of researchers from institutions across Japan are finding solutions to these issues, as part of the Global Precipitation Measurement (GPM) mission.

Designing an Effective Monitoring System

The first task of the GPM team was to design a satellite-based system that could accurately monitor patterns in rainfall on scales of continents. Clearly, this would be a tall order, but through their research, Dr Kubota and his colleagues found that their aims could be achieved by combining data from passive microwave sensors in low-Earth orbit, with the data gathered by infrared radiometers in geostationary orbit. In collaboration with JAXA, the National Aeronautics and Space Administration (NASA), and international agencies, the GPM researchers then developed specialised algorithms that can combine the data from these satellites, to produce a near-real-time map of rainfall.

As Dr Kubota explains, the end result of this research has been hugely successful so far. 'The Global Satellite Mapping for Precipitation (GSMaP), developed by JAXA as part of the GPM product, provides high-resolution and high-frequency global rainfall maps based on multi-satellite passive microwave radiometer observations,' he says. GSMaP began its real-time precipitation monitoring in 2007 as 'JAXA Global

‘Since its data release, GSMaP data has been used by various users for various purposes, such as rainfall monitoring, flood alert and warning, drought monitoring, crop yield forecast, and agricultural insurance’



Rainfall distribution by GSMaP (colour) at 19:00 on 9th April, 2014. CREDIT: JAXA

Rainfall Watch’ (https://sharaku.eorc.jaxa.jp/GSMaP/index.htm), clearly demonstrating a greatly improved precipitation monitoring system compared with earlier techniques. By accessing the JAXA’s home page, GSMaP data will provide critical insights into significant rainfall-related disasters to strike all over the world, including the Asia-Pacific region.

GSMaP in South-East Asia

A few years ago, in November and December of 2014, Thailand and Malaysia were hit with extremely high levels of rainfall, causing widespread flooding, and increasing the risk of landslides. As a region that remains hot and humid all year round, South-East Asia typically experiences heavy monsoons each year, but with climate change, the risk of dangerously high levels of rainfall is now increasing.

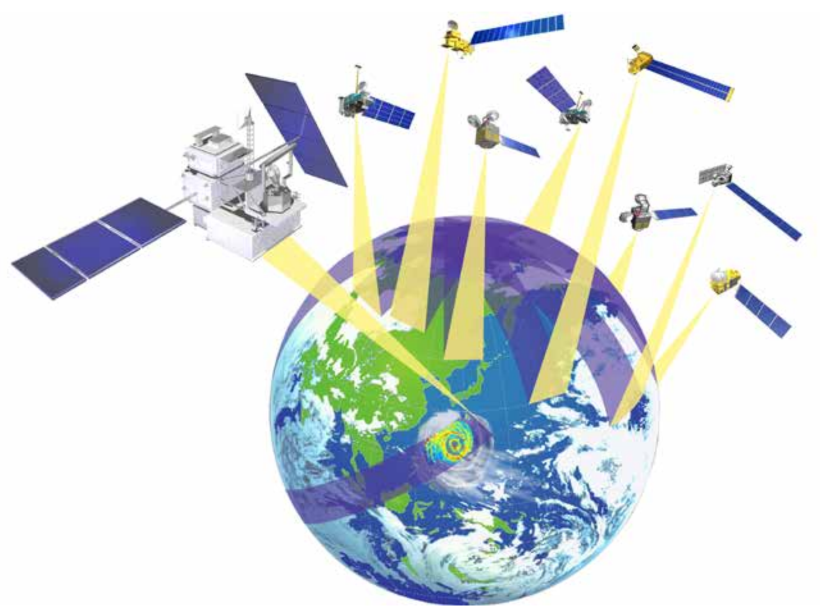
GSMaP data allowed researchers to pinpoint exactly when and where rainfall was strongest during the event. The assessment provided both governments and local communities with information that helped them to make critically important decisions about how best to focus their efforts to mitigate the worst effects of the extreme rainfall. Again, the researchers demonstrated how valuable space-based precipitation measurements can be.

In fact, the Meteorological, Climatological, and Geophysical Agency (BMKG) in Indonesia obtains GSMaP data and displays it as an image. GSMaP data are also used for the analysis of hourly and daily rainfall accumulation to verify weather forecasts, as well as meteorological hazard analysis. To support operational weather forecasts and warnings, GSMaP-derived products have been extended for other purposes, such as drought and forest fire potential monitoring.

The Hydro-Informatics Institute (HII) in Thailand developed methods to use the GSMaP data in their flood forecasting system and rainfall monitoring system. GSMaP data are used as input variables for the flood forecasting system to simulate more realistic runoff. HII’s rainfall monitoring information is used by stakeholders and water related agencies; it has been posted on their website since January 2017.

Launching GPM’s Core Satellite

Although the data gathered by GSMaP had already proved to be incredibly useful, the GPM researchers aimed for even higher degrees of precision in their data. This would only be achievable by sending an additional specialised satellite into space. In 2014, JAXA and NASA sent the GPM core satellite with two instruments into orbit – one to passively monitor microwave signals, and the other equipped with a dual



A concept of the Global Precipitation Measurement (GPM) mission: A GPM core satellite and constellation satellites. CREDIT: JAXA

frequency precipitation radar. The core spacecraft serves as a calibration standard for the other members of the GPM constellation, which would study precipitation in the global region in unprecedented levels of detail.

Using information derived from the GPM core satellite, Dr Kubota and his colleagues updated GSMaP's algorithms to allow for more accurate real-time images with spatial resolutions of 0.1 degrees in both latitude and longitude, and with temporal resolutions of just 1 hour. With these improvements, GSMaP was now able to measure quantities including hourly precipitation, and the percentage of rainy days throughout the year, for the global region as a whole. Such sophisticated capabilities have meant that GSMaP can now provide researchers with critical information about a diverse array of potential hazards caused by extreme rainfall.

Diverse New Measurement Capabilities

GSMaP now provides people from 122 countries with precipitation information that is crucial to protecting their lives and livelihoods. 'Since its data release, GSMaP data has been used by various users for various purposes, such as rainfall monitoring, flood alert and warning, drought monitoring, crop yield forecast, and agricultural insurance,' Dr Kubota describes. As well as general rainfall and drought monitoring, these capabilities can be divided into several broader themes.

Firstly, GSMaP applications can provide information about hydrology – a field that encompasses flood forecasting, analysis and risk management. In addition, they can predict landslide risks created by model predictions and send out early warning messages. Secondly, GSMaP can monitor numerous risks to agriculture, by measuring quantities including drought index, in particular patches of farmland – all of which can be used to determine the growing outlook for particular crops.

Finally, the data can be used to assess risks to public health, through the spread of tropical diseases including malaria and dengue fever. Since rainfall can have direct effects on the breeding of mosquitos and other parasites, GSMaP has helped researchers to predict how likely these diseases are to infect particular localised communities.

This broad set of measurement capabilities is now providing the global region, and the many diverse populations it represents, with the highly-resolved precipitation satellite data.

Critical Information for Communities

Having demonstrated the diverse capabilities of their satellite system, the GSMaP team has now joined forces with several other weather monitoring organisations. 'In particular, the GSMaP data are now used by the Space-based Weather and Climate Extremes Monitoring Demonstration Project (SEMDP), led by the World Meteorological Organisation, to enhance the capacity of National Meteorological and Hydrological Services for monitoring drought and heavy rainfall – assisting governments and local communities with informed decision making to help them adapt to climate variability and change,' Dr Kubota concludes.

Along with these humanitarian efforts, Dr Kubota and his colleagues are now aiming to further improve their algorithms to achieve even more precise precipitation data, with the newest version of the software scheduled for release in early 2020.

As the Earth's atmosphere becomes warmer, many climatologists are predicting that the effects of rainfall extremes will become increasingly severe in the coming decades. As this happens, GSMaP's data will be crucially important to billions of people around the world. Using the satellite system's high-resolution, real-time precipitation images, communities will be able to assess how their livelihoods will need to adapt to a changing climate, and how to avoid the worst effects of the rainfall-related disasters it will bring.

Meet the researcher

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Dr Takuji Kubota completed his PhD in Earth and Planetary Sciences at Kyoto University in 2004. Since 2007, he has worked for the Japan Aerospace Exploration Agency (JAXA), where he now participates a wide variety of projects run by JAXA, including the Tropical Rainfall Measuring Mission, Global Precipitation Measurement, Earth Cloud, Aerosol and Radiation Explorer missions. Dr Kubota has received several awards in both Japan and the US, including the Meteorological Society of Japan's Gambo-Tatehira Award in 2019 for 'Achievements related to development of global precipitation map by satellite observations and promotion of its applications in society'.

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REMOTE SENSING & COMPUTER MODELLING: UNDERSTANDING THE DYNAMIC WATER CYCLE

The Earth's water cycle is an incredibly complex system, and is closely coupled to the planet's energy and carbon cycles. One of the biggest challenges for hydrologists is to accurately model the components of this system and begin to understand how human-induced changes to the climate and landscape will affect it. Combining computer modelling with observational data, **Professor Leila Farhadi** and her team at the George Washington University created a novel approach to mapping two critical components of the water cycle: evapotranspiration from the landscape and recharge to aquifers. Their work has implications for predicting and responding to water shortages, towards ensuring global water and food security.

A Dynamic Planet

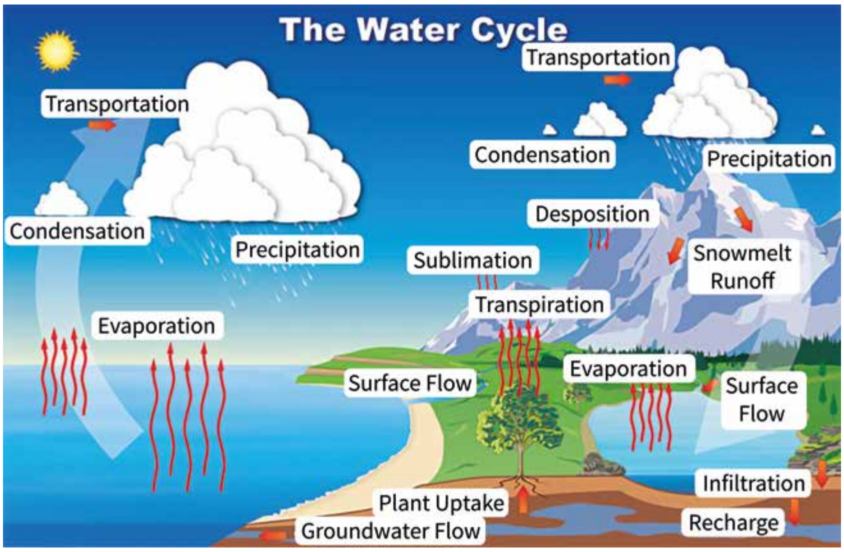
The Earth is a dynamic planet. The relationships between the atmosphere, land, ice and oceans are complex and constantly varying through a series of cycles and feedback loops. For example, a small change in the atmosphere will impact other environmental variables, leading to further changes in the atmosphere. Earth system science is the study of how these different environmental variables behave as a whole, linked by nutrient, carbon, water and energy cycles that are themselves extremely complex.

Professor Leila Farhadi, a hydrologist at the George Washington University, is particularly interested in the land component of the water cycle, known as the terrestrial water cycle. The terrestrial water cycle describes the continuous movement of water on, above and below the terrestrial landscape.

Water deposits on land in the form of rain and snow through the process of condensation (changing from vapour to liquid), flows on land as runoff, infiltrates into the soil and recharges to groundwater. It then moves back into the atmosphere through the process of evaporation (turning from liquid to vapour through the Sun's heat) and transpiration (moving from the soil to plant leaves to the atmosphere), or becomes stored in soil, lakes, streams, groundwater, and polar and glacial ice. This gigantic system, powered by energy from the Sun, comprises a continuous exchange of moisture between the land and the atmosphere.

The combination of evaporation and transpiration is known as evapotranspiration, and this is how water moves from the surface of the land to the atmosphere. Recharge flux is the primary process through which water enters subsurface aquifers and occurs below plant roots. Evapotranspiration flux, which links the surface and atmospheric system, and recharge flux, which links the surface and subsurface systems, are two key components of the terrestrial water cycle that are not well understood and are poorly monitored.

Evapotranspiration and recharge also play major roles in the energy and nutrient cycles on Earth. They are vital for the health of ecosystems – not just for the natural environment but also for human crop production. They are important for the sustainability of water sources, such as aquifers, and are strongly affected by climate. The effects of even small changes in climate are amplified due to subsequent changes in evapotranspiration and recharge rates. Professor Farhadi and her team aim to characterise and map the patterns and complex dynamics of these two processes, enabling us to better predict and prepare for water shortages, towards ensuring food security in the face of climate change.



The Challenge of Measuring Fluxes

Accurately estimating evapotranspiration and recharge is a challenge for hydrologists, as they change through time and under varying climate conditions. Complexities and interrelation of land surface processes, along with many unknown parameters of land surface models, make it very difficult to realistically map these fluxes using physical computer models. Direct measurements of these fluxes are difficult, costly and labour-intensive. Moreover, measurement of fluxes at a single point cannot be used to estimate or map these processes over a larger area.

A potential answer to this problem involves remote sensing technology, in which satellites collect scientific data from orbit over wide areas of the Earth throughout the year. Professor Farhadi has recently secured a NASA New Investigator Program grant to use observational satellite data combined with computer modelling to map evapotranspiration and recharge processes.

How to Model A Complex System

Land surface fluxes, such as evapotranspiration and recharge, cannot be measured directly through remote sensing, as they do not have a specific signature that can be detected directly by current remote sensing technologies. Instead, satellites gather observational surface data.

Soil moisture and land surface temperature data are a key focus for Professor Farhadi, as they contain hidden information about evapotranspiration and recharge flux. By assimilating such data into a computer model, her team can begin to estimate these fluxes. 'We are developing robust, efficient and reliable data assimilation techniques that enable us to map regional fluxes of evapotranspiration and recharge,' explains Professor Farhadi.

The team is developing a variational data assimilation (VDA) model to map evapotranspiration and recharge flux. Combining the outputs of physical computer models with environmental observations, VDAs are sophisticated mathematical techniques that produce states and parameters that most accurately approximate the current and future states of a true system.

In a study published this year, the researchers tested their method of estimating evapotranspiration flux. The team found that their technique is more accurate than previous attempts at mapping the evapotranspiration flux from observational surface data.

The team's novel model uses soil moisture measurements, as well as land surface temperature data. It then integrates these environmental observations into a system of water and energy balance model that are coupled through the flux of evapotranspiration. The model uses moisture and heat diffusion equations to define the transfer of water and heat between land and atmosphere. It then uses uncertainty analysis techniques to evaluate the accuracy of estimation.

The First Test

Professor Farhadi and her team initially tested the performance of their technique using a synthetic dataset. Using a combination of data from the simultaneous heat and water (SHAW) model and meteorological data (such as precipitation and solar radiation), they hoped to test the performance of their VDA model to indicate its feasibility for larger-scale studies using satellite data.

The team completed a set of tests on their VDA model to simulate different data scenarios. For example, they used the model to calculate land surface fluxes when there was a limited amount of soil moisture and land surface temperature data available to represent time periods when cloudy conditions reduced the number of measurements that a satellite could make.

The study successfully showed that the inclusion of soil moisture data along with land surface measurements improved the overall estimation and mapping of evapotranspiration rates. The team discovered that by using the moisture diffusion equation within the model, the parameters of the model were better constrained than in previous studies. The study was vital in proving that the team's proposed method could be applied to larger scale studies, and that space-based satellite data could be integrated into the model to create accurate estimates of land surface fluxes.

The Geostationary Operational Environmental Satellite. CREDIT: NASA

Integrating Satellite Data

In their most recent work, Professor Farhadi and her team used their VDA model with satellite data from a variety of sources. The study focused on a specific 31,500 square kilometre area of the Southern Great Plains, with data covering a nine-month period. Not only is this a large, regional-scale area of land, analysing data over a large time period confirms how well the mapping technique performs under changing seasonal conditions.

The team used the Geostationary Operational Environmental Satellite (GOES) operated by the National Oceanic and Atmospheric Administration (NOAA) as a source of land surface temperature data. This high-resolution dataset comprises hourly calculations of land surface temperature at a spatial resolution of five kilometres. The researchers obtained soil moisture data from the Soil Moisture Active Passive (SMAP) mission operated by National Aeronautics and Space Administration (NASA), which makes measurements every two to three days, with a spatial resolution of nine kilometres. The team then integrated these data into their VDA model.

When used with real remote sensing data, the coupled VDA modelling technique was a success. 'The developed computational tools have been successful in mapping regional fluxes of evapotranspiration in US southern great plains,' describes Professor Farhadi. Her team was able to evaluate its performance through a series of tests, which showed that the model performed consistently. They also compared the results from the model with real surface heat and evaporative flux measurements that were recorded in the study area. These measurements were made by the Atmospheric Radiation Measurement network and when compared to the model results, were an indication of how accurate the estimated fluxes were.

The research team also completed an uncertainty analysis to show that integrating the remotely sensed land surface temperature and soil moisture data helped to reduce uncertainties within the model parameters. Overall, they were able to prove that assimilating remotely sensed soil moisture and land surface temperature data into a coupled model of water and energy balance improved the accuracy of land surface flux estimations.

Earth System Future

The evaporation and transpiration maps that Professor Farhadi has produced have already been used to study a variety of other relationships. For example, the model has been used to look at how evapotranspiration is dependent on several factors, such as vegetation and solar radiation. It has also been used to look at microclimate and biogeographical controls on water limitation within the study area.

So far, Professor Farhadi has been focused on accurately estimating and mapping evapotranspiration using the coupled water-energy balance model. Her team's future research will also include studying the recharge flux using similar techniques. Looking further ahead, future models could couple the water and energy cycles with the carbon cycle, or include additional types of remote sensing data to improve understanding and accuracy of land surface fluxes.

Evapotranspiration and recharge maps have a wide range of applications for scientists, especially hydrologists working to understand this complex and dynamic system. Water availability and food security depend on accurate estimations of these fluxes. The recharge rate is exactly the rate of the sustainable use of subsurface aquifers. Evapotranspiration is the link between the water, energy and carbon cycles and therefore ecosystem productivity; biomass accumulation and net carbon exchange is dependent on this flux.

Moreover, variations in the land branch of these fundamental cycles would be essentially independent if it were not for the evapotranspiration flux that links the three. In order to understand how the Earth system works and how it will evolve in a changing climate, the scientific community requires accurate estimation of evapotranspiration flux, and Professor Farhadi's methods are bringing us significantly closer to achieving this goal.

Meet the researcher

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Professor Leila Farhadi is a hydrologist at the George Washington University in the US. After completing her PhD at the Massachusetts Institute of Technology, she spent some time working at the NASA Goddard Space Flight Centre as a research scientist in the Global Modelling and Assimilation Office (GMAO). Her particular research interest lies in the area of hydrology and land-atmosphere interaction. She is interested in understanding and modelling land surface and land-atmosphere interaction and exchange processes by utilising innovative remote sensing, optimisation and numerical modelling techniques. In 2018, she was awarded a prestigious NASA Early Career (New Investigator) Award in Earth Sciences, and is the Primary Investigator on multiple other research grants. Professor Farhadi has also supervised Masters and PhD students who themselves have moved forward with exciting research careers. She continues to teach alongside her research, and received the SEAS Outstanding Junior Teaching Award in 2018.

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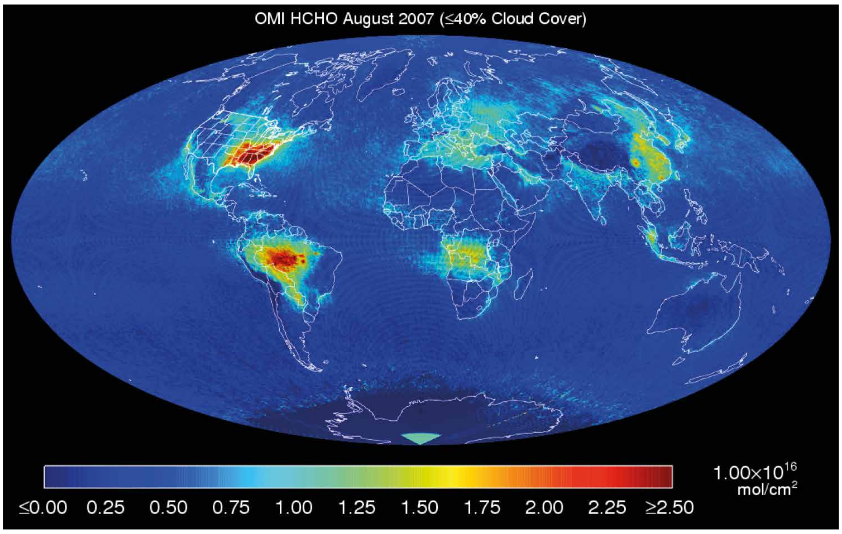
TEMPO: MONITORING NORTH AMERICA'S POLLUTION FROM SPACE

Created by sources ranging from campfires to cargo ships, air pollution is incredibly difficult to track. This has meant that the full impacts of air pollution are almost impossible to assess, but a solution is on the horizon. The TEMPO instrument (tempo.si.edu), built by Ball Aerospace to Smithsonian Astrophysical Observatory specifications and managed by the NASA Langley Research Center, will soon provide an all-encompassing view of pollution across North America. As part of a global constellation of satellite air quality missions, TEMPO will soon provide us with the most extensive view of pollution ever achieved, along with its impacts, allowing us to tackle it more effectively than ever before.



The Problem with Pollution

For several decades, increasingly powerful satellite-based instruments have provided us with critical insights into the physical processes that govern our atmosphere. However, when studying air pollution, even the latest technologies face a significant difficulty: the images they take have a severely limited spatial resolution, and can only be taken at daily time intervals. So far, this has prevented researchers from answering some of the most pressing questions relating to air quality, including precisely how much pollution is being emitted, where it comes from, and how it varies over time. This information is vital if we are to effectively combat atmospheric pollution and its devastating consequences for human health and ecosystems worldwide.

To address this problem, the Tropospheric Emissions: Monitoring of Pollution instrument (TEMPO) will soon be scanning for pollution across almost the entire North American continent. A global team of scientists, led by Dr Kelly Chance at the Harvard-Smithsonian Center for Astrophysics, will analyze these most in-depth measurements to date of North American pollution, which affects both natural environments and our own health.

Launching TEMPO

Once in orbit, TEMPO will examine a region home to a diverse array of communities, species, and environments. 'TEMPO is to be launched in early 2022, to measure atmospheric pollution from Mexico City, Puerto Rica, Cuba, and the Bahamas, to the Canadian oil sands in Alberta; and from the Atlantic to the Pacific,' explains Dr Chance.

The key to achieving this degree of coverage will be to place TEMPO in geostationary orbit – the position where satellites remain at the same point

relative to Earth's surface by orbiting above its equator, with an orbital time matching Earth's rotation. From this position, TEMPO will be able to 'sweep' the entire continent once every hour – picking up incredibly small details. 'TEMPO's mission is to measure atmospheric pollution over North America hourly in the daytime, at a spatial resolution of around 10 square kilometers,' says Dr Chance.

Achieving such sophisticated measurements is no mean feat. When designing TEMPO, Dr Chance's team needed to incorporate instrumental capability that could take measurements of many different pollutants simultaneously. The researchers achieved this by equipping TEMPO with an advanced two-dimensional spectrometer, producing a complete atmospheric chemistry lab in space. Once the commercial communications satellite on which it sits has reached geostationary orbit, TEMPO will look down at the Earth to detect the characteristic signals of pollution hidden within reflected sunlight.

Measuring Pollution

When the Sun's light is reflected by Earth's surface back into space, some of it is absorbed by molecules in Earth's atmosphere. Different molecules absorb different frequencies of light, meaning that some frequencies will be depleted from sunlight that has passed through the atmosphere. To measure atmospheric pollution, TEMPO can search for this absorption in reflected sunlight, characterizing each particular polluting chemical.

Because TEMPO has such high spatial and temporal resolutions, it will be able to pinpoint exactly where pollution is coming from, and how particular sources vary over time. 'TEMPO will track pollution loading, transport, and transformation,' explains Dr Chance. 'It also will provide near-real-time air quality products, measure the key elements of air pollution chemistry, and measure the UV exposure index.' The TEMPO team has now planned out many experiments that are made possible by these measurements, relating to a wide range of pollution-related issues.

Over Land and Sea

One group of studies will focus on the impacts of pollution on both marine and land-based environments. The first of these experiments will measure the ever-changing behaviors of living plants – including microscopic marine plants called phytoplankton and related potentially harmful blooms of algae, named 'red tides'.

Secondly, TEMPO will measure how emissions of a particular group of polluting chemicals, called nitrogen oxides, can escape from crop farms under certain conditions, polluting the atmosphere as well as wasting large amounts of fertilizer. 'Here, we will make measurements of croplands to follow the temporal evolution of nitrogen oxide emissions after fertilizer application and from rain-induced emissions from semi-arid soils,' states Dr Chance.

Thirdly, TEMPO will measure atmospheric total column water vapor, which is one of the so-called 'Essential Climate Variables'. The hourly high-density and high-resolution measurement can be used to monitor variability on a variety of spatial and temporal scales, providing new insights into Earth's water cycle and valuable information for improving the accuracy of mathematical models.

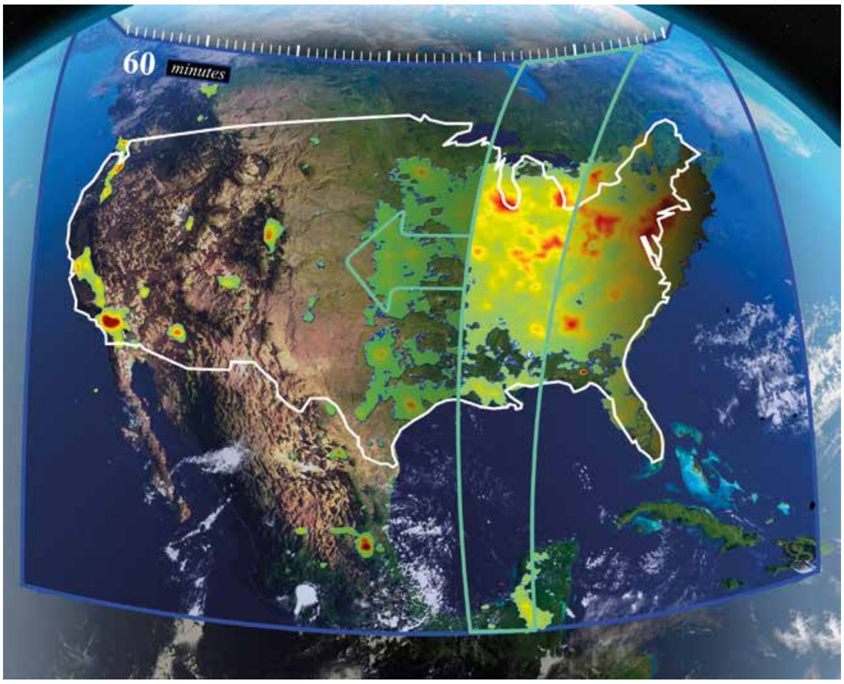
Finally, the instrument will explore the involvement of molecules called halogen oxides in coastal atmospheric chemistry, as these compounds can destroy ozone in the lower atmosphere.

These studies will provide researchers with unprecedented levels of detail about the impacts of pollution on environments ranging from the jungles of Mexico to Utah's vast salt lake.

Ozone Pollution

Another group of studies will examine the complex chemistry that plays out above the Earth's surface. The first of these studies will examine the impacts of lower atmospheric ozone. High up in the atmosphere, in the stratosphere, ozone protects us from the Sun's harmful ultraviolet radiation. However, ozone at ground level is the worst gaseous pollutant, as it is extremely damaging to animals and plants. 'TEMPO will take measurements of tropospheric production processes as well as stratospheric ozone intrusions that cause air quality exceedances,' says Dr Chance.

Secondly, TEMPO will study how thunderstorms produce polluting chemicals, and how they are spread around by air flowing outwards from storm systems. 'We will also take measurements of thunderstorm activity, including outflow regions, to better quantify lightning nitrogen radical and ozone production,' Dr Chance continues. There are already satellite-based instruments that monitor the Earth's atmosphere, but TEMPO will address critical gaps in our knowledge of how



pollution, in particular, is spread by natural atmospheric processes.

Pollution from Fires

As climate change accelerates, wildfires are becoming an increasing concern for many communities worldwide. Through a further group of studies, TEMPO will provide crucial insights into the pollution caused by these disasters. The direct destruction that fires create is their most visible impact, but they also cause massive amounts of pollution – itself the subject of further studies. 'TEMPO will investigate the chemical processing of primary fire emissions, and the secondary formation of volatile organic compounds and ozone,' says Dr Chance.

In addition to causing pollution, the danger of fires being started is increased by the presence of certain conditions that may be monitored by TEMPO. The instrument will help researchers to understand these risks better. These studies will allow researchers to assess the causes and effects of wildfires in unprecedented levels of detail, potentially allowing us to mitigate future disasters.

Human Activity

TEMPO will study the profound impacts of our activities, and the devastation they inflict through pollution. Transportation is one of the most significant sources of pollution we create. However, because vehicles are constantly on the move, and traffic varies widely throughout the day, the pollution it creates is incredibly difficult to track. Dr Chance explains how TEMPO can resolve this issue: 'We will take measurements at peaks in vehicle travel to capture the variability in emissions from mobile sources.'

In addition, light pollution is a substantial, albeit highly variable consequence of human activity. 'TEMPO will measure patterns of night-time lights, resolved by lighting type, as markers for human activity, energy conservation, and compliance with outdoor lighting standards intended to reduce light pollution,' says Dr Chance.

As our activities continue to affect our home planet through climate change and environmental degradation, these observations will come at a critical time.

Constructing a Global Constellation

Having made detailed plans for such a wide array of experiments, the TEMPO team has now, with their Asian and European partners, laid the groundwork for the most extensive analysis of pollution ever undertaken. However, the TEMPO team's work is far from over. In the next few years, the team aims to provide insights that will ramp up the capabilities of pollution monitoring over North America to levels never seen before.

'A longer-term goal for the TEMPO mission is to improve emission inventories, monitor population exposure, and enable emission-control strategies,' says Dr Chance. 'By demonstrating the utility of air quality and chemical weather measurements for North America, its capability might be included in future generations of NOAA geostationary weather satellites, for the ongoing benefit of the North American population.'

TEMPO will not be alone in its air quality monitoring, but will be joined by two other geostationary pollution-monitoring instruments. 'TEMPO is the North American component of the upcoming global geostationary constellation for pollution monitoring. The European Sentinel-4 mission will measure pollution over Europe and the Korean Geostationary Environmental Monitoring Spectrometer (GEMS), also built by Ball Aerospace, will monitor East Asia,' Dr Chance explains.

Dr Chance and his colleagues hope that these additional instruments will be as effective as TEMPO for monitoring pollution, allowing scientists around the world to make detailed, global-scale assessments of its impacts. In addition, they hope the project will engage public audiences around the world, raising awareness of the severe impacts of pollution, and what needs to be done to secure our future. At a time when the future of the Earth's natural environment is more uncertain than ever before, these efforts could soon prove critical to assessing and mitigating our own impacts on the planet we call home.

Meet the researchers

Dr Kelly Chance
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Dr Kelly Chance is a Senior Physicist in the Atomic and Molecular Physics (AMP) Division of the Harvard-Smithsonian Center for Astrophysics (CfA), and the Principal Investigator for the NASA/Smithsonian TEMPO satellite instrument (tempo.si.edu). Dr Chance has been measuring Earth's atmosphere from balloons, aircraft, the ground and, in particular, from satellites, since receiving his PhD from Harvard University. His atmospheric measurements encompass the physics and chemistry of the stratospheric ozone layer, climate-altering greenhouse gases, and atmospheric pollution. Together with Professor Randall V. Martin, Dr Chance published the textbook 'Spectroscopy and Radiative Transfer of Planetary Atmospheres' by Oxford University Press.

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Dr Xiong Liu is a physicist in the AMP Division of the CfA and the Deputy Principal Investigator for TEMPO. His research focuses on remote sensing of atmospheric trace gases, especially ozone, and on aerosols and clouds. He is responsible for the TEMPO Level 0 to Level 1 algorithm and the revolutionary TEMPO ozone profile measurements, which take advantage of the first satellite instrument specifically designed to make them.

Dr Christopher Chan Miller is a physicist in the AMP Division of the CfA. He develops realistic simulations of TEMPO data to validate the development of TEMPO data analysis. The simulations use meteorological and pollutant data from a 3D atmospheric model coupled to one that simulates how light propagates through the atmosphere. The synthetic pollution observations can also be used by early users for developing applications prior to TEMPO's launch, such as air pollution forecasts.

Ms Mary Dussault is a Program Manager in the Science Education Department at the CfA. She leads the Communications and Public Engagement effort for the TEMPO project, enhancing interest in and public awareness of TEMPO, in collaboration with NASA Langley Research Center.

Dr Gonzalo González Abad is a physicist in the AMP Division of the CfA. His current research focuses on the retrieval of trace gases (formaldehyde, glyoxal and water vapor) using ultraviolet and visible spectra measured by satellite spectrometers. He is member of the TEMPO science team and is heavily involved in the development of formaldehyde retrieval for TEMPO.

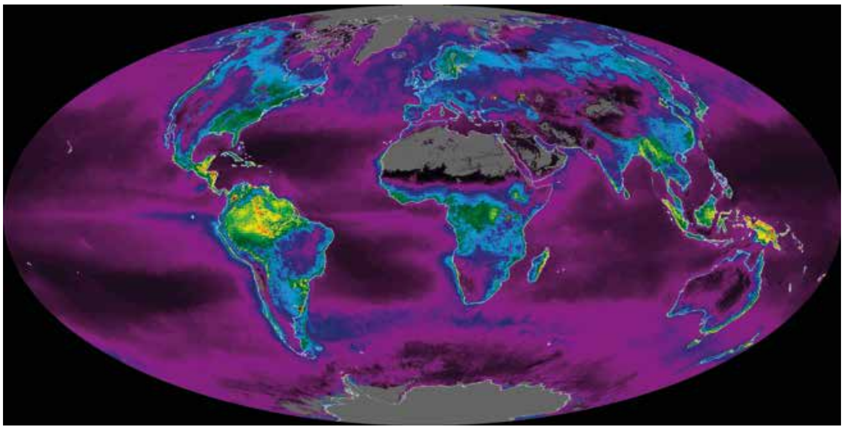
Dr Caroline Nowlan is a physicist in the AMP Division of the CfA. She leads efforts at the Smithsonian Astrophysical Observatory to analyze data from aircraft simulator instruments deployed by NASA to support TEMPO and similar missions, and to develop measurements of pollutant gases not yet measured from space but accessible to TEMPO.

Mr Raid M. Suleiman is a physicist in the AMP Division of the CfA. He is the Data Manager for TEMPO and other atmospheric measurement projects at the CfA. He oversees development of the Instrument Operations Center, which commands the instrument and monitors its performance, and the Science Data Processing Center, which produces the hourly maps of air pollution and derived air quality products.

Dr Huiqun Wang is a physicist in the AMP Division of the CfA. She leads efforts to develop measurements of water vapor, an Essential Climate Variable. Hourly high-density and high-resolution TEMPO measurements can be used to monitor variability on a variety of spatial and temporal scales, providing new insights into the water cycle and valuable constraints to numerical models. Applications include atmospheric rivers, corn sweat, and regional climate.

MONITORING PLANT PRODUCTIVITY ON A GLOBAL SCALE

Net primary productivity, or NPP, refers to the amount of carbon dioxide that plants take in during photosynthesis, minus the amount released during respiration, resulting in final observable biomass. As carbon dioxide is the primary driver of climate change, having a full understanding of this process is now critical. However, until recently, global NPP and how it is affected by climate change were poorly understood. To obtain a complete picture of NPP and the factors that drive global changes, **Dr Steven Running** and his team at the University of Montana have been investigating satellite data from the past few decades.



CREDIT: Reto Stöckli/MODIS Science Team

Photosynthesis and NPP

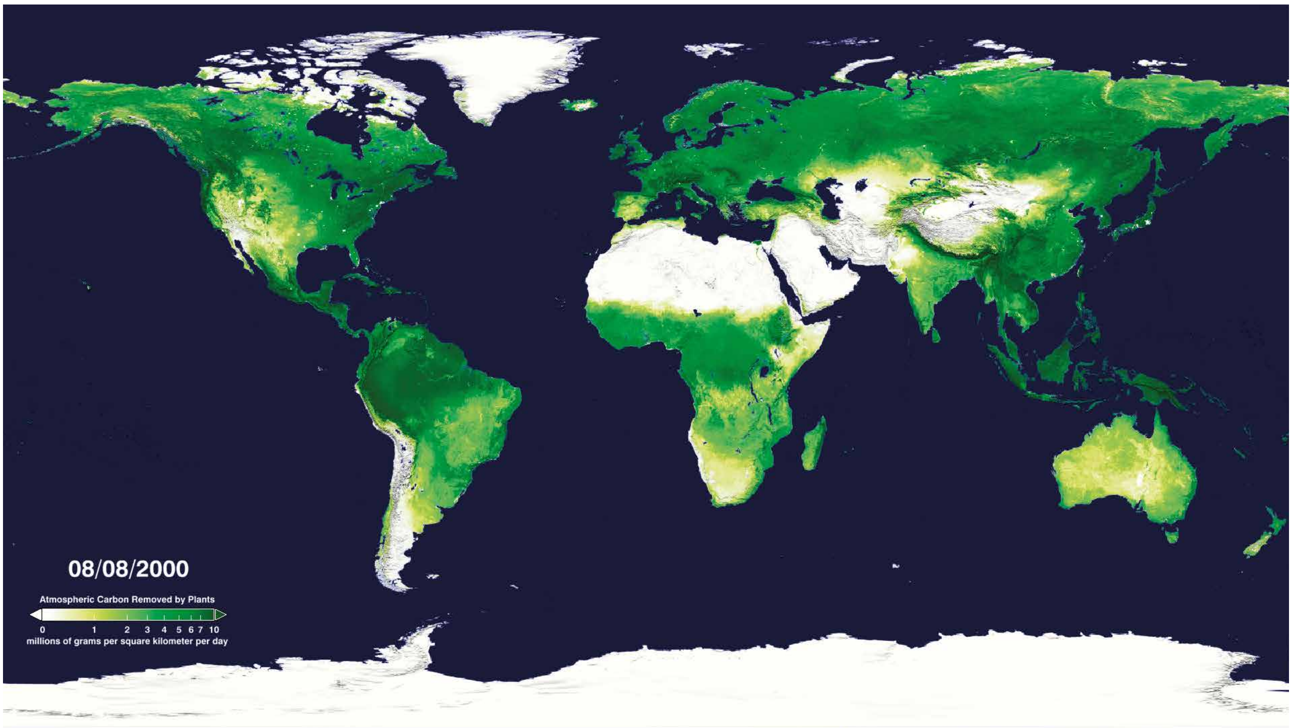
Photosynthesis, which occurs inside all plants and certain microbes, is arguably the most important chemical reaction on Earth. In this process, a plant uses carbon dioxide, water and energy from the Sun, to create new plant material, producing oxygen as a biproduct. The carbon is stored by the plant as carbohydrate (sugars and starches), while oxygen is released into the atmosphere. In fact, photosynthesis creates most of the atmospheric oxygen and all of the food on Earth, making it responsible for the emergence of life as we know it.

Furthermore, photosynthesis continually removes carbon dioxide from the atmosphere, in a process called carbon sequestration. As our carbon dioxide emissions are the primary driver of global warming, global photosynthesis helps to lessen their impact on the climate. In fact, land-based plants absorb around 30% of the carbon dioxide that human activity adds to the atmosphere, demonstrating the critical role of photosynthesis in climate change mitigation.

In addition to converting carbon dioxide into carbohydrate through photosynthesis, plants also break down a small amount of this carbohydrate for metabolic energy, releasing carbon dioxide back into the atmosphere in the process. Plant net primary productivity (NPP) is calculated by measuring how much carbon dioxide is absorbed minus how much is lost through this respiration process.

Scientists can use this valuable NPP measurement to calculate how much carbon is being sequestered by plants. Accurate NPP values are vital for scientists who are trying to understand and predict the severity and effects of future climate change on the biosphere. As Dr Steven Running of the University of Montana says, ‘if NPP is degraded, atmospheric carbon dioxide would increase faster, and global warming would accelerate. Conversely, if humanity can enhance NPP it slows global warming down.’

Until recently, measuring NPP continuously on a global scale was not possible. Most previous estimates have been made by taking measurements of plant biomass from a small plot and extrapolating them to calculate global NPP. To obtain a more accurate picture,



CREDIT: NASA/Goddard Space Flight Center Scientific Visualization Studio

Dr Running started to work closely with NASA in the early 1980s, where he aided in the development of NASA's Earth Observing System. This fleet of satellites has been monitoring the Earth's land, oceans and atmosphere for 20 years. The Earth Observing System is at the forefront of Earth system science, helping scientists to understand the atmosphere, oceans and land surface as an integrated system.

Monitoring on a Global Scale

The Terra and Aqua satellites are part of the Earth Observing System and are equipped with a Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS measures the proportion of Earth's land surface that is covered in vegetation and the reflected sunlight in special wavelengths. Dr Running and his team have developed an algorithm to calculate NPP from these measurements, along with daily climate data, creating a large dataset of continuous global NPP measurements. The model assesses the amount of sunlight that can be absorbed by vegetation, along with the local weather conditions, to calculate the rate of photosynthesis, and therefore the amount of carbon dioxide that is being absorbed. During their early research, Dr Running and his colleagues identified various climate factors that limit the rate of photosynthesis and plant growth. The team found that water availability is the most important factor, followed by temperature and solar radiation.

Daily climate data is collected from the US National Centre for Environmental Prediction and combined with the vegetation measurements taken by MODIS. The team releases new NPP data every eight days, where it is used by various groups, including NASA, government organisations, many other countries and private landowners to aid in land management. Dr Running and his team have also combined earlier satellite records to monitor global NPP and how it has changed with climate since 1982. Their work has provided valuable insights into how NPP has changed over time, especially how it is affected by extreme climate events.

Long-term Trends

Climate records between 1982 and 2009 show that atmospheric carbon dioxide and global temperatures have steadily increased. Using earlier satellites to consistently monitor NPP and its response to changes in climate during this period, Dr Running and his colleagues discovered some interesting trends.

The team found that global NPP increased over the 18-year period, suggesting that global changes in growing season length might actually encourage plant growth. As photosynthesis increased, carbon sequestration rates increased too.

However, the long-term trends between 2000 and 2009 were not quite as reassuring. Despite continuously rising temperatures, global NPP appeared to decrease slightly, due to longer periods of drought. Dr Running wondered if this was simply a normal variation, or if it indicated a point after which NPP starts to decline due to more pronounced climate change. Only continued, long-term global monitoring can wholly answer that question.

Relationship Between Climate and NPP

Next, Dr Running and his colleagues went on to measure the impacts of

NASA's Terra (left) and Aqua (right) satellites, carrying the MODIS instrument. CREDIT: NASA

specific climatic events on NPP. They found that the 1991 eruption of Mount Pinotubo in the Philippines caused the NPP of high-latitude vegetation in the Northern Hemisphere to temporarily decrease from cooler temperatures. Three El Niño events between 1982 and 1998 also appeared to cause global NPP to temporarily decrease from drought effects, but not significantly enough to deviate from the overall rising trend during this time. Conversely a strong La Nina in 2011 increased rainfall so much that ocean sea level temporarily declined, and this rainfall caused NPP on land to increase.

The team also noticed significant differences between the Northern and Southern Hemispheres. Whilst NPP in the Northern Hemisphere continued to increase between 2000 and 2009, the Southern Hemisphere showed very large decreases in plant NPP from drought that contributed to an overall reduction in global NPP.

The team's long-term monitoring of NPP has helped them to understand how changes in climate can affect global NPP. For instance, rising temperatures increase growing season length, but decrease water availability, and many of the NPP trends that the team identified can be directly attributed to these effects. They showed how significant droughts between 2000 and 2009 caused the reduction in NPP in the Southern Hemisphere. Decreases in cloud cover increased sunlight over tropical areas causing the largest increases in NPP, particularly in the Amazon rainforest.

It initially appeared that rising global temperatures were having a positive effect on the growth of plants, potentially increasing their ability to act as a sink for excess carbon dioxide produced by human activity. However, the reduction in NPP from 2000 to 2009 from drought effects raises serious issues. If rising global temperatures reduce plant growth, the ability of vegetation to act as a carbon sink will be reduced, accelerating climate change.

Importance of NPP in Modelling

Our climate is changing rapidly, and the effects of these changes require incredibly complex Earth systems models to predict. These models require detailed information of vegetation cover and trends in carbon sequestration. Dr Running and his colleagues can provide extensive NPP data that can be used to increase the accuracy of these climate models. Without accurate climate models, preparation of effective climate policies and meeting global food and energy requirements would be extremely challenging.

Monitoring NPP is not only essential for understanding the effects of climate change. The global population, currently at 7.5 billion people, is projected to rise beyond 10 billion by 2100. Feeding all these people is a moral imperative, yet this global NPP data does not show sufficient increases in crop production to meet these future needs.

Plant material is also a source of bioenergy – a renewable energy source such as wood, agricultural waste and specifically-grown energy crops, which is burnt for heating, cooking or electricity production. In the future, bioenergy could meet a proportion of our energy needs, as the carbon footprint is far lower than that of fossil fuels. However, our current estimates vary greatly due to unknown factors, such as the future availability and productive potential of land, which needs to be balanced with food production to feed the growing human population.

Using their extensive measurements of NPP, Dr Running and his colleagues investigated the maximum global primary bioenergy potential. The team calculated a potential bioenergy capacity that is four times lower than previous estimates and would require 55.6 million square kilometres of natural vegetation to be converted to bioenergy cropland – an area greater than Asia and Europe combined! The conversion of natural ecosystems to cropland is not only destructive to the environment, but would also significantly reduce the amount of carbon that can be sequestered. By 2050, the demand for global energy is predicted to double, but the team suggest that bioenergy can only meet less than 15% of our energy needs in a sustainable manner.

The Future of NPP Monitoring

Understanding and monitoring NPP is essential for maintaining land-based vegetation as a carbon sink and for food and bioenergy production. Modelling the movement of carbon and long-term changes to global ecosystems is complex and cannot be accurately completed without a clear understanding of NPP and how it evolves as the climate changes.

The NPP data that Dr Running and his colleagues provide is also vital for landscape management and planning. For instance, the team's results could be used for determining the most sustainable use of grazing and rangeland. As wildfires and droughts become increasingly intense and widespread, MODIS also provides a way of monitoring both at-risk areas and how the vegetation recovers after a disturbance event. As the Earth's climate continues to change, the team's consistent monitoring of NPP will become an even more essential tool for understanding and mitigating damage caused to the biosphere.

Meet the researcher

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Dr Steven Running was awarded his PhD from Colorado State University in 1979, and has worked with the NASA Earth Observing System since 1982. He currently holds the post of Regents Professor Emeritus of Ecosystem and Conservation Sciences at the University of Montana and is Director Emeritus of the Numerical Terradynamic Simulation Group. Dr Running has been a Lead Author for the Intergovernmental Panel on Climate Change (IPCC) and the US National Climate Assessment, as well as chairing the NASA Earth Science Subcommittee between 2013 and 2017. He currently co-chairs the Committee on Earth Sciences and Applications from Space for the US National Academy of Science. His long and successful career has led to over 300 publications within his research field of ecosystem carbon cycles and global climate change.

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ADVANCING SATELLITE TECHNOLOGY TO MONITOR OCEAN PHYTOPLANKTON

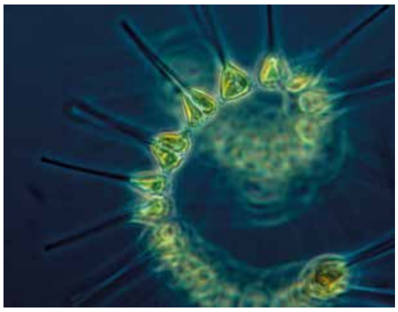
Tiny marine plants known as 'phytoplankton' play a disproportionately large role in maintaining the health of our planet, and they provide a rapid signal of changing climate conditions. **Professor Michael Behrenfeld** at Oregon State University and his many collaborators are developing new satellite approaches, including space-based lasers, to monitor ocean ecosystems. With these technologies, a 3D map of global phytoplankton communities is on the horizon, which will revolutionise our understanding of how these microscopic organisms make Earth a healthy place to live.

Phytoplankton

Phytoplankton are the life force of our oceans. Every day, these countless little engines absorb the Sun's energy and convert it into sugars, which feed nearly all marine food webs – including the fisheries we rely on for sustenance and a blue economy. Phytoplankton live fast and die young. Over periods of just a few days, the entire global population is either eaten, killed by viruses, or lost through sinking from the sunlit surface into the dark depths of the ocean. Fortunately, these losses are continually replaced by new individuals, so the stock of phytoplankton remains in balance.

Just like land-based plants, photosynthesis fuels the growth of phytoplankton. However, instead of taking carbon dioxide directly from the atmosphere, phytoplankton use the carbon dissolved in seawater. This dissolved carbon is then replaced by atmospheric carbon dioxide, creating a direct line between phytoplankton and climate change. 'An amazing fact about phytoplankton is that in total they perform around half of the photosynthetic production on Earth, yet they represent only about 2% of the total mass of plants,' says Professor Michael Behrenfeld of Oregon State University. 'This is possible because phytoplankton populations turn over quickly, so nearly as fast as they create new cells their carbon is passed on to animals higher up in the food web.'

An important consequence of this rapid turnover is that any change in surface ocean conditions, such as that resulting from a change in climate, quickly results in a change in phytoplankton populations. 'The distribution of phytoplankton thus provides a sensitive signature of environmental change,' explains Professor Behrenfeld, 'and we can globally observe these signatures using satellites.' By monitoring these changes today, satellite measurements are telling us a lot about how future ocean ecosystems may look, and their overall health, as the climate continues to warm.



To study phytoplankton, satellites currently enable the monitoring of one key property: the colour of the ocean's surface. In the absence of phytoplankton, an ocean of pure seawater would be a uniform shade of deep blue. However, as the phytoplankton population grows, the chlorophyll pigments they use for photosynthesis cause the water to become greener. 'With very sensitive instruments, we detect these shifts in colour from space and we have been doing this now for more than three decades,' says Professor Behrenfeld. 'The record we've collected clearly shows that ocean warming results in lower levels of phytoplankton chlorophyll, implying reduced production, but it is also becoming

PACE. CREDIT: NASA-GSFC

clear that a full understanding of climate change implications requires advances in satellite technology.'

Ocean Ecosystems in Technicolor

Phytoplankton have been evolving in the oceans for over three billion years and today thousands of different species share the sunlit surface layer. Some of these species are excellent food for crustaceans, such as shrimp, making phytoplankton the cornerstone of the marine food webs that fuel a global fishing industry worth over $200 billion in 2017. Other phytoplankton species are less valuable food sources and their production largely ends up being converted back to carbon dioxide. 'One of the big unknowns regarding climate change is how it will change the species that populate our future oceans,' emphasises Professor Behrenfeld. 'This question cannot be answered with the satellites we've launched so far.'

To address the problem, NASA is developing a new satellite, call PACE, that will be launched in late 2022. Rather than just measuring six or seven specific colours of visible light like past satellites, the PACE instrument will measure the full spectrum from ultraviolet to near-infrared light at an astonishing resolution of every five nanometres. 'This is the key, because different species have evolved with different pigments and this gives them different colours. By measuring the full colour spectrum, PACE will be able to distinguish different types of phytoplankton and give us a first glimpse into how these species uniquely respond to environmental changes,' explains Professor Behrenfeld. 'Borrowing a term from the 1970s, the PACE mission will allow us to study ocean ecosystems in Technicolor!'

Difficulties with Ocean Colour Measurements

With the PACE satellite now in development, Professor Behrenfeld is refocussing his energy on shortcomings in the satellite record that not even PACE can address. 'Since the first satellite was launched into space to observe ocean ecosystems, we have recognised some unavoidable limitations of the measurements,' he emphasises. 'The exciting thing is that we now have a way to solve these problems.'

One of the big problems he is referring to is that the ocean's surface colour reveals nothing about the phytoplankton below the first 10 meters or so, making scientists effectively blind to how deeper populations are changing. Light penetrates the ocean much deeper than ten meters in many places, and so a lot of productivity can occur below what traditional ocean colour satellites can sense. What is known from ship measurements is that the subsurface populations can be more abundant, more productive, and even composed of different species than phytoplankton near the surface.

Another limitation is that the ocean only displays colour when the sun is shining, and measuring this colour from space requires the Sun to be shining at just the right angle. This means that observations close to the poles, where phytoplankton populations are showing the most extreme responses to climate

CREDIT: NASA

change, are unavailable for many months during the year. The requirement for sunlight also means that ocean ecosystems cannot be observed at night, which is the only time when huge numbers of ocean animals migrate to the surface to feed on the day's production. 'The solution to these problems is to use a new technology that does not rely on sunlight, but rather carries its own source of light,' concludes Professor Behrenfeld, 'and that technology is now available.'

Ocean Exploration with Lidar

Professor Behrenfeld's current research focuses on a technology called 'lidar', which stands for 'light detection and ranging'. Lidar combines a laser-based light source with a large telescope receiver. 'The laser sends out a short pulse of light at a very specific wavelength,' describes Professor Behrenfeld. 'As this laser light travels toward Earth it intercepts particles in the atmosphere and phytoplankton in the ocean. When this happens, some of the laser light is scattered backward and into the telescope. Detectors in the telescope measure this return signal at close to the speed of light, allowing the precise location of the scattering events in the atmosphere and ocean to be calculated.'

The outcome of this is that a lidar allows phytoplankton concentrations and distributions to be mapped out at meter-scale resolution through the water column. This solves one of the major shortfalls of traditional ocean colour measurements. But that's not all. By using an artificial light source instead of sunlight, a lidar can monitor changes in polar phytoplankton populations when clouds or the angle of the Sun prevent any ocean colour measurements. Likewise, the artificial light allows lidar to operate at night and globally study deep sea animals that migrate to the surface after sunset – a very important part of the ocean ecosystem puzzle.

Graveyard of Great Ideas

It is very common practice to build prototype aircraft instruments as a stepping stone toward flight in space. These prototypes allow scientists to 'work out the bugs' of new technology and demonstrate its feasibility for space. Aircraft instruments are also relatively cheap. However, with far greater costs and far greater risks, the final step from airplane to space has proven the graveyard of most instrument concepts. 'We got lucky this time,' Professor Behrenfeld recalls, 'because a satellite lidar already existed that we could potentially use to transition our concept to space with essentially no cost and no risk.'

The lidar he is referring to is called CALIOP and it was launched in 2006 on the CALIPSO satellite as a joint mission between NASA and CNES in France. CALIOP was built to study clouds and aerosols in the atmosphere, not phytoplankton in the ocean. Undeterred, Professor Behrenfeld and his colleagues at NASA's Langley Research Centre began looking for an ocean signal in the CALIOP data as soon as the instrument was on orbit and operating. And they found it: CALIOP was registering a distinct signal of backscattered laser light that was coming from up to 20 meters below the ocean's surface.

The critical next step was to verify the apparent ocean signal. To do this, the researchers coordinated a large experiment near the Azores Islands in the Atlantic Ocean, where ship and airplane data were simultaneously collected with CALIOP measurements. All three sources of data gave the same results, meaning that the CALIOP ocean signal was real. With this success, the team boldly gathered all CALIOP ocean data into a single global map of phytoplankton biomass – the first to be created by a spaceborne lidar. It was the dawn of a new lidar era in satellite oceanography.

Breaking Science

'Creating the global map of phytoplankton with a lidar was important as a technological proof-of-concept,' says Professor Behrenfeld, 'but the fact was that similar maps had been made with ocean colour data. What we really needed was to show how lidar enables new science, so we turned our attention on polar ecosystems.' With 10 years of CALIOP data now in hand, Professor Behrenfeld's team published a paper in the journal Nature Geoscience demonstrating how a lidar can continuously monitor polar phytoplankton populations right up to the ice edge throughout the months when traditional ocean colour data are absent. It was the first unbroken satellite record of these critical and threatened ecosystems. What the study also showed is that changes in polar phytoplankton over the past decade were caused by ice cover changes in the south and ecological disturbances in predator-prey relationships in the north. These discoveries could never have been made without a satellite lidar.

'After the polar study, the next target I wanted to investigate was a signal from the migrating animals,' Professor Behrenfeld says. 'The basic idea is that a night-time invasion of the surface ocean by these animals should cause an intense increase in the laser light scattered back to the telescope.'

Professor Behrenfeld and his colleagues are now working to publish their findings, which will represent a landmark in oceanography, because it will be the first time that marine animals have been detected from space at a global scale. It will also be important because this daily animal migration is crucial for fisheries and the ocean's ability to rapidly move the carbon taken up by phytoplankton in the sunlit ocean layer to the deep ocean, where it can be stored for decades to centuries.

Doing it Right

As mentioned, the CALIOP instrument was built to study the atmosphere, not the ocean. Its receiver detectors are far too insensitive to retrieve ocean signals from deep in the water, its electronics are too slow to see phytoplankton layers, and the types of measurements it makes can't separate different components of ocean ecosystems. Having celebrated its 13th birthday, it is also unlikely to last much longer. 'CALIOP has been a ground breaking instrument and given us the proof we needed that ocean plankton can be measured with a satellite lidar,' Professor Behrenfeld concludes, 'but it is now time to get serious about putting a lidar in space that is actually built for studying the oceans.' In preparation for this, Professor Behrenfeld's colleagues at the NASA Langley Research Centre have successfully developed a more sophisticated lidar technique called high-spectral resolution lidar (HSRL).

HSRL adds an additional detector system to independently separate scattering and absorbing components in the water. More importantly, it can retrieve these signals at meter-scale resolution deep into the surface ocean to map distributions of phytoplankton in the water column. Airplane-mounted HSRL instruments have already been extensively deployed over the ocean and demonstrate superior skill in observing phytoplankton compared to earlier lidar. Professor Behrenfeld is hoping that an opportunity will soon arise to launch an ocean-optimised HSRL lidar into space. 'It looks like we might get lucky again,' he says. 'The Europeans are planning to soon launch an HSRL lidar to conduct advanced atmospheric measurements. The instrument will not have the right laser wavelength or depth resolution for ocean studies, but it will provide the needed proof-of-concept for HSRL measurements from space.'

An Oceanographic Revolution

No single satellite technology can provide all the measurements needed to understand our global ocean ecosystems and how they are being influenced by environmental change. Lidar can address the limitations of traditional ocean colour monitoring that have been recognised for decades, but lidar does not replace the need for ocean colour data. Ocean colour instruments can observe the entire Earth every two days, whereas a lidar globally samples the Earth approximately every 16 days. Passive ocean colour sensors also provide measurements at more wavelengths of light than lidar, which provides details on phytoplankton communities. It has therefore been Professor Behrenfeld's long term vision to create a constellation of satellites providing important and complementary measurements.

'We are at a very special time in the history of satellite ocean observations,' he says. 'When the PACE mission is launched, we'll begin an ocean colour record with unprecedented science potential. If we could get a lidar in space at the same time that was actually designed for ocean studies, the complement of the two instruments would yield a value for society far greater than the sum of its parts. CALIOP has demonstrated that ocean retrievals are feasible from space. An advanced HSRL technique has been shown to greatly improve the lidar retrievals. The time is now to realise this PACE-lidar vision. With it, we could reconstruct 3D representations of ocean ecosystems, and tie their structures to the physics driving them. It would present an amazing opportunity to understand more about what controls the distribution and function of these fragile and Earth-sustaining ecosystems.'

Meet the researcher

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Professor Michael Behrenfeld received his PhD in Oceanography in 1993 from Oregon State University. Since then, he has worked in many universities and research institutes, including Brookhaven National Laboratory, Long Island University, Rutgers University, and the NASA Goddard Space Flight Center. He currently works as a Professor in the Department of Botany and Plant Pathology at Oregon State University. Beginning in 2001, he was deeply involved in a grass-roots community effort promoting an advanced ocean colour sensor, an effort that ultimately led to the PACE mission. In 2015, he was awarded an Earth Venture Suborbital grant to conduct the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES), which has combined ship and aircraft measurements to improve understanding of ocean plankton blooms and their impact on atmospheric aerosols and clouds. Professor Behrenfeld is recognised as a world leader in the physiological ecology of marine phytoplankton; his research interests include remote sensing of the biosphere, photosynthesis, physiological adaptation to environmental stress, climate change, and carbon cycling.

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FLYING SEA SNAILS AS POTENTIAL INDICATORS OF OCEAN ACIDIFICATION

Ocean acidification, caused by increasing atmospheric carbon dioxide, is having a negative impact on marine ecosystems. To effectively respond to the issue, a deep understanding of it is absolutely necessary. At the Georgia Institute of Technology, **Drs Jeannette Yen, David Murphy, Deepak Adhikari** and **Don Webster** propose a novel method for monitoring ocean acidification. Their approach involves a miniscule marine snail and investigating how changes in ocean acidity affect its unique locomotive behaviour.

A Significant and Ongoing Problem

Ocean acidification is caused primarily by the absorption of carbon dioxide from the atmosphere. Atmospheric carbon dioxide, which has been on the rise for some time due to human activity, essentially dissolves into sea water to form carbonic acid – making the ocean more acidic.

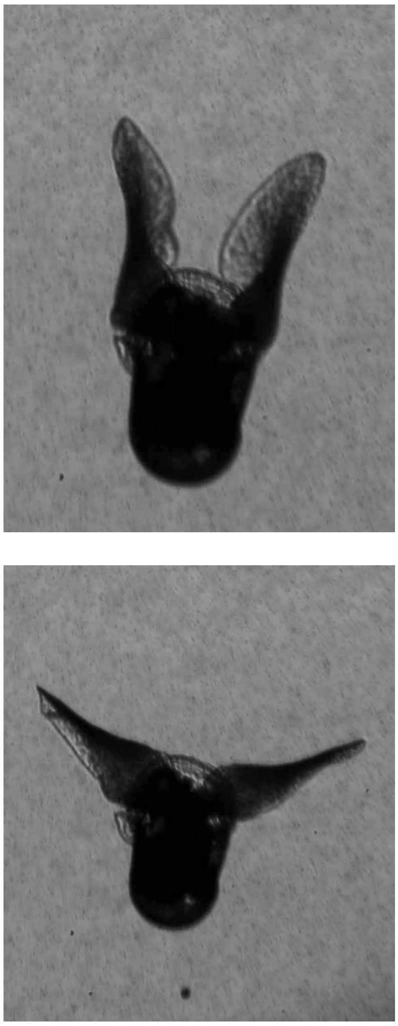
While estimates vary, the National Oceanic and Atmospheric Administration (NOAA) suggests that the ocean absorbs about 30% of the carbon dioxide that is released into the atmosphere. That's a lot of carbon dioxide – and the resulting acidification is a real problem for marine ecosystems. In fact, it is often referred to as 'climate change's evil twin'.

The problem lies in the fact that acid dissolves calcium carbonate – a chemical used by organisms such as oysters, clams, sea urchins, corals and calcareous plankton to make their shells, skeletons and other structures. Although living creatures are resilient and can adapt to changing conditions, the sheer quantity of atmospheric carbon dioxide and rate of uptake by oceans all over the world is presenting quite a challenge for these marine organisms.

One of those organisms is the Thecosome pteropod. Thecosome pteropods are a type of miniscule marine snail characterised by a most bizarre feature – thin, wing-like swimming organs. Hence, Thecosome pteropods are more commonly known as 'sea butterflies'. Dr Jeannette Yen and her team at Georgia Institute of Technology's School of Biological Sciences and School of Civil and Environmental Engineering have devoted much time to studying this organism. What they have discovered about the anatomy and locomotion of the sea butterfly is truly amazing. However, these creatures also have a unique role to play in the study of ocean acidification.

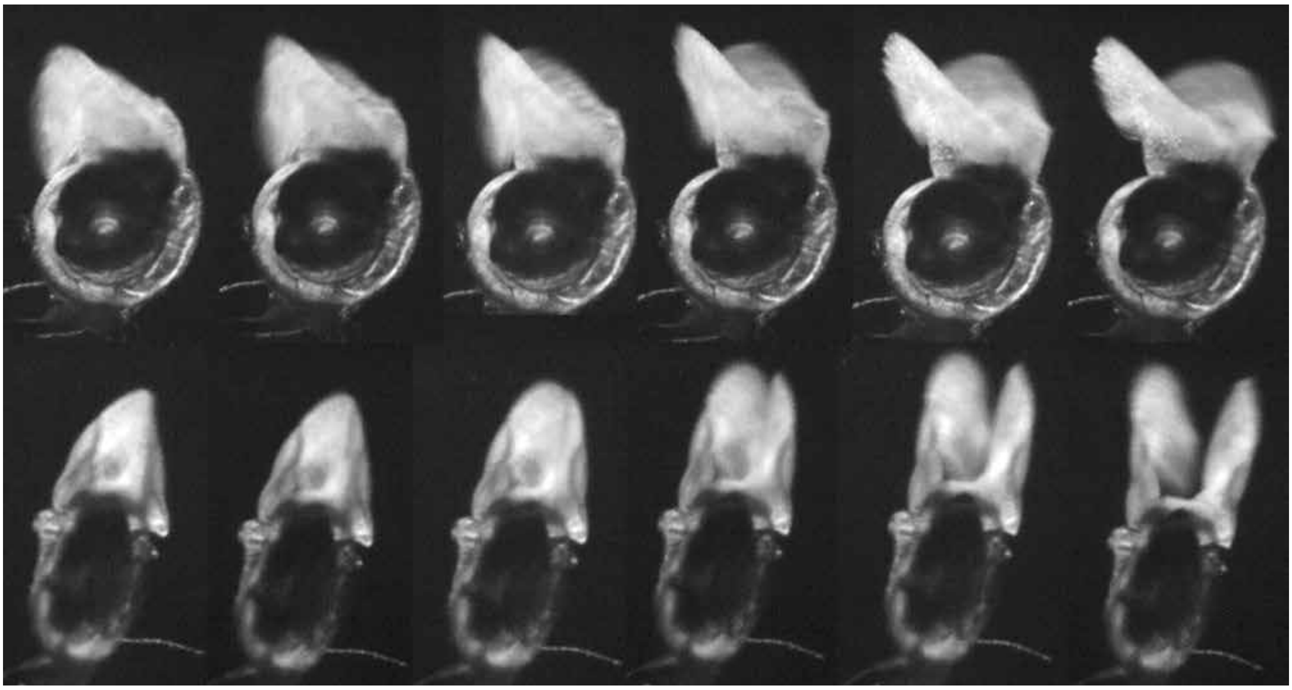
The Sea Butterfly's Peculiar Locomotion

In research published in 2012, Dr Yen's colleague Dr David Murphy conducted detailed studies of sea butterfly locomotion. During this project, they were able to determine



CREDIT: David Murphy and Ferhat Karakas

‘Our goal is to develop a behavioural assay to provide an early warning of the effects of ocean acidification.’



average speeds, stroke frequencies and general swimming paths by studying the trajectories of free-swimming individuals. In their paper, they noted that sea butterflies ‘ascend along a sawtooth trajectory in mostly linear and sometimes helical paths. Mean speeds varied from 13 to 44 mm/s for straight ascents and slightly more for helical paths. During swimming, the stroke cycle caused oscillations in body orientation, whereas sinking is characterised by smooth straight descents.’

Another intriguing discovery was that sea butterflies employ the so-called Weis-Fogh clap-and-fling mechanism when moving through water. The Weis-Fogh clap-and-fling is a characteristic wing stroke that proceeds in a figure-of-eight pattern. It is used commonly by insects to produce lift and fly about in the air. Dr Yen’s colleagues later focused on this most fascinating behaviour to confirm that, despite living deep underwater, sea butterflies do indeed employ this wing stroke mechanism. However, doing so would require a specialist technique.

Hydrodynamic Studies Using Tomographic PIV

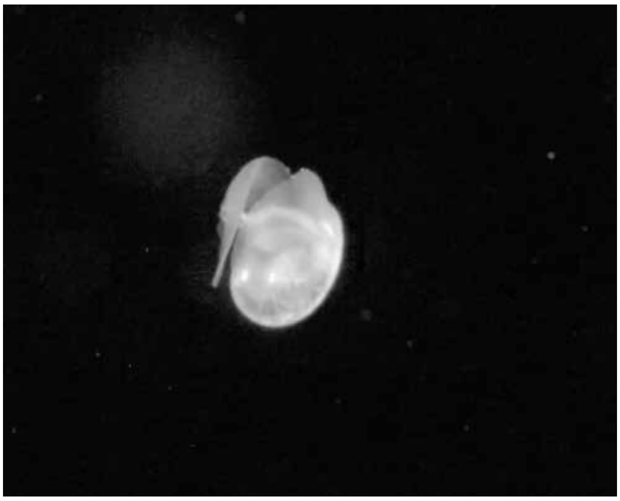
Particle Image Velocimetry, or PIV, is a technique used for studying the properties of fluids, such as flow velocity. It works by seeding the flow with ‘tracer’ particles, which are assumed to faithfully follow the related flow patterns. The movement of these over an illuminated plane is monitored using special digital cameras. The images produced offer insights into the flow dynamics and enable scientists to make calculations of speed and direction (flow velocity).

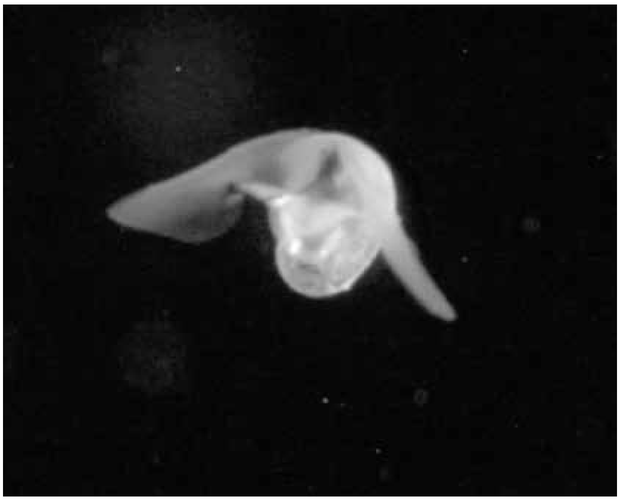
PIV is commonly used to study the locomotive characteristics of marine creatures. However, typical PIV techniques have their limitations. Of note is their inability to accurately measure flow dynamics on the small scale – the scale required to study the locomotive attributes of sea butterflies. This presented a challenge to Dr Yen and her team. So, concurrent with their studies of sea butterfly locomotion discussed above, the team adapted the tomographic PIV technique to zooplankton flows. This is known as ‘high-speed tomographic PIV’.

In 2012, Dr Yen and her team developed the technology, and later in 2016, they even incorporated it into a portable unit, which they took to Antarctica. Over the course of developing it, they found that it does indeed address many of the challenges associated with more traditional techniques. Most importantly, it proved to be effective on the small scale, and the team was able to study the flow dynamics associated with the high-speed escape of a tiny crustacean called a copepod in truly remarkable detail. Based on this success, the team moved forward with using high-speed tomographic PIV to further study other miniscule marine creatures such as sea butterflies.

Further Studies of Sea Butterfly Locomotion

As was mentioned above, Dr Yen and her team had evidence that sea butterflies employ a Weis-Fogh clap-and-fling mechanism when moving through water. Subsequently, in research published in 2016, they utilised high-speed tomographic PIV to confirm that this was the case. As explained in the associated paper, sea butterflies





do indeed 'fly' underwater using a Weis-Fogh clap-and-fling mechanism at a high angle of attack in much the same way that tiny insects fly in air.

Why is was this discovery significant? Well, the locomotive method employed by the sea butterfly is lift-based. In the world of miniscule marine creatures this is most unique. As is highlighted in the team's associated paper, other zooplankton (organisms that drift in the ocean, including copepods, krill and jellyfish) almost always employ drag-based swimming techniques. In other words, sea butterflies 'fly' through the water rather than 'paddling'. Indeed, referring to Thecosome pteropod as the 'sea butterfly' is most appropriate. However, as was alluded to at the outset, these tiny little creatures and their unique locomotive characteristics offer insights into a far bigger issue – acid acidification.

The Relationship Between Pteropods and Ocean Acidification

In 2012, Dr Yen and her team published an interesting observation. They noted that the wing-beat frequency of the sea butterfly decreased with body size. Although not the focus of their project, this turned out to be a significant observation. How so? Given that sea butterflies possess a calcium carbonate-based shell that can be easily broken down by acids, rapidly rising ocean acidity would obviously have an impact on the size and weight of sea butterflies. This, in turn, would affect the way they move through the water. Could the locomotive behaviour of the sea butterfly, therefore, be an indicator of ocean acidity?

In their work with the portable high-speed tomographic PIV instrument, during which they studied shelled Antarctic pteropods at Palmer Station, Antarctica, they made this inference: '[Shelled pteropods] are important organisms to study because of their novel swimming characteristics and the potential for these characteristics to serve as indicators of ocean acidification.' Indeed, as they mentioned in the associated paper, increased ocean acidity dissolves the shells of sea butterflies, which reduces their weight, and affects their locomotion. In summary, changes to the locomotive characteristics of shelled planktonic species such as the sea butterfly may, in fact, be an indicator of increasing ocean acidity.

Insights from a Tiny World

Of course, as is often the case with ground-breaking work, further studies are required to establish and validate the link. In fact, that very much describes the current work of Dr Yen and her team. As she highlights, 'Our goal is to develop a behavioural assay to provide an early warning of the effects of ocean acidification. Our focus is on the plankton, a key link in the aquatic food web. The behaviour of interest is the locomotion by [the sea butterfly]'. Work has already begun on this project and detailed studies of planktonic locomotion are underway.

To summarise, Drs Yen, Murphy, Adhikari and Webster aim to document the biomechanics of a range of planktonic species, including the sea butterfly, and input the data acquired into computational fluid dynamics models. These models, in turn, will be used to predict how their behaviour will change in relation to variations in shell weight. If the link between ocean acidification and shell weight reduction is established and validated, planktonic locomotion could be used as an indicator of ocean acidification.

It goes without saying, this is most certainly intriguing work. Not only is it fascinating to learn about the unique anatomy and behaviour of the sea butterfly, it is interesting to learn how this intricate process can be affected by a gradually changing environment. Given the threat that ocean acidification presents to marine ecosystems, the insights acquired in this research will be invaluable. In conclusion, Dr Yen's research offers an incredibly detailed insight into a massive environmental problem – from the tiny world of the sea butterfly.

Meet the researcher

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Dr Jeannette Yen received her PhD in biological oceanography from the University of Washington, Seattle in 1982. She currently serves as Professor of Biology at the Georgia Institute of Technology, and has been with the institution since 2000. She is also the Director of Georgia Tech's Center for Biologically Inspired Design. The Center brings together a group of biologists, engineers, designers and physical scientists who seek to facilitate interdisciplinary research and education for innovative products and techniques based on biologically-inspired design solutions. For example, she and her colleagues have been working on understanding the unique locomotive characteristics of the Thecosome pteropod, commonly known as the sea butterfly. Specifically, they are researching the relationship between these characteristics and changing oceanic conditions, with emphasis on ocean acidification. Dr Yen has also contributed much to the public communication of science. For example, she recently collaborated with Mel Chin to project plankton above Times Square using augmented reality.

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Georgia Tech

UNDERSTANDING WILDFIRE EFFECTS TO INFORM BETTER FOREST MANAGEMENT

Forest wildfires are increasing in frequency and severity across the globe, and this trend is expected to continue as climate change worsens. However, measuring the impacts of wildfire on forest ecosystems is extremely difficult. **Dr Bianca Eskelson** from the University of British Columbia and her colleagues at the United States Forest Service utilise vast datasets and investigate conditions before and after wildfires, to quantify their immediate and long-term effects on forest ecosystems. The team's research is improving our understanding of the effects of forest wildfires to inform better forest management.

A Growing Threat

In recent years, forest wildfires have been increasing in frequency, severity and extent, and this trend is set to continue into the future. This is because our carbon dioxide emissions are driving up global temperatures, causing parts of the world to become drier, and substantially increasing the chances of wildfire.

Furthermore, the world's forests hold enormous amounts of carbon, and trees continuously remove carbon dioxide from the atmosphere as they grow, partially offsetting our emissions. Wildfires can release this stored carbon into the atmosphere, and reduce the number of trees available to absorb it, driving up levels of atmospheric carbon dioxide.

Therefore, it is critical to quantify the impacts of forest wildfires, in terms of the amount of carbon released to the atmosphere and the damage caused to forest ecosystems. It is now more important than ever before to closely monitor the world's forests, to identify forest ecosystem recovery trajectories, in order to fully understand wildfire impacts on carbon and devise management strategies that mitigate wildfire severity and ameliorate fire impacts on carbon.

Large-scale forest surveys have traditionally only focused on estimating timber production. However, over the last few decades, surveys have been updated to include the assessment of other forest resources and to consider ecosystem health. Of course, this means that the ways in which forests are surveyed have also changed to include more variables. This data can now be used to observe and quantify changes in forest resources caused by wildfires.

Dr Bianca Eskelson of the University of British Columbia, and her collaborator, Dr Vicente Monleon of the US Pacific Northwest Research Station, focus on observing forest conditions both before and after wildfires occur, and quantifying the impacts of fires. Because dead wood left over after fires can

continue to release carbon dioxide for years, some of their work focuses on investigating the post-fire dynamics of forest carbon.

Using Forest Inventory Data

Forest Inventory and Analysis (FIA) Program data is incredibly useful when carrying out any kind of study on US forests. It provides a spatially balanced sample across all forest regions of the US, with one plot for every 24 square kilometres. It also provides a large sample, representative of past wildfires across all burn severities, which can help improve our knowledge of wildfire effects and inform future forest management and policy decisions.

The use of FIA data for regional analyses has increased over the last 15 years. Yet most previous research on wildfire impacts has focused on individual, high-severity fires in small areas. However, using FIA data for large-scale studies to evaluate both the pre-fire and post-fire conditions of forests produces results that are highly accurate, not just for a specific area, but for anywhere with similar forests, meaning the findings of these studies can be applied to US forests in general and are not restricted to a single fire that was studied intensively.

Dr Eskelson and her colleagues overlaid FIA plots with existing Burn Severity Mosaics from the Monitoring Trends in Burn Severity program, which maps the location and severity of wildfires. This allowed them to identify unburned areas, and areas that experienced wildfires of varying levels of severity (low, moderate and high) for use in their studies. This provided the team with a dataset that offers the full picture of how wildfires of different severities affect forest carbon.

Changes in Woody Carbon

Carbon pool dynamics (a forest's capacity to store or release carbon) after wildfire represent a gap in our understanding of how fires can affect forest carbon storage many years after a fire occurred. Much previous research has been restricted to case studies of individual fires and has focused on very limited conditions.

Therefore, to gain deeper insight into how fire alters forest carbon pools, Dr Eskelson and her colleagues used data from the FIA Program based on 32 wildfires across California from 2002 to 2009. The team found that pre-fire carbon and post-fire carbon are highly linked regardless of burn severity, meaning the pre-burn state of a forest is important in predicting fire impacts.

Their results showed that, compared to a typically assumed 100% decrease in live woody carbon in high-severity wildfires, low-severity wildfires only result in a 3% reduction in live woody carbon, while moderate-severity fires lead to a 37% decrease on average. This result highlights that the amount of carbon dioxide released in a wildfire can vary greatly depending on the severity of the fire. It also confirms that using post-fire estimates for high-severity fires, which have been the focus of many previous studies, is not appropriate when estimating the likely damage to forests that are prone to moderate or low-severity fires.

Changes in Ground Fuels

Forest floor litter consists of freshly fallen, dead, non-woody plant material, such as leaves. Meanwhile, duff forms the layer below litter and is made up of partially decomposed organic material that is no longer identifiable. Together, litter and duff make up the ground fuel of a forest, which can facilitate the spread of a fire and determine its severity. During forest wildfires, duff and litter tend to burn away, and it can take a long time to recover this ground fuel layer. The amount of ground fuel present can also influence future fire behaviour and affect the productivity and nutrient availability of the surrounding forest ecosystem.

Dr Eskelson and her colleagues observed that the amount of duff changed very little in the first nine years following fire in the surveyed plots. They determined that this was likely due to the lack of litter available after a wildfire and the long time it takes for litter to decompose and replace the duff that was lost. This is especially true for forests in the dry climate of California.

Dr Eskelson and her colleagues discovered that the amount of forest floor litter was lower one year following a high-severity wildfire compared to that after a low- or moderate-severity fire. However, this difference was not as pronounced compared with the difference between the amount of duff one year after a high-severity wildfire and that present following a low- or moderate-severity fire. This suggests that the litter they observed one year post-fire fell and accumulated after the fire. In particular, they found that dry conifer plots have a higher litter input in the first year after a fire than hardwood plots, due to the fall of needles from scorched crowns.

The team's results offer new insights into ground fuel dynamics after wildfire, and the conditions are representative of what occurs in other similar forests. This means that the trends revealed in their research can be generalised to all wildfires in the region that burned with low, moderate or high severity in both hardwood and dry conifer forests in California.

Calculating Combustion Factors

By matching burned plots with similar unburned plots in the Pacific Coast states, USA, the researchers were able to analyse large-scale forest survey data in a way that was similar to a controlled experiment. This allowed them to more accurately quantify the effects that wildfires have on forests. Dr Eskelson and Dr Monleon used this matched data to estimate the average combustion factor of coarse woody material and determine how much wildfire decreases the amount of material present. The combustion factor is simply the fraction of coarse woody material that is consumed by fire.

Their estimated combustion factors were much higher than those previously reported in the regions surveyed. This means that wildfire decreases the amount of coarse woody material more than had been previously thought. As mentioned earlier, previous studies in the area have never been done on this scale and cannot be generalised in the same way that the team's results can, which are based on a large spatially-balanced dataset representative across a range of fire severities and forest types.

From their findings, the researchers conclude that the combustion of coarse woody material in wildfires should be taken into account as an important factor when estimating carbon emissions due to wildfire. Understanding the amount of carbon consumed in different pools across a range of fire severities, will prove extremely useful in mitigating or even preventing future fires, as well as informing climate change predictions.

Future Fire Management

As large wildfires become more common, post-fire management such as reforestation and fuel reduction are vital in reducing the likelihood of reburning. This is why Dr Eskelson's work on post-fire conditions and fuel dynamics is so important, as these factors determine burn severity. Understanding post-fire dynamics will allow forest managers to choose appropriate management strategies that reduce reburn probability and severity, resulting in conservation efforts that are truly effective.

The research team's approaches to analysing long-term monitoring data can be adapted for data collected in other regions and used to assess the effects of other natural disturbances, such as insect outbreaks, drought or storms. It may provide insight on the magnitude of such disturbances and guide future research directions, allowing effects to be quantified and management plans to be adapted accordingly. The team's results on surface fuel dynamics will help fire managers to assess the probability of reburning so that they can develop mitigation strategies.

Dr Eskelson's future work will focus on analysing more post-fire data as it is being collected by the FIA program, enabling future analysis of longer recovery periods in forests after a wildfire. Her team's research serves as a foundation for using long-term monitoring data to assess post-fire recovery, and more generally post-disturbance recovery, across US forest ecosystems.

Meet the researcher

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Dr Bianca Eskelson earned her Bachelor's in Forest Sciences and Forest Ecology from the Georg-August University, Göttingen and her Master's in Statistics from Oregon State University, Corvallis. She was then awarded her PhD in Forest Biometrics from Oregon State University in 2008. Dr Eskelson is currently an Assistant Professor of Forest Biometrics in the department of Forest Resources Management at the University of British Columbia, Vancouver, Canada. Here, she works on quantifying natural disturbance effects and assessing post-disturbance dynamics from forest inventory data.

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THE UNIVERSITY OF BRITISH COLUMBIA

MAINTAINING PEATLAND HEALTH TO MITIGATE CLIMATE CHANGE

The global peatland ecosystem has often been overlooked in its importance within the global geochemical cycle. It contains approximately 21% of global carbon, and their maintenance and restoration are vital for lowering atmospheric carbon dioxide, the primary driver of climate change. **Dr Bernd Lennartz** of the University of Rostock and his team of interdisciplinary scientists are investigating peatlands and how they respond to changing climate conditions.

Valuable Ecosystems

You might think that the desolate bog stretches in the Scottish Highlands are merely a frustratingly soggy obstacle for hikers, but peatlands are an extremely significant ecosystem on Earth. Found in almost every country, they cover 3% of the Earth's land surface, and support a wide biodiversity.

Peatlands form over thousands of years, in waterlogged areas. Under these conditions, the decomposition of plant material is extremely slow. New plants grow on top of dead material and so plant material accumulates. These partially decayed plants form peat soil, which has a high carbon content, a low density and a high water content.

Peatlands have a significant impact on both the local and global environment. They act as a source of food and habitat for countless species, while also regulating the global water cycle and filtering pollutants. They also play a major role in global biogeochemical cycles, especially acting as a major carbon sink. In fact, peatlands remove 0.37 billion tonnes of carbon dioxide from the atmosphere each year, meaning that their maintenance and restoration is vital in the fight against climate change.

Dr Bernd Lennartz of the University of Rostock and his team of interdisciplinary scientists are investigating the functions of peatland ecosystems. Using a combination of in-situ measurements and modelling approaches, they are furthering our understanding of these complex ecosystems and how they may be affected by Earth's changing climate.

Human Impacts

Human activity is having a severe effect on the health of peatland ecosystems. Peatland areas are frequently drained to provide space for agriculture and construction. They are often found along coastal stretches, where the placement of structures such as dykes and levees alter the water and nutrient exchange between the ocean and wetland. Peatlands have also been over-exploited, with peat material being used as a fossil fuel in many countries.

As peatland is drained of its water, the soil's pore structure is altered and becomes aerated. This means that the plant material is mineralised, and the peat starts to be transformed into a mineral soil. This process is termed 'peat degradation' and is accompanied by soil subsidence (of several metres in selected locations) and a loss of ecosystem functions.

Research into peatland ecosystems has been limited until recently, particularly the behaviour of water in peat soil (its 'hydraulic' properties). Dr Lennartz and his colleagues established a dataset of hydraulic information collated from previously published research (including their own) representing a wide range of peat types from all over the world. This included information about soil water retention, as well as data on hydraulic conductivity (how easily water can move through the soil). The analysis of the data employing various hydraulic models allowed the team to identify general information on the hydraulic behaviour of peat-soils in various stages of degradation.

They found that degraded peat soils possess different hydraulic properties to pristine peatland. Peat in good condition has a low density with high porosity. However, as it degrades through drainage, its porosity decreases, and its overall density rises. This affects how easily water can move through the soil, how well it is filtered by the peat soil and how much can be stored. The team revealed that the bulk density of peatland serves as an excellent proxy for determining the extent of peat degradation.

Dr Lennartz and his colleagues then went on to propose a system of categorising degraded peat soils with respect to their ecosystem function in the water cycle. By identifying their soil water storage capacity and their hydraulic conductivity, along with the importance of the peatland within the surrounding ecosystem, the team created a scale ranging from pristine to extremely degraded. The researchers hope that this categorisation system will help future peatland conservation projects to identify the best methods of peat restoration.

Interdisciplinary Research

Dr Lennartz is part of a working research group that combines in-situ measurements with modelling, the Baltic TRANSCOAST research training group. The team comprises an interdisciplinary group studying how hydraulic, geochemical and biological processes are connected using a low-lying coastal peatland adjacent to the Baltic Sea as a case study. They found that changes in this peatland ecosystem have far-reaching effects, within both the neighbouring terrestrial ecosystem and the marine environment.

The team is particularly interested in how the Baltic peatland may respond as sea levels rise due to global warming, fundamentally altering the ecosystem. The study area exhibits a complex relationship between groundwater, river and marine water sources that affects the peatland soils. The interdisciplinary nature of the research team means they are able to analyse a wide range of peatland features using various measurements throughout the peatland, the surrounding ecosystems and the adjacent marine environment. This includes changes in salinity caused by flood events, the effects of increased nutrients in degraded peat and the emission of greenhouse gases. Eventually, the team hopes to establish models based on these measurements to analyse peatlands in coastal settings around the world.

Climate Change and Peatland

The degradation of peatlands has far-reaching global effects. They act as a major freshwater store, containing approximately 10% of global freshwater. As mentioned earlier, they also represent a large carbon sink, containing around 21% of the global soil carbon, owing to the large quantities of plant material. As peatland is drained, the peat soil becomes aerated, and organic matter and nitrogen become mineralised. This leads to the production of greenhouses gases including carbon dioxide, methane and nitrous oxide.

In a recent study, Dr Lennartz and his team compiled a large dataset of peatland properties, such as pore structure, the ratios of oxygen and hydrogen to carbon and changes in dissolved carbon compounds, from peatlands in Europe, Russia and Canada. This was built both from published data as well as a variety of in-situ measurements, such as bulk density and pH. The team then completed statistical analysis to estimate nitrous oxide emissions.

The team used bulk density to represent the extent of peat degradation, and discovered that the release of nitrous oxide and dissolved carbon compounds was correlated to this. They found that the more degraded the peatland, the more compounds are released. The researchers then created a model that can be used to predict these emissions across different types of land management areas. This information has not been well defined in previous predictions of peatland emissions, and so this is vital information for accurately modelling the effects of climate change. The functions the team derived are even more accurate than those used in the latest IPCC report.

Dr Lennartz and his team's expertise in nutrient dynamics has proved to be invaluable in their research into peatlands. These vitally important ecosystems play significant roles in global biogeochemical cycles, exporting nutrients to rivers and seas. About 15% of the world's peatlands have already been drained, and due to climate change, an increased level and intensity of droughts will continue to threaten the health of peatland ecosystems.

The ability to accurately understand and predict greenhouse gas emissions from peatlands will be vital for understanding how the global climate will continue to change. As human-induced greenhouse gas levels continue to rise, it is important we find ways to reliably conserve and restore our peatlands, and understanding their complex, interconnected systems is the best place to start.

Agricultural Soils

In another research direction, Dr Lennartz has also used modelling and experimental methods to study the movement of nutrients in agricultural soils as well as catchments – ranging from individual field sites to river basins. Although their use is usually carefully monitored in crop production, nitrogen and phosphorous-based fertilisers often enter ground and surface water, where they can have severe consequences for the aquatic ecology.

In several published studies, the researchers found that the yearly nutrient export from agricultural fields is related to the amount of precipitation and the ways in which nutrients move through the soil. In this context, the artificial drainage of agricultural fields plays a central role, as it fast-tracks the movement of nutrients from the soil surface into water bodies. Therefore, artificial drainage systems may cause unexpected high concentrations of nutrients in ground and surface water.

Dr Lennartz and his colleagues then assessed the applicability of a well-established model called the Soil and Water Assessment Tool (SWAT) for predicting the nitrogen and phosphorus concentrations, along with the crop yield, in agricultural catchments within Germany. Using the SWAT model, the team was able to reproduce daily measurements of streamflow and nutrient concentrations with high accuracy, indicating that it could be a useful tool for predicting the movement of water and nutrients in various climate change and land-use change scenarios.

Understanding how nutrients may be exported from a catchment area to the sea, or other large water bodies, is vital for reducing agricultural pollution and enhancing water quality. The team has shown that a combination of in-situ measurements and modelling can provide accurate information and therefore aid with sustainable land management.

In their research, the group is now focusing on the so-called legacy effect, which describes the accumulation of nutrients in catchments over decades. This effect means that nutrients will continue to be exported from the land to the sea for many years, even if radical changes in land management are promptly implemented.

Meet the researcher

Professor Bernd Lennartz
Agricultural and Environmental Sciences
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Professor Bernd Lennartz was awarded his PhD in 1992 at the University of Kiel in Germany. He is currently a Professor of Soil Physics at the University of Rostock. He has also worked as the Scientific Director of the Jimma Institute of Technology, Ethiopia, and Head of the Maritime Systems Department at the University of Rostock. Now, Professor Lennartz is the spokesperson for Baltic TRANSCOAST, a research group that investigates the biogeochemical processes where land and sea meet, and the impact of climate change on low-lying coastal peatland. Professor Lennartz is particularly interested in the movement of water though soil, fields and the landscape, with a focus on nutrient mobility and management of agricultural soils.

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FUNDING

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Universität Rostock

REWILDING: BET ON NATURE

Opinion article by Dr Nathalie Pettorelli of ZSL (Zoological Society of London)

Climate & Biodiversity Crises

If there is one thing to celebrate about in the past year, it's the fact that the country has finally started to wake up to the climate emergency. Thanks, among other things, to the thousands of children regularly striking for their right to have a better future than the one we have been building for them, a majority of the UK public, now back a 2030 zero-carbon target.

But the climate emergency has to be understood and tackled within the context of the current biodiversity crisis, which is equally severe and far-reaching. Climate is indeed the predominant driver of life on Earth, with climate and biodiversity being closely intertwined.

On one hand, biodiversity is being affected by the rapid changes we see in temperatures, precipitation, sea levels and the frequency and severity of extreme natural events, with some species being put at direct risk of extinction with climate change, and others having started to move out of their known distribution range (as we recently showed for the UK).

On the other hand, biodiversity loss, shaped by climate change but also by other factors such as habitat degradation and loss or overexploitation, can accelerate climate change. The loss of coastal ecosystems such as mangroves, sea grass and salt marshes, for example, reduces nature's ability to help soak up carbon; forest loss and other land use changes account for a significant proportion of greenhouse gas emissions; wildlife loss can influence plant nutrient availability, which itself impacts, for example, how much carbon is released by forests.

Turning the Tide

As the planet's life-support systems are fast approaching a danger zone for humanity, there is a need to be strategic about the changes we promote for adequately turning the tide on climate change. Geoengineering solutions, sometimes introduced as the magic wand likely to solve our climate change crisis without us needing to alter our ways of living, won't stop us from losing wildlife at the unprecedented rates we are witnessing.

What we need is a shift in how we conceptualise our relationship with nature, as well as the adoption of a vision that not only promotes a different path for development underpinned by the sustainable use of natural resources, but that also acknowledges that our ability to tackle the current climate crisis is closely linked to our ability to retain and increase biodiversity.

Increasing biological diversity in a rapidly changing world is not easy however, and challenges old ways to think about biodiversity conservation. Until recently, conservation science has been busy researching how we can bring back degraded ecosystems to known 'healthy' baselines. However, the intensity and speed of global environmental changes have pressed many practitioners and scientists to realise that some species are being pushed far beyond their traditional ranges and some ecosystems far beyond their limits.

In many places on Earth, it now makes little sense to force the restoration of historical conditions, given the expected changes in environmental conditions in the coming years. In such situations, the facilitation of the emergence of novel ecosystems through rewilding may prove a more sensible and cost-effective alternative to address declining biodiversity and the delivery of ecosystem services.

‘Well-planned rewilding projects could increase carbon capture and storage capabilities and help protect communities at risk of flooding.’

Rewilding

What rewilding could offer in the context of the current climate emergency is exciting. Well-planned rewilding projects could increase carbon capture and storage capabilities and help protect communities at risk of flooding. However, rewilding also breaks many traditions in conservation, which partly explains why it has proven so controversial.

First, it promotes the idea that the future isn’t about bringing back what we know where we want it, but about supporting the emergence of functioning and biodiverse ecosystems, in whatever forms they may come. It therefore acknowledges that human control on what the wild is, where it goes, and how it should look, has to be significantly reduced if we are to see global biodiversity increase again – a stark contrast to the old Victorian vision that nature needs to be managed, controlled, and dominated.

Second, by placing the emphasis on reduced control and increased unpredictability, it recognises the overwhelming importance of securing successful coexistence between humans and nature for effective conservation-based environmental management. This consequently leads to a change of focus, from ecosystems to socio-ecological

systems, thereby leading to a repositioning of the conservation narratives, where humans are firmly part of nature, not separate and not above.

Third, it promotes a more dynamic approach to conservation, where changes and self-reorganisations are welcome, and the norm. Fourth, by being concerned with the level of functioning ecosystems exhibit rather than by their species composition, rewilding opens the door to species being introduced or welcomed in ecosystems outside of their historic distribution range – thereby firmly endorsing assisted colonisation as a

‘To make rewilding a widely implemented and efficient nature-based solution to address climate change, we need a science-based foundation that is able to inform policy and management.’

conservation tool fit for the environmental management in the 21st century.

Ultimately, rewilding is only one of the nature-based solutions that aim to co-address the current climate and biodiversity crises. But it’s by far the most tantalising one, because it has the potential to drastically impact our relationship with nature.

Admittedly, there are uncertainties and difficulties associated with the practical implementation of rewilding projects, while the evidence available for facilitating sound decision-making for rewilding initiatives is growing but remains scarce. Moreover, rewilding means different things to different people, having been interpreted by some as a way to promote the conservation of human-free landscapes, leading to conflicts between various fractions of society.

That said, as divisive as the topic may be and as tense as the current debate may appear, whoever is concerned with environmental management can simply not afford to ignore discussions on rewilding and miss potential opportunities to build a better future for the generations to come.

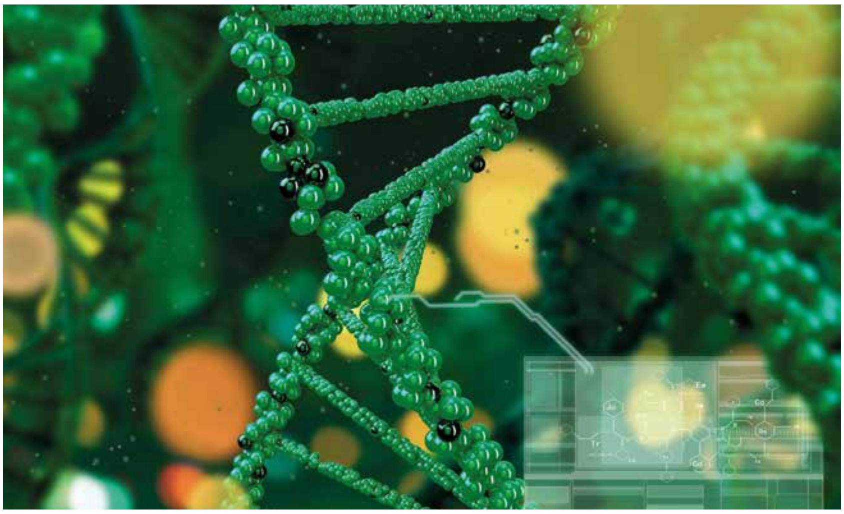
To make rewilding a widely implemented and efficient nature-based solution to address climate change, we need a science-based foundation that is able to inform policy and management: generating this foundation will require dialogue and expertise from all sectors of society. This is why I hope that, if you haven’t yet engaged with these discussions, you’ll soon do.

MEET THE AUTHOR

Dr Nathalie Pettorelli is a Senior Research Fellow at ZSL’s (Zoological Society of London) Institute of Zoology. A climate change and rewilding expert, her scientific achievements include demonstrating how satellite data can be used to support vulnerability assessments of species and ecosystems to climate change, to pioneering social media as a source of data for species on the move due to climate change. Dr Pettorelli has recently edited a book on rewilding, which provides an inclusive and representative overview of where current thinking on this topic sits.

GENETICALLY ENGINEERED PLANTS: A POTENTIAL SOLUTION TO CLIMATE CHANGE

Climate change is already having devastating effects felt across the globe. Without adequate measures to counteract the human drivers behind climate change, these negative consequences are guaranteed to increase in severity in the coming decades. Esteemed biomedical scientist, **Dr Charles DeLisi** of Boston University, urges that a multi-disciplinary approach to mitigating climate change is vital. Using predictive modelling, he has demonstrated the potential power of genetically engineering plants to remove excess carbon dioxide from the atmosphere, thereby mitigating climate change.



The Climate Emergency

Climate change is, arguably, the most significant global threat that society faces. Even small perturbations in the planet's climatic system have disproportionately severe consequences, leading to water shortages, crop failures, biodiversity loss, and increasingly common natural disasters. Without drastic measures to combat climate change, these impacts will continue to increase in severity and frequency, posing a major threat to the stability of human society and all life on Earth.

These changes are driven by increasing levels of atmospheric 'greenhouse gases', such as carbon dioxide. Released as a by-product of fossil fuel combustion and other human activities, the level of carbon dioxide in the atmosphere is over 45% higher than it was 200 years ago. Like all greenhouse gases, carbon dioxide slows the dissipation of heat from the Earth's surface into outer space, causing the planet to heat up, and disrupting its delicate climate systems.

'During the post-industrial period, the planetary temperature has increased rapidly,' explains Dr Charles DeLisi of Boston University. 'Ice sheet melting has accelerated, ocean levels have risen with concomitant increases in coastal flooding, and extreme weather events have increased in frequency.'

Emissions Reductions: Not the Whole Solution

Thus far, measures to tackle climate change have focused on reducing our emissions of carbon dioxide and other greenhouse gases. Over the last three decades, over 100 nations across the globe have signed multiple agreements to voluntarily limit their emissions, but these measures alone are proving ineffective at slowing climatic disruption.

Even if completely effective, current measures would still only solve a small proportion of the problem. Emissions from agriculture, construction and transportation are largely unaffected by current emissions restrictions, while carbon dioxide remains in the atmosphere for hundreds of years. 'Consequently, even an immediate halt

‘It is crucial that the international community agree on and develop technologies that would augment regulatory approaches by irreversibly drawing carbon from the atmosphere.’

to all emissions would not help the current situation, and the temperature would have to increase another 0.5°C or so before the heat radiated from the planet would match the incoming solar radiation,’ says Dr DeLisi.

Additionally, developing nations rely on the readily available and relatively cost-effective use of coal to meet their growing energy requirements, which will make rapid reduction in the near future difficult. Therefore, by relying solely on reducing emissions, we risk irreversibly damaging the planet’s delicate ecosystems and our own ability to sustain the human population.

Without additional measures to counteract the impact of human activity on Earth’s climate, the annual global temperature is likely to be greater than 2°C higher than pre-industrial levels before the end of the century. Methods to physically remove carbon from the atmosphere – called ‘negative emission’ – are gaining traction as a necessary strategy to slow climate warming over the next few decades while countries across the globe develop the infrastructure required to use greener energy sources. As Dr DeLisi explains: ‘It is crucial that the international community agree on and develop technologies that would augment regulatory approaches by irreversibly drawing carbon from the atmosphere.’

Removing Atmospheric Carbon

Dr DeLisi, whose academic achievements include the development of the Human Genome Project, proposes the use of Synthetic and Systems Biology (SSB) to develop powerful tools to remove carbon from the atmosphere. He suggests that by using the revolutionary genetic techniques of SSB that could scarcely have been imagined just a decade ago, genetically modified plants could help regulate the carbon cycle and achieve negative emission. Dr DeLisi’s proposals have the potential to inform an interdisciplinary approach to mitigating climate change that could help society avoid disastrous consequences.

A number of carbon removal strategies have been proposed previously, however, Dr DeLisi’s recent opinion piece in the peer-reviewed journal *Biology Direct* is the first of its kind to incorporate suggestions based on SSB technologies into an atmospheric carbon dioxide prediction model.

By using SSB technologies to develop plants with a greater capacity for removal and storage of carbon from the atmosphere, Dr DeLisi suggests that the ‘fast carbon cycle’ – the exchange of carbon between land, sea and atmosphere over decadal time scales – could be manipulated to achieve negative emission. Without human influence, approximately 120 gigatons (120 billion tonnes) of carbon is removed from the atmosphere each year by plants during photosynthesis, while almost the same amount of carbon is returned to the atmosphere through plant and microbe respiration.

Dr DeLisi explains that SSB technologies could be used to design plants and microbes that return less carbon dioxide to the atmosphere than they remove, thus shifting the annual cycle towards carbon-negative values.

Modelling Atmospheric Carbon Removal

Dr DeLisi proposes a few potential methods of using SSB technologies to modulate the fast carbon cycle that warrant further investigation. For example, genetically engineering plants that have an increased ‘root to

shoot' ratio could help them to capture more carbon beneath the soil. Genetically engineered soil microbes that perform a similar function are also within the realms of possibility. Other strategies warranting further investigation include genetically modifying trees that are not under large forest canopies to produce pigments that help to reflect heat away from the planet's surface – which may become increasingly important as larger areas of the polar ice caps are lost to melting.

To demonstrate the potential power of atmospheric carbon removal strategies that employ SSB technology, Dr DeLisi modelled the potential reductions that could be achieved using genetically modified trees under different hypothetical scenarios. 'Trees were used to fix ideas because they are the dominant engine of carbon turnover, so in the longer term I expect they will be the major mitigant,' he says.
If 10% of the planet's trees were genetically engineered to operate at 90% efficiency, atmospheric carbon would drop from its current level of 850 gigatons to 647 gigatons over a period of 80 years. However, the model also highlights the importance of using atmospheric carbon removal strategies in conjunction with measures to reduce emissions, as these results can only be achieved if emissions also steadily reduce to zero over the next 80 years.

Currently, an extra 5 gigatons of carbon is added to the atmosphere each year due to human activity. Without a reduction in emissions, Dr DeLisi's model demonstrates that even with the best outcomes for modified tree efficiency, atmospheric carbon would only be reduced to 833 gigatons over the 80-year period. In contrast, reducing emissions without using additional removal techniques would see the atmospheric carbon levels rise to 1047 gigatons during the same period.

Delaying these actions also has significant consequences. Reducing emissions, as we are currently attempting, but delaying implementation of carbon removal strategies by 20 years, adds approximately 100 gigatons of carbon to the atmosphere. Even at optimum modified tree efficiency and successful reduction of emissions, a delay of 20 years would result in atmospheric carbon levels of 793 gigatons after an 80-year period, in comparison to the 647 gigatons achievable if actions were implemented immediately.

The Future is Collaboration

Trees are likely to be an important component in long-term strategies to mitigate climate change. However, the complexity of their genomes is likely to delay their utility in carbon removal strategies. In contrast, many agricultural crop plants have already been genetically altered to produce desirable characteristics. As Sir Richard Roberts, a leading molecular biologist commented: 'Agricultural crops grown for food production might be a better short-term target. Many are already understood genetically sufficiently well that further modification might be relatively straightforward.'

Having demonstrated the ramifications of delaying atmospheric carbon removal strategies, Dr DeLisi agrees that using other plants as short-term solutions may be vital. 'The fact that many agricultural plants are much better understood than trees and would offer a quicker start is especially important given the urgency of the problem,' he says.

However, Dr DeLisi emphasises that to progress towards these goals, a thorough evaluation of various potential strategies is necessary. 'What's needed now is a careful vetting by the scientific community of the various technical strategies, including the state of the underlying science, plausible timelines and trade-offs between different approaches, costs, environmental impact, efficacy and governance,' he elaborates.

Ideally, the success of climate change mitigation strategies will be amplified through collaboration between researchers from multiple scientific disciplines. For example, plant physiologists and synthetic and systems biologists and engineers will need to work closely together to genetically engineer plants with the required carbon removal characteristics. 'We're hoping that some of the ideas generated by engaging various communities – climate scientists, biotechnologists, ethicists, policy experts – will be helpful in formulating a scientific plan to begin addressing this challenge, which will require strong international collaboration,' says Dr DeLisi.

Given the immense complexity and potentially devastating consequences of climate change, it is imperative that all available technologies are given serious consideration. In previous decades, focus has largely been on strategies to reduce greenhouse gas emissions. However, Dr DeLisi's model demonstrates absolutely that a multifaceted plan employing many different strategies is necessary to avoid a worldwide climate disaster.

Meet the researcher

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Dr Charles DeLisi earned his PhD in Physics from New York University, before continuing onto postdoctoral research in Chemistry and Engineering at Yale University. His pioneering research into immunology, cell biophysics, genomics, and protein and nucleic acid structure and function has been internationally recognised. He is considered the father of the Human Genome Project. Dr DeLisi currently holds the positions of Professor of Biomedical Engineering, and Metcalf professor of Science and Engineering at Boston University. His research team within the Bimolecular Systems Laboratory develops and applies computational and mathematical methods to investigate gene and protein expression within cells. Dr DeLisi has recently been applying his extensive expertise to identifying potential solutions to global problems such as climate change.

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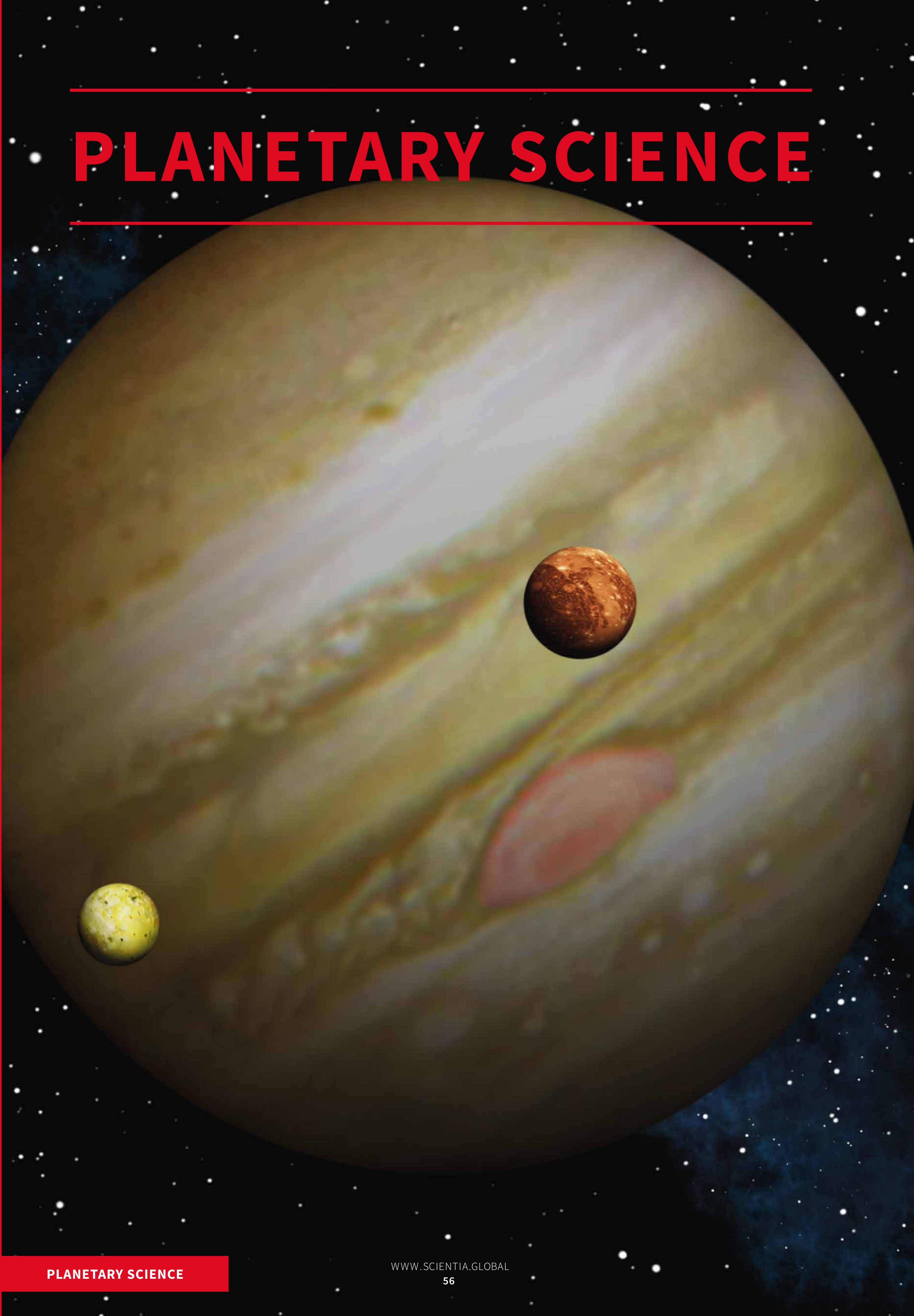
BOSTON UNIVERSITY

PLANETARY SCIENCE



GROUND-BREAKING RESEARCH IN GEOPHYSICS AND PLANETARY SCIENCE

In this section of the edition, we highlight some of the latest research in the diverse fields of geophysics and planetary science. Here we explore everything from the threat of anomalous solar activity, to the origins of water ice on Mercury.

Our first section dealt with climate change, and methods to predict and mitigate its damaging effects. Therefore, to kickstart this section, we move beyond Earth's atmosphere, where another danger looms. While the instability of Earth's climate is causing more extreme weather events, the conditions surrounding our planet – 'space weather' – can also become unstable, leading to significant problems for human society.

Space weather is caused by the continuous stream of charged particles emitted by the Sun called the 'solar wind'. Fortunately for us, Earth's protective magnetic field bends the paths of these charged particles, deflecting them away from the Earth's surface. Without this protective 'magnetosphere', life as we know it would be unable to survive.

However, during solar flares and other events, the Sun can spew out enormous bursts of particles, which can trigger dramatic phenomena such as geomagnetic storms and auroral displays upon interacting with our magnetosphere. During a geomagnetic storm, the increased electric current in the Earth's magnetosphere can flow into electricity transmission lines, destroying transformers and causing widespread blackouts.

These bursts of solar wind can also severely damage the satellites we depend on for communication, air-traffic control, weather forecasting, GPS and the internet. If they fail, our societies could begin to deteriorate, with food supply chains rapidly breaking down. For these reasons, space weather is an active area of research.

Space weather phenomena are the focus of our first four articles of this section, the first of which directly investigates the source of solar wind bursts – the Sun's corona. Because the Sun is so much brighter than its surrounding environment, the properties of its corona can be incredibly hard to spot under typical observing conditions. To solve this problem, Dr Shadia Habbal at the University of Hawaii and Dr Miloslav Druckmüller at Brno University make use of one of the most well-known astronomical phenomena: total solar eclipses.

Next, we showcase the work of Dr Robert Ebert at the Southwest Research Institute, who combines spacecraft observations with the latest computer models to explore the interactions between the solar wind and interplanetary material. He also investigates how these interactions can cause charged particles from the Sun to become even more energetic, increasing their ability to cause problems on Earth.

Dr Andreas Keiling of the University of California at Berkeley, who we feature in the next article, has a particular interest in the complex processes that take place during geomagnetic storms. Using data collected by the Polar satellite, his team has been able to investigate the role of a type of wave called 'Alfvén waves' in transporting energy through Earth's magnetosphere.

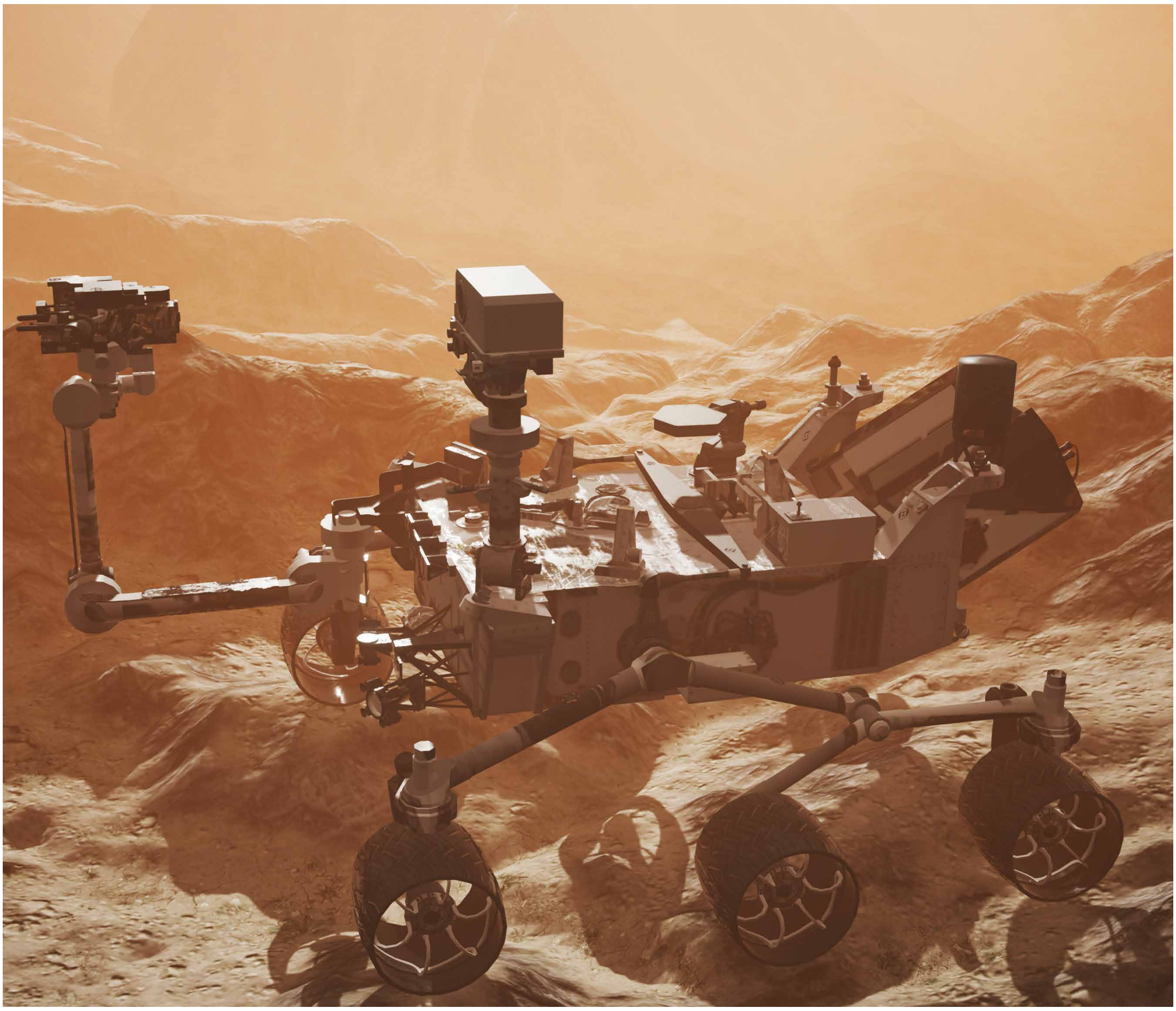
Also studying the complex relationship between the solar wind and Earth's magnetosphere is Dr Joe Borovsky at the Space Science Institute of Boulder, Colorado. By helping to predict when our communication and power transmission systems will come under threat from anomalous solar activity, the team's research may prove invaluable to safeguarding our increasingly connected society.

Continuing on the theme of predicting natural disasters, we now shift our attention to forecasting earthquakes. Between the 2000 and 2016, there were nearly 30,000 earthquakes recorded worldwide with a magnitude of 5 or greater. These devastating earthquakes caused hundreds of thousand fatalities, many of which could have been avoided if such events could be anticipated, allowing time for people to evacuate. However, earthquake prediction is often dismissed by seismologists and geophysicists as a pipedream.

In this section, we meet Professor Friedemann Freund, who has developed a deep understanding of the processes that give rise to non-seismic signals before major earthquakes. He and his research team at the NASA's Ames Research Center in California have shown that there is a single physical process, occurring deep in the Earth's crust, that could explain all of these non-seismic, precursory effects. In future, their work holds the potential to change the course of earthquake prediction.

Keeping our focus underground, we introduce Dr Mike Müller-Petke of the Leibniz Institute for Applied Geophysics, and Dr Stephan Costabel of the Federal Institute for Geosciences and Natural Resources, who investigate methods to improve the detection of underground water, using a technology known as nuclear magnetic resonance. Developing more reliable methods for detecting underground water is of considerable importance, particularly for applications such as groundwater exploration, predicting the movement of contaminants in soils and building underground tunnels.

Dr Nancy Chabot and Dr Carolyn Ernst of Johns Hopkins University Applied Physics Laboratory, and Ariel Deutsch at Brown University, are also interested in detecting water. However, they focus on measuring the amount of water ice that exists in the permanently shadowed polar regions of Mercury. Using data from NASA's MESSENGER mission, the team has



been working hard to uncover how water may have arrived on Mercury, potentially revealing clues about how the planets evolved.

Also studying planetary evolution is Dr Scott King of Virginia Tech, who has a particular interest in the dwarf planet Ceres, which lies within the asteroid belt between Mars and Jupiter. Here, we showcase his team's investigations exploring the interior structure of Ceres, which holds valuable information about the formation and evolution of our solar system.

Although a vast wealth of planetary information has been obtained by orbiting spacecraft, such as MESSENGER in the case of Mercury, and Dawn in the case of Ceres, obtaining actual samples from planetary bodies could offer even greater insight into the formation and evolution of the solar system. This is the focus of our next article, where we feature the work of Dr Robert Winglee at the University of Washington. Through detailed computer design and field experiments, his team has now demonstrated that obtaining core samples from planetary surfaces could one day become a reality.

In the next two articles of this section, we shift our attention to the weather on the moons and rocky planets of the solar system. First up is Dr Scot Rafkin, a planetary scientist at the Southwest Research Institute, who demonstrates that small-scale patterns in the atmospheres of Titan and Mars are directly comparable with Earth's weather. Also working in this field is Dr Liming Li at the University of Houston, who studies how planetary atmospheres generate, transfer and convert energy in different ways. His research has revealed fascinating new insights, both for astronomers and for scientists studying our own changing climate.

To close this section, we speak with Professor Mike Cruise, President of the Royal Astronomical Society – the UK's learned society dedicated to facilitating and promoting the study of astronomy, solar-system science and geophysics. In this exclusive interview, Professor Cruise tells us about the Society's exciting and varied activities, while also describing some of the latest advances in the world of astronomical research.

HIDING THE SUN: CORONAL DISCOVERIES DURING TOTAL SOLAR ECLIPSES

Extending far beyond its surface, the Sun's corona hosts a variety of intricate structures and behaviours. Yet because the Sun is so much brighter than its surrounding environment, these properties can be incredibly hard to spot under typical observing conditions. In their research, **Dr Shadia Habbal** at the University of Hawaii and **Dr Miloslav Druckmüller** at Brno University make use of one of the most well-known astronomical phenomena to solve this issue: total solar eclipses.

The Sun's Complex Behaviours

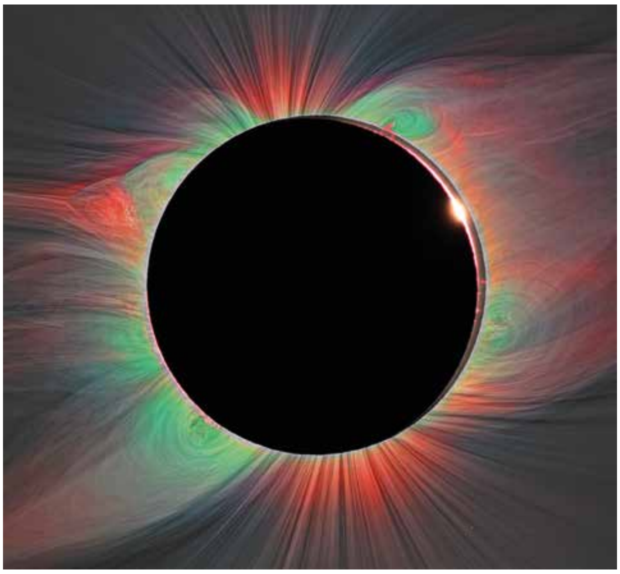
Over the past decades, astronomers have learnt much about the vast yet intricate processes that play out both on the Sun's surface, and deep within its interior. However, the complex behaviours of our host star cannot be explained by observing these properties alone. In fact, a vibrant array of physical processes also occurs in the Sun's surrounding environment, known as its 'corona'. While it is easy to observe the Sun's surface with the right equipment, the corona is far dimmer within the range of wavelengths that our eyes perceive as light. This makes the corona far more difficult to study.

'The visible surface, or "photosphere" of the Sun emits in the visible wavelength range, but it is a million times brighter than the corona,' explains Shadia Habbal, of the University of Hawaii. 'Therefore, we need to block the solar disk and photosphere to see what is happening in the corona.' Astronomers can partially solve this problem using a telescope attachment called a 'coronagraph', which artificially obscures the Sun's surface with an opaque disc. However, this technique is limited by factors including diffraction, which makes observing the innermost corona impossible, as well as scattering from the Earth's atmosphere, which decreases the contrast of coronal features significantly.

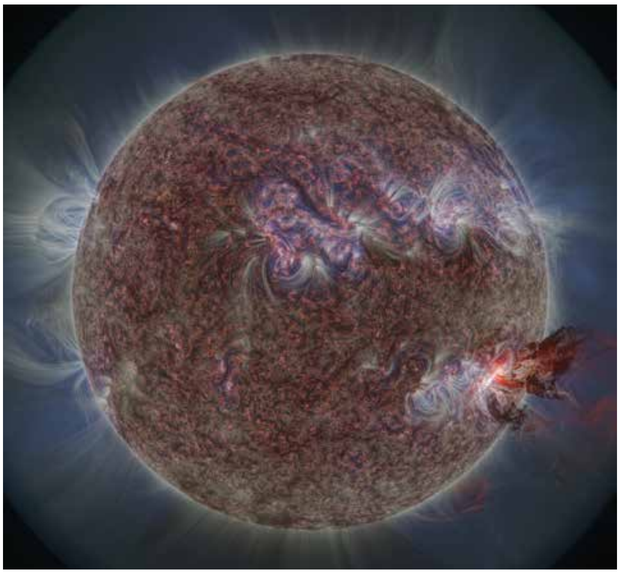
Alternatively, they can make observations in the extreme ultraviolet (EUV) range of wavelengths, instead of the visible. The solar photosphere appears as a black sphere emitting no light in the EUV range and therefore it does not need to be obscured. This makes studying the solar corona far easier. However, this technique requires access to space, and isn't without its shortcomings.

'In the EUV, the corona is visible both on the solar disk and over some distance away from its surface,' continues Dr Habbal. 'This provides a way to track the connection between features on the surface, as they project outwards, away from the Sun. However, the extension of the EUV emission beyond the surface of the Sun is limited to about a quarter of its radius. This is too short a distance to be able to follow the features as they change and evolve rapidly during their expansion away from the Sun.' To solve this issue, astronomers need a way to easily view the visible wavelengths emitted by the corona.

Solar corona during total solar eclipse of July 11, 2010. CREDIT: Miloslav Druckmüller, Martin Dietzel, Shadia Habbal, Vojtech Rušin.



Solar corona during total solar eclipse of August 1, 2008 with enhanced emission of iron ions. The green colour represents Fe XIV and the red one represents Fe XI. CREDIT: Miloslav Druckmüller, Shadia Habbal, Peter Aniol.



Solar corona in the extreme ultraviolet light taken by the AIA instrument on SDO, during a significant flare and following a huge prominence eruption on June 7, 2011. The image was created by Miloslav Druckmüller, by applying his PM-NAFE technique.

Searching Far from the Surface

Thankfully, one completely natural quirk of the solar system's dynamics has provided astronomers with the ideal solution to tackle this problem. The relative sizes of the Moon and the Sun, combined with their relative distances from Earth, mean that the Moon can almost perfectly obscure the solar disc when viewed from just the right position on Earth, and at just the right time. When this occurs, the motion of the Moon's shadow projects a dark band onto the Earth's surface, ranging from only several kilometres to around 100 kilometres wide, and a few thousands of kilometres long, which changes from one eclipse to another.

For a few crucial moments – lasting from a few seconds to seven minutes – the corona alone is visible beyond the obscuring Moon's surface, extremely close to the edge, or 'limb' of the Sun, out to distances several times the Sun's radius. This gives astronomers access to ideal conditions for observing coronal plasmas and streams of charged particles called the solar wind.

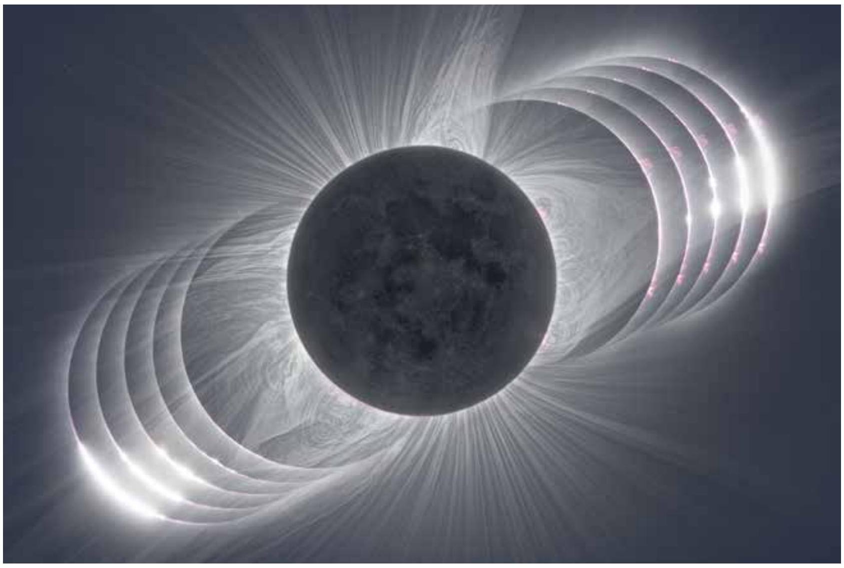
'In the visible, the coronal emission can be observed to much larger distances from the Sun,' describes Dr Habbal. 'Total solar eclipses provide the best observing conditions to capture that extent. In white light, one can capture the corona out to tens of solar radii. We can also observe specific emission lines in the visible range, produced by ions from elements such as iron, magnesium and nickel, which can be observed out to 2–3 solar radii.'

Clearly, these ranges extend far beyond those reached by emissions of EUV light in the corona. This means that by searching for visible light emission during a total solar eclipse, in combination with EUV emission, Dr Habbal, Dr Druckmüller and their team can gather far more extensive data about the properties of the corona as a whole. In particular, they are interested in studying the behaviours of plasmas and solar wind in the Sun's surrounding environment, which give rise to a variety of intriguing properties as they form and evolve over time.

Revealing Magnetic Structures

Unlike the Earth's magnetic field, which forms a simple loop connecting the north and south poles, the Sun's magnetic field is highly complex and dynamic. Since the Sun rotates faster at its equator than towards its poles, the varying motions of plasmas in its interior result in magnetic fields that become wound up into complicated patterns of twists and knots. As these fields expand, they pass through coronal gases with different densities and temperatures, creating even more complex patterns. Over time, this means that highly intricate magnetic structures will arise in the corona, which themselves give rise to a variety of interesting phenomena as they evolve.

Dr Habbal and Dr Druckmüller's group are particularly interested in the evolution of magnetic structures named 'prominences' – small, bright features made up of neutral and low ionised gases, which are anchored to the Sun's surface. Despite being cloaked in extremely hot plasma, reaching temperatures of over one million degrees, prominences themselves maintain temperatures around 100 times cooler, and are also around 100 times denser than their surroundings. By searching for evidence of these structures close to the solar surface in the visible wavelength range, the group aims to establish the role that prominences play in the behaviour of the corona as a whole.



Total solar eclipse of August 21, 2017, solar corona and Baily's beads before and after the total eclipse. CREDIT: Miloslav Druckmüller, Petr Horálek, Shadia Habbal.

'Through imaging in white light and a selection of emission lines from known ions in the corona, we search for the connection between prominences and the overlying and surrounding coronal structures,' Dr Habbal describes. 'Prominence material shows up in eclipse images in spectral lines in the visible range, which are produced by the excitation of neutral and low ionised atoms. What we have seen are cool prominence materials embedded in the hotter surrounding material.' By studying these prominences, and the surrounding plasmas that indicate their presence, Dr Habbal and Dr Druckmuller's team can link their properties to coronal phenomena on far larger scales.

Connecting Prominences with Coronal Mass Ejections

Compared with coronal plasmas and solar wind, the magnetic structures of prominences are highly complex, making them highly dynamic. This means that prominences may evolve rapidly over time, and will also erupt frequently, spewing some of their gases into space, while the rest falls back down to the solar surface. This behaviour is strongly linked to that of coronal mass ejections (CMEs) – vast releases of plasmas into the solar wind, which often precede or follow solar flares into interplanetary space. While many aspects of prominences, including their formation, cool temperatures, and densely packed, low-ionised material remain a mystery, Dr Habbal and Dr Druckmüller's team believe they have now found indisputable evidence that they are connected with CME formation.

'Prominences are the "release button" of CMEs,' Dr Habbal describes. 'A lot of turbulent motions are observed in the immediate vicinity of prominences, whose origin we still need to understand. At instances when prominences are caught detached or semi-detached from the solar surface, they will be most likely associated with CMEs.' In their total solar eclipse observations, Dr Habbal, Dr Druckmüller and their team have confirmed that as prominences erupt and unravel, they accelerate the hot plasma surrounding them to speeds of thousands of kilometres per second. Clearly, the properties of these structures have profound effects on the behaviour of the corona as a whole.

The group has also made an unexpected new discovery through observations of ionic emission lines, whose wavelengths have been shifted from our perspective due to the Doppler effect. The shifts suggest that blobs of cold, dense prominence material are travelling into interplanetary space at speeds of between 100 and 1500 kilometres per second. Furthermore, these blobs remain cloaked in hot CME material as they travel, yet still appear to escape the corona unscathed; creating a source of low-ionised interplanetary material. Such strange behaviour highlights just how much we have left to learn about the Sun and its surrounding environment.

Uncovering the Mysteries of the Corona

Dr Habbal, Dr Druckmüller and their colleagues have now made a wide variety of discoveries – many of them from observations of the total solar eclipse that darkened the arctic island of Svalbard in March 2015, as well as the more famous event that travelled the entire width of the continental US in August 2017. Through their continuing studies, the group is now searching for connections with other unexplained behaviours, including accelerations of different types of solar wind, namely the fast and the slow, and flows of heat within the corona.

Such studies would have limited impact through observations made by a coronograph, or in the EUV alone. However, through the techniques they have developed, Dr Habbal and Dr Druckmüller's team can now realistically aim to measure properties including the chemical compositions and ionisation states of coronal material as they evolve through the corona, for the first time. Their research promises to bring about ever more intriguing discoveries about the elaborate properties of our host star and its surrounding environment, many of which remain shrouded in mystery.

Meet the researchers

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Shadia Habbal is a Professor of Physics and Astrophysics, as well as Faculty Chair, at the Institute for Astronomy of the University of Hawaii. As part of her scientific research, she embarked on observations of the corona during total solar eclipses starting in 1995. Since the dimming of the sky during these events offers unsurpassed conditions for such observations, it was clear that total solar eclipses offered unique opportunities for exploring the properties of coronal structures, out to several radii above the solar surface. Known as the Solar Wind Sherpas, her team now includes up to 25 scientists, engineers and students, at any given event, as observations from multiple sites during eclipses have become imperative. Her collaborator, Miloslav Druckmüller, is a professor of Applied Mathematics at Institute of Mathematics at Faculty of Mechanical Engineering at Brno University of Technology in the Czech Republic. His main specialisation is image analysis and image processing. A mathematician by profession, he is recognised worldwide as an avid photographer specialising in eclipse and astrophotography. He joined the Solar Wind Sherpas as a key member in 2006. The synergy of their collaboration has led to significant advances in understanding some of the clues of coronal structures, most notably the role of prominences, as described in this article.

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PINPOINTING THE PHYSICS OF ENERGETIC STORM PARTICLES OBSERVED IN NEAR EARTH ORBIT

When the Sun's surrounding corona erupts, colossal streams of charged particles are ejected out into interplanetary space, and go on to interact with the material that resides there. **Dr Robert Ebert** at the Southwest Research Institute and his colleagues combine observations from spacecraft with the latest computer models to uncover the mysteries of these interactions. Their research focuses on advancing astronomers' understanding of the highly energetic processes that play out in the void that comprises over 99% of the Solar System's volume.

Energetic Storm Particle Events

Interplanetary space is home to vast numbers of charged particles, which spend most of their time being transported through the Solar System. Occasionally, however, large-scale astronomical events can drastically change their behaviour. Such events include energetic bursts of plasma originating from the Sun known as Coronal Mass Ejections (CMEs), which are thought to be caused by the intricate behaviours of the Sun's magnetic field. When interplanetary ions interact with these CMEs, they become shocked, and are accelerated to extremely high energies.

Ions accelerated at shocks associated with CMEs observed near Earth are known as energetic storm particles (ESPs). Astronomers believe that these accelerations are likely affected by a variety of factors, including the speed, strength, orientation, and magnetic turbulence of the CME shocks that caused them. Currently, however, our understanding of the process is far from complete and requires further research.

When a CME interacts with the Earth's magnetic field, it can release vast amounts of energy, creating particularly strong and beautiful aurora in the Earth's polar regions, but it can also cause significant disruption to satellites and electrical transmissions, as well as health issues for astronauts.

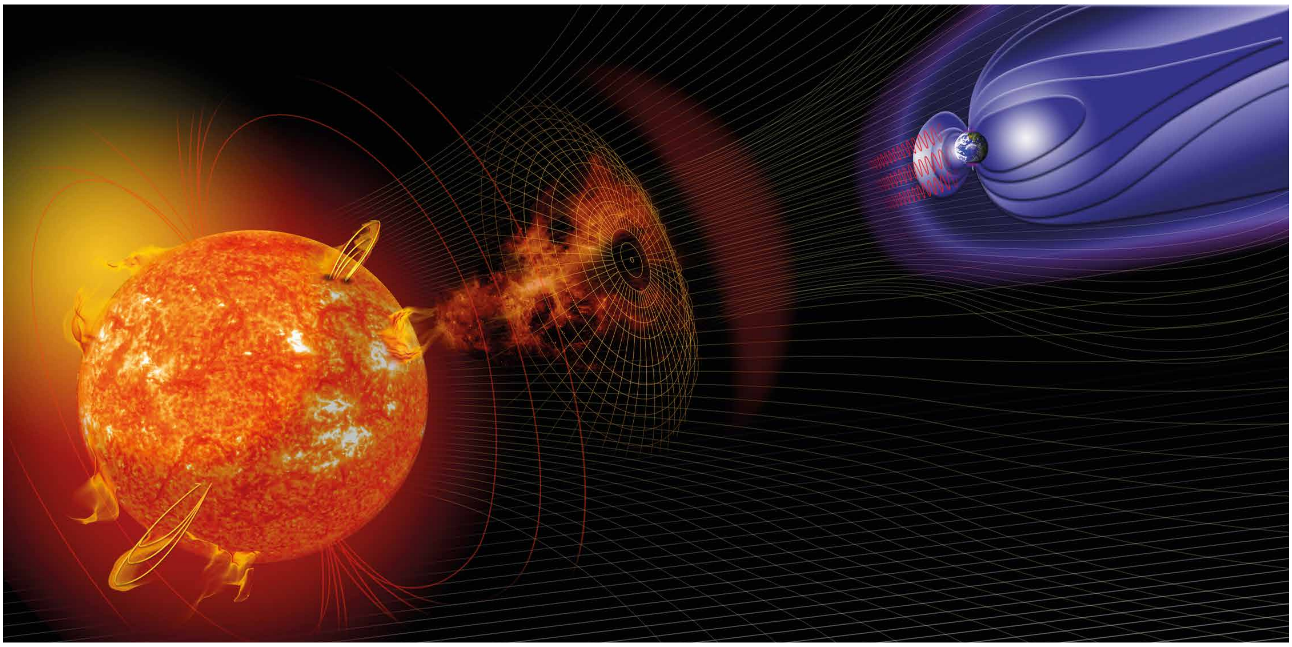
Without a complete knowledge of the physics behind these events, attempts to prepare for them will be incomplete, making our global communications networks more vulnerable. To fill these gaps in our awareness, Dr Robert Ebert at the Southwest Research Institute acknowledges that a combination of detailed observations from spacecraft with sophisticated computer modelling is urgently needed.

Learning from Observations

Over the past few decades, astronomers have used observations of ESP events to make a variety of predictions about their connections with the properties of shocks caused by CMEs. For example, the range of energies to which particles become accelerated, known as their

spectra, is thought to be dependent on the density of shocked interstellar material, while the orientation of the shock is predicted to have a strong influence on the abundances of the particles it contains. Furthermore, the properties of ESPs are believed to depend on magnetic turbulence 'upstream' from the shock.

In a 2016 study, Dr Ebert and his colleagues aimed to learn more about the properties of ESPs themselves, by observing them from two separate spacecraft. In their study, the craft took their observations at the same distance from the Sun as Earth's orbit, but at different longitudes – or distances parallel to the Sun's equator. By doing this, the researchers hoped to



Solar activity from events such as solar flares and coronal mass ejections can influence the space environment around Earth, and can affect both spaceborne and Earthbound resources such as satellites and power grids. CREDIT: NASA

uncover longitudinal variations in the relationships between the properties of interplanetary shocks caused by CMEs, and ions of oxygen and iron, during ESP events.

Their discoveries included the fact that as ESP events progress, their intensities varied significantly between the measurements of each spacecraft. On the other hand, properties including shock speed, density, and magnetic field compression and orientation, showed little organisation with longitude. Yet despite these discoveries, a variety of properties remained unexplained, which called for a more detailed examination in future research.

Identifying Gaps in Understanding

Leading on from this study, Dr Ebert and his colleagues have identified a variety of areas that could potentially lead to new insights into the physical mechanisms underlying ESP accelerations by CME shocks. Several theories in the past have attempted to link the properties of energetic particles with those of local shocks in the interplanetary medium. So far, however, these efforts have been unable to precisely predict the intensities of ion accelerations indicative of ESPs. In addition, they haven't yet consistently determined the spectra of ESPs, along with the overall abundances of the ions they contain.

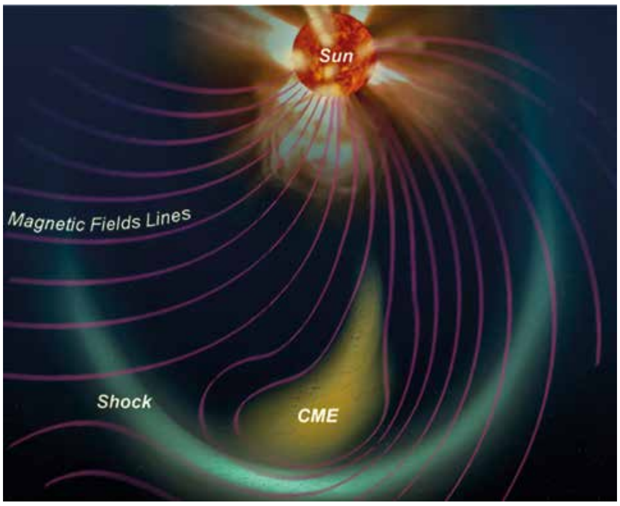
In the face of these challenges, Dr Ebert and his colleagues aim to compare the properties of interplanetary shocks, turbulence, and source material, with the intensities, spectra, and ionic abundances of associated ESP events. To pinpoint the physical drivers of these ESP properties, they have identified three key questions, to be answered through analysis incorporating both computer models and spacecraft observations.

The first of their questions is: what is the relationship between locally observed shock properties, and ESP properties such as intensities, spectra, and abundances? The second is: how does magnetic turbulence situated upstream from the shock, and the presence of ions that act as 'seeds' for particle acceleration, affect the properties of ESPs? And finally: what is the cause of variability both between separate ESP events, and within individual events, as observed from longitudinally separated spacecraft?

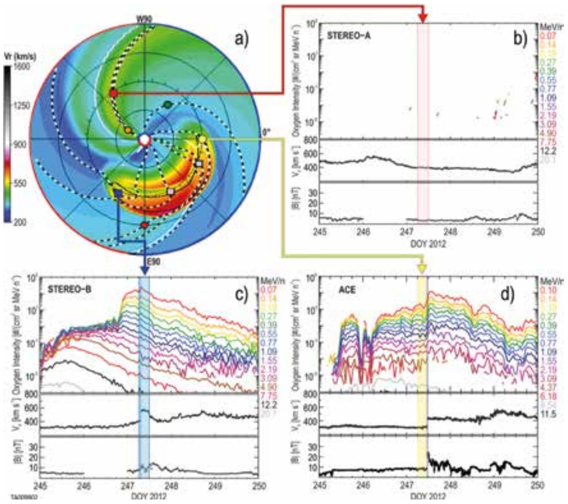
By addressing each of these questions in turn, Dr Ebert hopes to advance astronomers' current understanding of the physics that plays out as interplanetary particles are accelerated by CMEs. However, in order to find these solutions, another experimental step needs to be taken. Since the physical mechanisms that trigger particular ESP properties are so complex, and may depend on multiple parameters, the team has enlisted the help of a tool that many other branches of astronomy have turned to in recent years: the power of computer modelling.

Enlisting Computer Models

To answer their three questions, Dr Ebert and his colleagues now plan to use an advanced computer model named 'Particle Acceleration and Transport in the Inner Heliosphere' (PATH). The model is highly sophisticated, and has already been used by many astronomers studying the properties of the environment surrounding our host star during CMEs. Clearly, however, PATH would still be useless if it were not given the right instructions. In this case, Dr Ebert's team plans to use ESP and CME shock data gathered by real spacecraft to act as PATH's inputs.



Interplanetary shocks produced upstream of CMEs can accelerate ions and electrons to high energies. When observed near Earth, these high energy particles are called Energetic Storm Particles (ESPs).



Observations of CMEs, shocks and energetic particles from NASA spacecraft orbiting the Sun, along with simulations of these events, are used to study the physical processes that produce ESPs near Earth. CREDIT: The Astrophysical Journal

With this setup, they are able to systematically vary the different aspects of shock acceleration within the model, and then observe their influence on the resulting ESP intensities, spectra and abundances. This allows them to isolate the CME properties responsible for particular physical aspects of ESP production and their properties. The researchers also acknowledge that PATH would allow them to model selected ESP events from the vantage points of different spacecraft, allowing them to identify the mechanisms responsible for longitudinal variations in some properties of ESPs, as observed by Dr Ebert in his 2016 study.

This modelling framework gives the researchers a suitable basis for laying out descriptions of what they needed to measure, the tasks these measurements would address, and the expected results of their analysis.

Advancing our knowledge of ESPs

The first of these questions regarded the relationship between the plasma and magnetic properties of shocks with those properties of the ESP event as a whole. Dr Ebert's team predicts that solving this issue would require them to systematically study the influence of interplanetary shocks on ESP properties using the PATH model, and to survey several dozen ESP events within the solar cycle.

If carried out correctly, the team expects to identify whether the speed of interplanetary shocks, their strength as measured by density and magnetic field enhancements, and their orientation relative to the interplanetary magnetic field, can influence the intensities, energy spectra, and ionic abundances of ESP events.

The second question asks how magnetic turbulence and the presence of ions with energies above the nominal solar wind upstream of the shock may affect the properties of ESPs. Dr Ebert's team uses spacecraft observations and the sophisticated modelling capabilities of PATH to identify the conditions under which upstream turbulence, and the energy spectra of seed particles, affect ESP intensities, spectra and abundances.

Finally, the third question considers why there are clear differences between different ESP events, and even between single events from the perspectives of different spacecraft. Dr Ebert's team proposes that this could be answered by using PATH to model ESP events from the vantage points of different spacecraft that are longitudinally separated in space. They would then compare the results of the simulations with real spacecraft observations. The team expects that this would allow them to uncover the causes of variability in ESP intensities, spectra and abundances between these events.

A Roadmap to Future Discoveries

Having set out these clear goals, Dr Ebert and his colleagues believe they have developed a strong basis for advancing our understanding of CME-driven ion accelerations. Their roadmap lays the foundations for a three-year research project, in which they will combine data analysis with the latest efforts in computer modelling.

By setting out these goals, the researchers have a reliable roadmap for uncovering the mysteries surrounding the colossal, highly energetic processes that play out in the vastness of space. With further research, they could also allow for developments of crucial safeguards to our global communications networks against the damaging effects of CMEs and the energetic particles associated with them.

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Dr Ebert completed his PhD in Space Physics at the University of Texas at San Antonio in 2010. His research now focuses on the physics of plasma and energetic particles in interplanetary space and Jupiter's magnetosphere. He is currently the plasma ion sensor lead for the Jovian Auroral Distributions Experiment on Juno and has contributed to the pre- and post-flight calibration of flight instruments on several NASA missions. He has recently developed SmallSat mission concepts to study the solar wind's interaction with Jupiter's magnetosphere and the space environment around Mars.

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ALFVÉN WAVES: WHEN EARTH'S SHIELD COMES UNDER ATTACK

The Earth's magnetic field has long protected us from surges of harmful charged particles originating from the Sun, yet physicists still don't entirely understand what happens during this interaction. To explore the issue, **Dr Andreas Keiling** of the University of California at Berkeley studies the complex processes that take place during these so-called solar storms. His work has now begun to unravel the mysteries of the electromagnetic battleground far above Earth's surface.

Solar Storms

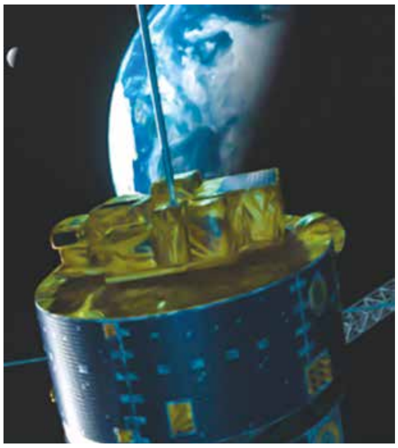
The surface of the Sun is a vibrant, ever-changing landscape. As complex reactions and collisions take place endlessly throughout our host star, it sends a continual stream of hot, charged particles (plasma) hurtling into space in every direction – a phenomenon astrophysicists have dubbed the 'solar wind'. Occasionally, highly energetic events on the solar surface send brief yet powerful bursts of these particles, collectively known as 'coronal mass ejections', in specific directions, in episodes known as 'solar storms'.

Inevitably, some of these plasma surges will stream continually towards Earth – a threat that could have prevented life from ever forming on our planet. However, the Earth has put a safeguard in place that significantly reduces this risk. When plasma interacts with the Earth's magnetic field, electromagnetic forces cause its particles to be deflected, largely preventing them from reaching our atmosphere.

Yet despite this robust shield, Earth's magnetic field is not always invincible against the strongest surges of charged particles. During solar storms, when the energy of the plasma hitting the field is particularly strong, it can have a strong influence on the field – potentially allowing significant amounts of energy to transfer down to Earth's atmosphere. Therefore, it is vital that we understand exactly what is happening when our planet feels the effects of solar storms.

'When a hurricane is forming over the ocean, we want to know where it is heading and what kind of damages it might cause on land. Similarly, when a solar storm in outer space is launched from the Sun, we want to understand how it affects our planet and our near-Earth space environment – or "geospace"', explains Dr Andreas Keiling of the University of California at Berkeley.

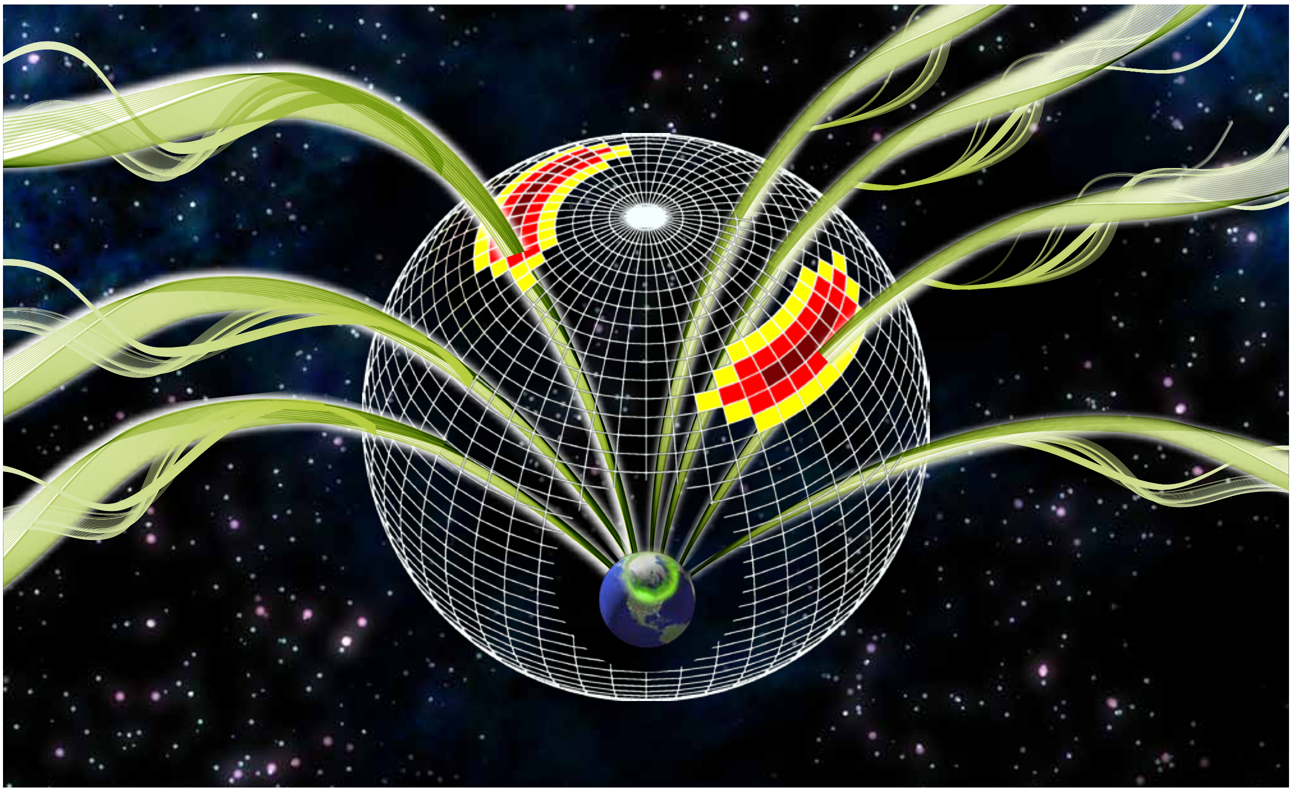
'Solar storms dump increased amounts of energy into geospace, which trickles down to Earth through a sequence of energy transfer processes,' he adds. 'Space physicists study how energy travels through geospace, and how much of this energy reaches Earth's atmosphere.' By gaining a more in-depth knowledge of these processes, Dr Keiling hopes that we will be able to prepare for and mitigate the damage that solar storms create, such as widespread power outages and disruptions to communications.



CREDIT: NASA/Polar satellite

Making Waves

For some time, space physicists have roughly understood how Earth's magnetic field influences incoming solar winds. Through satellite observations,



we now know that after hitting the field, plasma tends to slow down in front of Earth, after which it is diverted around it. Nevertheless, through various mechanisms, energy can cross the magnetic barrier. 'Some of the energy shows up in a special kind of wave, called an Alfvén wave – named after Swedish physicist Hannes Alfvén,' says Dr Keiling. 'In the 1940s, Alfvén first predicted the waves theoretically by describing how magnetic field lines "wiggle" when disturbed by solar energy.'

Another important discovery was that in geospace, some of the energy travels along Earth's magnetic field, which acts like a giant "magnetic funnel" above the polar regions. Alfvén waves preferentially travel along this magnetic funnel toward Earth.

'Waves play a central role in nature. They pick up energy and then carry it to other regions, sometimes very far away from the source region,' says Dr Keiling 'This is their most important role, and that's why it is important to study Alfvén waves in geospace.'

Nature's Most Impressive Light Display

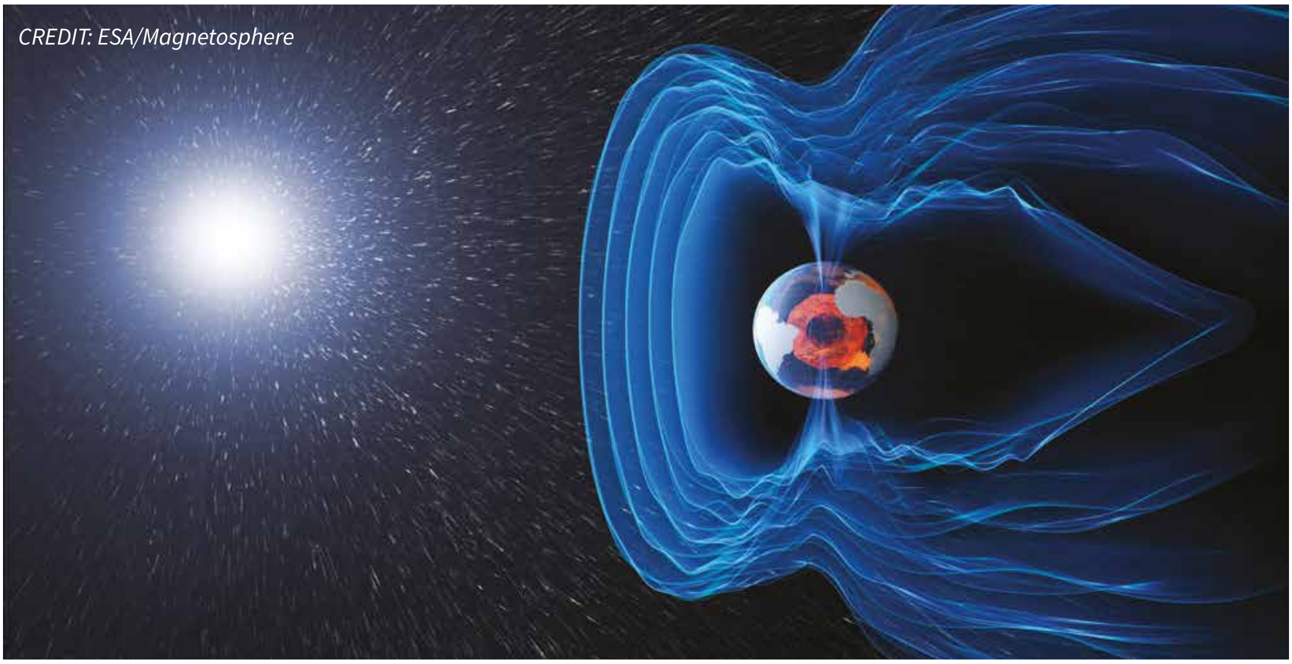
Dr Keiling has now spent years studying the influence of Alfvén waves on the Earth, paying particular attention to how they vary over time and space. In a 2003 study, he and his colleagues focused on where the waves occur above Earth's polar regions. Their research took account of the shape of Earth's magnetic field in high latitudes, where field lines protrude from the north pole – wrapping around the entire planet before disappearing again around the south pole and creating a 'funnel' shape above both poles.

Perhaps most notably, Dr Keiling's team found that Alfvén waves are partly responsible for a remarkable feat of nature we are all familiar with. Because the waves travel along magnetic field lines, they can travel close enough to Earth to reach its polar regions (north and south) when inside the magnetic funnel. When this happens, Alfvén waves cause vibrant swirls and flashes of colour which can be seen with the naked eye. 'In this case, Alfvén waves in outer space do not directly cause the aurora, but instead dump their energy onto electrons, making them go faster,' Dr Keiling explains. 'At some later point, the electrons collide with molecules in the ionosphere, causing them to give off light – the aurora.'

In their study, Dr Keiling's team used the NASA satellite Polar – launched specially to observe the aurora – to investigate Alfvén waves above Earth's poles. 'We discovered that the energy carried by Alfvén waves from far away along the "magnetic funnel" is partially but significantly used to generate the aurora over the entire polar region,' he explains.

This research offered some fascinating insights into the origins of these spectacular events, and the extent to which Alfvén waves are involved in their formation. Using the insights gathered in this early research, the physicists could shed new light on the influence of Alfvén waves on Earth's entire magnetosphere, particularly at times when the solar wind is dangerously energetic.

‘When a solar storm in outer space is launched from the Sun, we want to understand how it affects our planet and our near-Earth space environment’



CREDIT: ESA/Magnetosphere

Defending Against Solar Storms

Ambient solar winds may interact with Earth’s magnetic field continuously, but in the case of solar storms, Dr Keiling notes that far more energy can be transferred from incoming plasma to our atmosphere – a process for which Alfvén waves can at least partly be held responsible. ‘In the case of a solar storm, the solar wind “shakes” the entire magnetosphere strongly, generating much more wave activity,’ he explains.

As this shaking becomes more pronounced, the energy of the resulting Alfvén waves will increase, potentially having a strong impact on the total energy dissipated into the atmosphere. However, physicists have previously had little idea of the extent of the waves’ influence during intense solar winds. To answer this question, ‘we decided to look at the most dynamic space event – the solar storm – and asked: how different is the impact of Alfvén waves during solar storms compared to less disturbed times?’ Dr Keiling describes.

In their latest work, Dr Keiling and his colleagues again used the Polar satellite to measure Alfvén waves from above Earth’s poles. ‘The satellite traversed the “magnetic funnel” relatively close to Earth – at 20,000–30,000 km – while enabling measurements over the entire polar region,’ he says.

In this case, the magnetic funnel was particularly useful, because Alfvén waves – which travel along magnetic field lines – could reach the satellite from multiple directions. This gave the researchers a global picture of the total energy due to Alfvén waves flowing toward Earth’s atmosphere during solar storms. ‘Because of the “funnelling effect”, we could capture a significant portion of these waves, even those that might have been generated 200,000 kilometres and more away,’ explains Dr Keiling.

Dr Keiling and his colleagues analysed Polar’s measurements collected over six years, which is half a solar cycle, when many bursts of plasma originating from the Sun reached Earth’s magnetosphere. For the first time, the measurements allowed the team to quantify precisely how much more energy is carried toward the atmosphere in the form of Alfvén waves during solar storms.

‘We found that the energy input is about four times higher during storms, meaning there is even more energy available from Alfvén waves to power parts of the aurora,’ says Dr Keiling. The experiment confirmed that Alfvén waves do indeed play an increased role in carrying energy to Earth’s atmosphere during solar storms.

Continuing Research

The results uncovered by Dr Keiling and his colleagues provide much-awaited answers for space physicists and other researchers interested in the processes that play out in Earth’s magnetosphere, particularly during strong surges of solar activity. However, mysteries still remain about the physical processes that form Alfvén waves, giving the researchers a wide scope for future research.

In the future, Dr Keiling hopes to study these processes in yet more detail. ‘Our work continues,’ he says. ‘We want to understand more aspects of these waves, such as how the solar wind affects the turning on and off of these waves.’ Through this work, researchers could soon gain a more in-depth knowledge of the systems that protect us from some of the most harmful effects of outer space.

Meet the researcher

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Born in Berlin, Germany, Dr Andreas Keiling was an undergraduate student at Imperial College, London, before moving to the University of Minnesota, where he completed his PhD in 2001. Following a two-year postdoctoral position at Paul Sabatier University in Toulouse, France, he moved to the Space Sciences Laboratory at the University of California, Berkeley in 2004, where he currently works as a Research Physicist. Dr Keiling has also taught at the University of Wisconsin-River Falls and the University of Maryland-University College, and is a visiting researcher at institutions in Japan and Korea. His research covers a broad range of topics within space science, and he has been the editor of four scientific books, and the organiser of numerous conferences on this subject.

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ANALYSING EARTH'S MAGNETOSPHERIC SYSTEM: A WEB OF INTERCONNECTIONS

The behaviours of physical systems are often decided by complex webs of connections between properties, where a small change in just one variable could cause changes in every other one. **Dr Joe Borovsky** at the Space Science Institute of Boulder, Colorado, and his colleagues have dedicated their research to understanding one such web: the complex relationship between the solar wind and Earth's magnetosphere.

Space Weather

As the Sun converts hydrogen into helium through nuclear fusion, it sends a continual stream of hot, charged particles hurtling into space. This is 'the solar wind'. Sometimes the solar wind carries deadly radiation that could have prevented life from ever forming on Earth, but thankfully, our planet possesses an in-built safeguard that has protected the atmosphere for billions of years.

'Solar wind fills the solar system, but the Earth's magnetic field presents an obstacle, preventing it from reaching the Earth,' explains Dr Joe Borovsky of the Space Science Institute. 'The space where the Earth's magnetic field dominates over the solar wind is called the "magnetosphere". The magnetic field lines of the magnetosphere are connected to the Earth, so they are connected to the Earth's ionosphere, at the top of the atmosphere.'

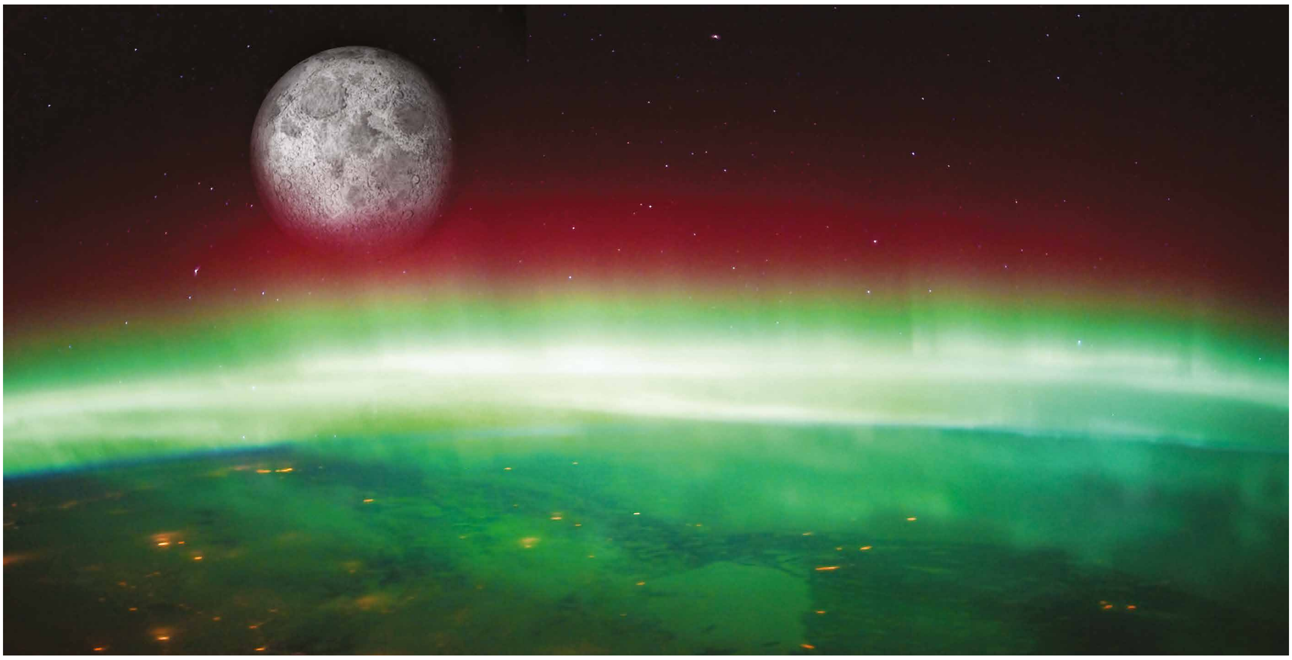
Some fascinating behaviours occur when these two complex systems come into contact with each other. 'As the solar wind interacts with the magnetosphere-ionosphere system, it induces several types of activity,' Dr Borovsky continues. 'It drives convection in the magnetosphere and in the ionosphere, it activates the aurora, it displaces various plasmas, it energises the radiation belts in the magnetosphere, and it produces outflows of plasma from the Earth's ionosphere into the magnetosphere.' Researchers have understood these phenomena for some time, but many physical processes that play out as the solar wind interacts with the magnetosphere are still not well understood.

Safeguarding Against the Solar Wind

Dr Borovsky believes that in the age of modern communications, it is important that we gain a more in-depth understanding of this interaction. 'Knowing how the magnetospheric system operates is important for predicting "space weather", which affects spacecraft operations, electromagnetic communications, and electrical power transmission,' he continues.

When the time-varying solar wind produces activity in the magnetosphere, the Earth's radiation belts can strengthen. This enhanced radiation can damage and even destroy spacecraft electrical components. Satellite damage endangers operations that we have become reliant on, from weather forecasting to GPS navigation. Closer to the ground, magnetospheric activity perturbs the ionosphere, which can greatly distort signals such as radio waves, potentially jeopardising critical communications. Yet despite these

‘Knowing how the magnetospheric system operates is important for predicting “space weather”, which affects spacecraft operations, electromagnetic communications, and electrical power transmission’



threats, it is incredibly difficult for physicists to predict when variations in space weather will result in our infrastructure being exposed to dangerous levels of radiation. By studying the complex physical processes associated with magnetospheric activity in greater detail, Dr Borovsky hopes to provide valuable insights into how our communications systems can be protected. ‘Understanding the various processes ongoing in the magnetosphere advances our understanding of astrophysical processes and our understanding of plasma physics,’ he says. To gain this understanding, Dr Borovsky and his colleagues have turned to a method that has previously offered insights in disciplines ranging from economics to ecology: the diverse field of ‘systems science’.

Two Aspects of Systems Science

When thinking about the interaction between the solar wind and the magnetosphere, Dr Borovsky argues that we cannot simply consider a simple single-connection relationship between their behaviours. Instead, the interaction represents a complex web of connections between the many different variables governing the behaviour of the magnetospheric system.

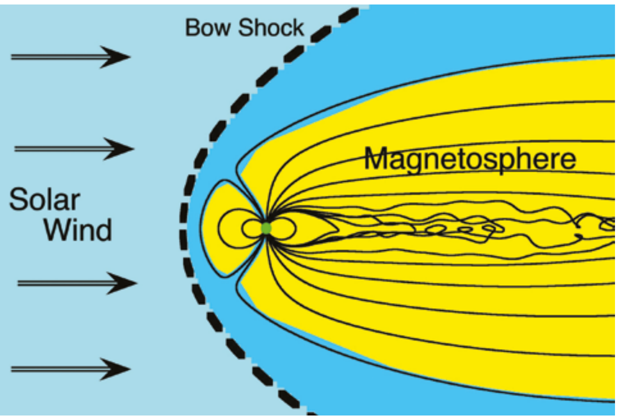
As Dr Borovsky explains, systems science is ideal for describing such an interaction. ‘Systems science has two aspects: systems thinking and systems analysis,’ he says. ‘Systems thinking means taking care to consider all the diverse parts of a system when studying the system, and also ensuring that there is a diversity of expertise when studying the system. Magnetospheric physics is very advanced in systems thinking.’

Through knowledge gained using systems thinking, researchers have now been able to identify how a variety of individual properties of both the solar wind and the magnetosphere influence the complex behaviours we observe, including the aurora and ionospheric convection. However, without the insights of systems analysis, our understanding of the interaction is still incomplete.

‘Systems analysis means using mathematical tools and methods designed to analyse the behaviour of systems in general,’ Dr Borovsky continues. ‘Magnetospheric physics is lacking in systems analysis between magnetospheric variables.’ Clearly, this calls for a new, more mathematical approach to studying the interaction between the solar wind and the magnetosphere.

Improving Systems Analysis

In their research, Dr Borovsky and his colleagues are now working towards improving our understanding of the mathematical relationships underlying the web of variables connecting the properties of the solar wind with those of the magnetosphere. Their overall aim is ‘to develop a systems analysis methodology designed for the specific problem of the solar-wind-driven magnetosphere-ionosphere system.’ To do this, the researchers have broken the interaction down into several mathematical variables, allowing them to explore how they influence one another.



'The first important property of the system is that the various properties of the time-dependent solar wind, such as speed, density and magnetic-field strength, are strongly intercorrelated with each other,' says Dr Borovsky. In addition to these properties, the researchers have accounted for how the magnetosphere comprises several different populations of hot, charged particles, collectively known as 'plasmas'. 'The multiple plasmas inside the magnetosphere interact with each other and the nature of the interactions evolves as those plasmas evolve, making a time-dependent "web of correlations".'

Correlating the Solar Wind with the Magnetosphere

In a 2014 study, Dr Borovsky and his colleague Dr Michael Denton first examined how the different properties of the solar wind and the magnetosphere, measured using observations from orbiting satellites, can be correlated with each other. This first involved constructing a simplified mathematical model of the magnetosphere, allowing the system to be described using six variables. Using systems science analysis on the model, the duo was able to identify the density of particles in the solar wind, along with the type of plasma, as properties that are correlated most strongly with subsequent behaviour of the Earth's radiation belt.

In further studies carried out in 2014 and 2017, Drs Borovsky and Denton analysed the correlation in more detail by breaking both the magnetosphere and the solar wind down into simplified systems of variables. Through this work, the researchers were able to describe new sets of variables to describe both the solar wind and the magnetosphere, each accounting for variations in the other. These insights laid the groundwork for an in-depth systems science examination of the solar wind-magnetosphere interaction for the first time.

A Detailed Mathematical Web

In a 2018 study, Dr Borovsky and another colleague, Dr Juan Alejandro Valdivia at the University of Chile, introduced a more complex set of variables to represent the magnetosphere – this time consisting of 14 interconnected subsystems comprising the overall behaviour of the system. Along with Earth's atmosphere, these variables included the behaviours of 12 different types of plasma, as well as a very thick layer of hydrogen above the outer atmosphere known as the geocorona.

The pair then applied several different descriptions of systems science to the model, allowing them to identify and explain connections between the different subsystems. This led to what they described in their paper as a 'roadmap of connectivity' in the magnetosphere, allowing them to assess the causes of phenomena including the aurora in high levels of detail.

Having qualitatively analysed these interconnections, Drs Borovsky and Denton then aimed to construct a mathematical description of the web, enabling them to perform systems analysis on the magnetospheric system. In a further study, the researchers constructed a 'magnetospheric state vector' – a mathematical description of the magnetosphere which incorporated 11 time-dependent variables. They also constructed a similar vector for the solar wind, itself incorporating eight time-dependent variables, allowing them to construct a robust mathematical relationship between the solar wind and the magnetosphere for the first time.

When testing the model, Drs Borovsky and Denton found that they were able to compare the behaviours of the magnetosphere during periods of high solar activity, including solar storms when Earth is barraged with intense streams of solar wind, with quieter periods, far more effectively than previous studies.

Aiming for a More Realistic Description

Having identified these relationships, Dr Borovsky and his colleagues now hope to increase the complexity of their descriptions, making them even more realistic. 'There are three goals for the future of this project,' he says. 'The first is to improve this analysis of the magnetosphere-ionosphere system, first by adding more magnetospheric measurements to the method and then introducing time lags between the solar-wind variables and the magnetospheric variables.'

Dr Borovsky also hopes that in the future, systems science will be used to explore an even broader web of variables connected to Earth's magnetosphere. 'The second goal is to integrate this magnetosphere-ionosphere systems science into the broader "Earth systems science". Finally, we hope to try this magnetosphere-developed methodology on other driven systems,' he concludes.

Through this work, physicists may soon be able to identify new links between the unusual phenomena playing out above our heads with the interaction between the solar wind and the magnetosphere. By helping us to know when our communication and power transmission systems are under threat from natural systems beyond our control, this improved knowledge could also prove invaluable to safeguarding our increasingly connected society.

Meet the researcher

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Dr Joe Borovsky received his PhD in Physics in 1981 from the University of Iowa. Between 1982 and 2012, he was a Staff Member at Los Alamos National Laboratory, and continues to conduct his research in the city of Los Alamos. Currently, he is a Senior Research Scientist at the Space Science Institute, where he is also the Chair of the Center for Space Plasma Physics. He has experience in theoretical, computational, and experimental physics, and is a Fellow of the American Geophysical Union. Dr Borovsky's current research interests focus on structure in the solar wind, the systems science of the Earth's magnetosphere, and coupling between solar wind and the magnetosphere.

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FUNDING

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SPACE SCIENCE INSTITUTE

CHANGING THE LANDSCAPE OF GEOLOGY: FORECASTING EARTHQUAKES

Imagine a world where we knew about earthquakes before they strike – days before a potentially lethal event. A world with an early warning system that would give us time to evacuate vulnerable buildings, to activate civil defence organisations, to minimise the loss of life and reduce recovery costs. Although the dream of earthquake prediction has been on people's minds for centuries, it is dismissed by most seismologists and geophysicists as a pipedream. However, all that could change dramatically, thanks to **Professor Friedemann Freund** at the NASA's Ames Research Center.

Between the years 2000 and 2016, there were nearly 30,000 earthquakes recorded worldwide with a magnitude of 5 or greater. These earthquakes caused hundreds of thousand fatalities and trillions of dollars in economic damage, some with long-lasting effects that will linger on for years, decades and even centuries, such as the radioactive contamination from the preventable Fukushima Nuclear Power Plant disaster.

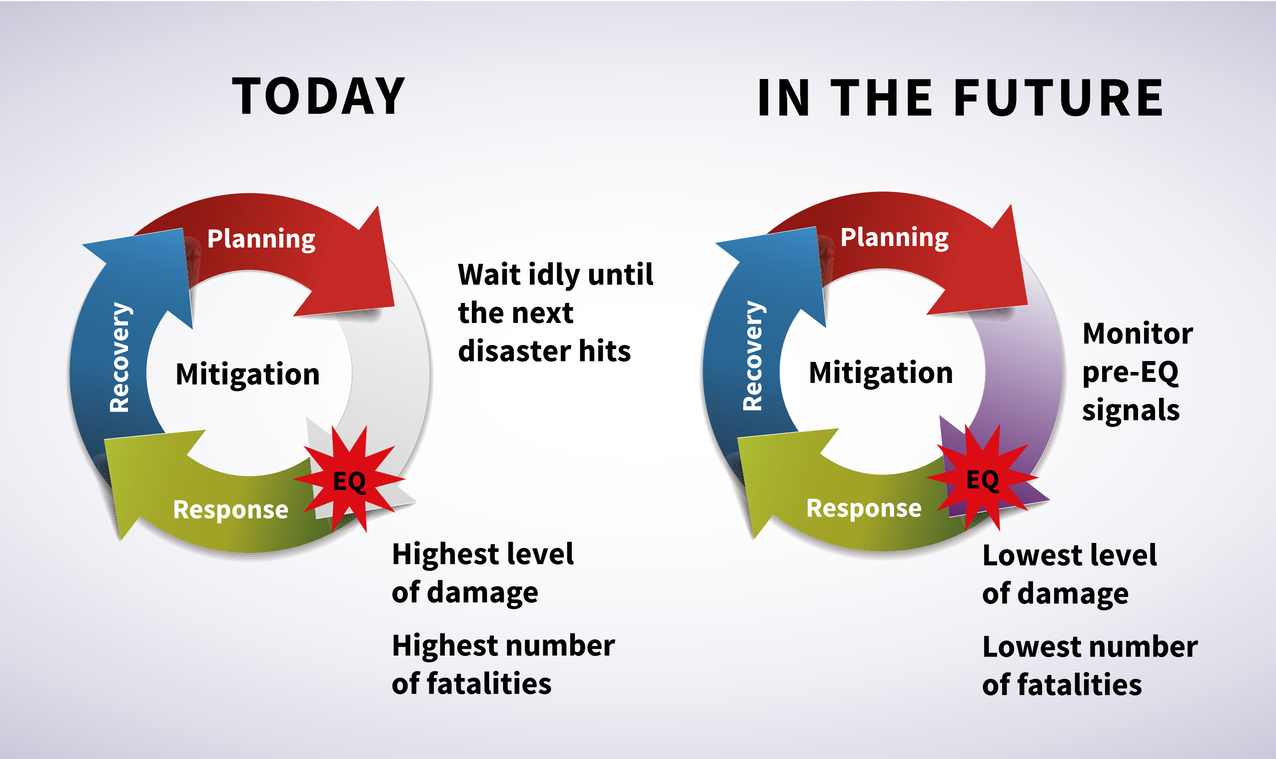
The famous San Francisco earthquake of 1906 led to the destruction of more than 80% of the city, more than 3,000 deaths and an estimated $400 million in damage – approximately $10.7 billion in today's money. More recently, the 2011 Tōhoku earthquake in Japan left more than 15,000 people dead and caused over $360 billion in direct damage in Japan and around the Pacific rim. These costs continue to accumulate due to the need to manage the Fukushima Nuclear Power Plant site. With so much at stake, it's no wonder that efforts to forecast earthquakes have been underway since the very beginning of seismology.

What Causes Earthquakes?

The Earth's outer shell, the 'crust', is made up of tectonic plates, about 150 km thick, that fit together like pieces of a giant puzzle. These rigid plates move around over timescales of millions of years, changing the face of our planet slowly but inextricably. As these plates slide past each other or collide, stresses build up. When these stresses reach a critical range, rocks rupture catastrophically, sending out powerful seismic waves that can be highly destructive at the Earth's surface.

Large earthquakes are monstrous mechanical events, with ruptures that can run over tens, sometimes hundreds of kilometres. Because they are mechanical events, those who wanted to develop the means to predict them, the seismologists, started out by focusing on mechanical precursors. Despite a concerted effort spanning more than a century and ample public funding, the seismology community has failed in its effort to develop tools for actionable prediction.

There is, however, a collection of seemingly unrelated, non-seismic pre-earthquake signatures that have largely gone ignored due to their disparate nature. These signatures include subtle, often fleeting phenomena, mostly electrical or electromagnetic in nature, such as transient electric currents in the ground, emission of electromagnetic radiation from within the Earth, lights near the ground or in the sky, and even abnormal animal behaviour. Science has never been able to offer sound, testable explanations for the origins of such precursory signals. As a result, the mainstream geoscience community has come to view them with suspicion, more as folklore than anything else.



Over the years, Professor Friedemann Freund, in collaboration with his son Mino, has developed a deeper understanding of the processes that give rise to a bewildering multitude of non-seismic signals before major earthquakes. He and his research team at the NASA's Ames Research Center in California have shown that there is a single physical process, occurring deep in the crust, that could explain all of these unconventional precursory effects. Thus, a unifying picture emerges, which is likely to change the course of earthquake prediction for ever. In a forthcoming volume of the *European Physical Journal*, a number of papers will be published supporting the contention that all non-seismic pre-earthquake phenomena can be traced back to one fundamental physical process: the activation of electronic charges in rocks in response to the ever-increasing tectonic stresses prior to any major seismic event, namely the rupture of peroxy bonds.

Peroxy Bonds: Shaking Up the Science of Earthquake Prediction

Professor Freund's journey started decades ago with work that was published back in 1976 with the discovery of a previously unknown chemical reaction that leads to the formation of so-called 'peroxy bonds'. Although quite familiar to chemists, peroxy bonds are totally alien to geoscientists.

At its most basic level, the reaction leading to the formation of peroxy bonds involves a rearrangement of electrons between two atoms in the structure of a mineral. An oxygen atom with two extra electrons, O^{2-}, donates one of its extra electrons to a suitable acceptor, such as a proton, H^{+}. This proton thereby turns into a hydrogen atom, H, and combines with another H to form a hydrogen molecule, H_2. Meanwhile, O^{2-} turns into an oxygen atom with just one extra electron, O^{-}, and combines with another O^{-} to form a peroxy bond, O^{-}–O^{-}.

This process happens deep within the Earth's crust and along the boundaries between mineral grains. The peroxy bonds not only exist inside the mineral grains but also along grain boundaries and even across grain boundaries, linking adjacent grains together like a 'glue'.

This last aspect is important for understanding what happens when rocks are stressed. Professor Freund has been able to show that when very slight stresses are applied to a rock and its grains start to shift relative to each other, peroxy bonds break. In that moment, the rocks change from an insulator to a semiconductor state: the rocks become laced with mobile electrons (e') and holes ($h^{\bullet}$), similar to semiconductors that are used in electronic devices. The stress-activated electrons are mobile inside the stressed rock but lack the ability to flow out. The holes, by contrast, have the remarkable ability to spread into the surrounding less stressed or unstressed rocks. They can travel at up to 100 metres per second and over distances of tens of kilometres – even hundreds of kilometres in the case of large earthquakes getting ready to strike.

The situation is very dynamic. As electrons and holes are activated inside a stressed rock volume, these charge carriers start to flow out but also instantly begin to recombine, returning to the inactive peroxy state. By measuring in the laboratory the speeds at which electrons and holes are activated and holes flow out, Professor Freund has been able to shed light on these processes that happen deep in the Earth's crust way beyond direct observability. This has led to a conceptual picture of the balance between production of electrons and holes and their return to the inactive state, coupled to the outflow holes from the rock.

The situation is further complicated by the fact that, once the holes have flowed out of the stressed rock, they spread, travelling ever more slowly as the distance increases. When the positive holes arrive at the Earth's surface, they become trapped and initiate secondary processes. One important secondary process is recombination, which leads to the emission of infrared light. This infrared light is widely interpreted as temperature increase, while in fact it is due to a non-thermal infrared emission process. Another follow-on process is air ionisation, first producing positive airborne ions, followed by negative ions alongside ozone production and a rise in radiofrequency noise.

Although this multitude of reactions holds the key to a potential paradigm shift in the Earth sciences, the omnipresence of peroxy bonds in the constituent minerals of crustal rocks has been largely overlooked by the geoscience community. Convinced of the significance of his discovery, Professor Freund continued to pursue this line of research throughout the 1980s and 1990s with little, or sometimes no, external funding. Due to his sheer determination and persistence, he made a breakthrough in the early 2000s, when he began looking more closely at the electron density distribution in the so-called 'oxygen anion sublattice' – the collection of negatively charged oxygen ions within a material – from the perspective of a semiconductor physicist. He made two ground-breaking observations: (i) that stresses applied to a rock cause it to turn into a new form of semiconductor, and (ii) that the charges flowing out of the stressed rock volume are positive. Never had such a behaviour been reported in the scientific literature.

Based on these observations and his broad interdisciplinary knowledge, he began to develop a new approach for forecasting earthquakes. He postulated that the outflow of these positive electric currents is responsible for the wide range of widely reported but never properly understood phenomena that occur before and sometimes during earthquakes – phenomena that range from electric and magnetic field anomalies in the Earth's surface, light flashes rising out of the ground or appearing high up in the skies, and – most puzzling – abnormal animal behaviour.

What is the Impact on Our Current Understanding?

Indeed, throughout history, there have been countless reports of pre-earthquake phenomena that science has been unable to explain due to a lack of understanding of the physical processes occurring deep in the Earth's crust. Today, with a global network of observation satellites, ground-based observation stations and even the video-capable smartphones, there is a growing body of evidence that helps us to understand why electromagnetic radiation, electric and magnetic field anomalies, radon gas, ionospheric disturbances, and many more precursory signals are *bona fide* signs of an approaching major seismic event. Although there are still no properly funded efforts to collect such pre-earthquake data systematically, the scientific community is beginning to take notice.

This theory is an important step forward in humanity's quest to be able to forecast major earthquakes days or even weeks in advance, and to understand the multitude of seemingly unrelated pre-earthquake signals. In the forthcoming *European Physical Journal* issue mentioned previously, Professor Freund and a team of collaborators put the theory to the test: 'We review a credible, unifying theory for a solid-state mechanism, which is based on decades of research bridging semiconductor physics, chemistry and rock physics. This theory, which we refer to as the "peroxy defect theory", is capable of providing explanations for the multitude of reported pre-earthquake phenomena.'

This *European Physical Journal* issue examines a wide range of independent studies into previously disregarded phenomena that occur before – or during – earthquakes, and many of them provide results that are consistent with Professor Freund's theory. Although his work is far from complete, Professor Freund has opened the door to an area of Earth Science that was previously thought to be replete with nothing but wishful thinking.

Perseverance in the Face of Controversy

The story of how Professor Freund developed his paradigm-shifting theory is not one that is merely about science, it's a tale about tenacity, determination and perseverance in the face of controversy – about pursuing the evidence and working towards a goal, even when others cast doubt on the value of this work.

Professor Freund is inspiring and, when asked about his journey, he is happy to provide some words of wisdom. 'As we make progress in demonstrating the validity of my semiconductor approach to pre-earthquake signals, the resistance in the seismology community starts to erode,' he says. 'I view my academic career as setting an example for the younger generation that a paradigm-shifting discovery may require an enormous amount of patience and the willingness to pursue an idea with dogged persistence.' It is this attitude that has allowed him to change the landscape of the science of changing landscapes.

Meet the researcher

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Professor Friedemann Freund completed his PhD in Mineralogy and Crystallography in Marburg University, Germany, in 1959. His career has spanned over fifty years and he has worked with NASA at the Ames Research Center since 1985. His research interests include organic chemistry, astrobiology, the study of defects and impurities in crystalline solids and semiconductor aspects of mineral and rock physics in relation to earthquake and pre-earthquake phenomena. Throughout his career, he has demonstrated an absolute determination to pursue his scientific goals in the face of controversy and, as a result, he is on the cusp of ushering in a paradigm shift in the geosciences.

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FUNDING

NASA

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ENHANCING GROUNDWATER DETECTION WITH MAGNETIC RESONANCE

Detecting underground water is of considerable importance, particularly for applications such as groundwater exploration, predicting the movement of contaminants in soils or building underground tunnels and mining facilities. Underground water is a limited resource that is essential for human life, but it can pose a safety threat in cases where the structural integrity of underground structures, such as tunnels, depends on solid earth being present throughout. **Dr Mike Müller-Petke** of the Leibniz Institute for Applied Geophysics, and **Dr Stephan Costabel** of the Federal Institute for Geosciences and Natural Resources, are investigating methods to greatly improve the detection of underground water, using a technology known as nuclear magnetic resonance.

Nuclear Magnetic Resonance

Nuclear Magnetic Resonance, or 'NMR', is a technique used in a wide variety of applications, from determining the structures of organic compounds to creating images of the human body in Magnetic Resonance Imaging (MRI).

In geophysics, the technique is used for measuring underground water. These NMR measurements are taken on the ground surface, as a way to detect subsurface water deposits without having to dig. Non-invasive groundwater detection is important in a variety of situations, such as when an understanding of groundwater flow is needed for agricultural applications or when planning underground tunnelling work, which requires that the surrounding soil and rock is strong enough to withstand collapse.

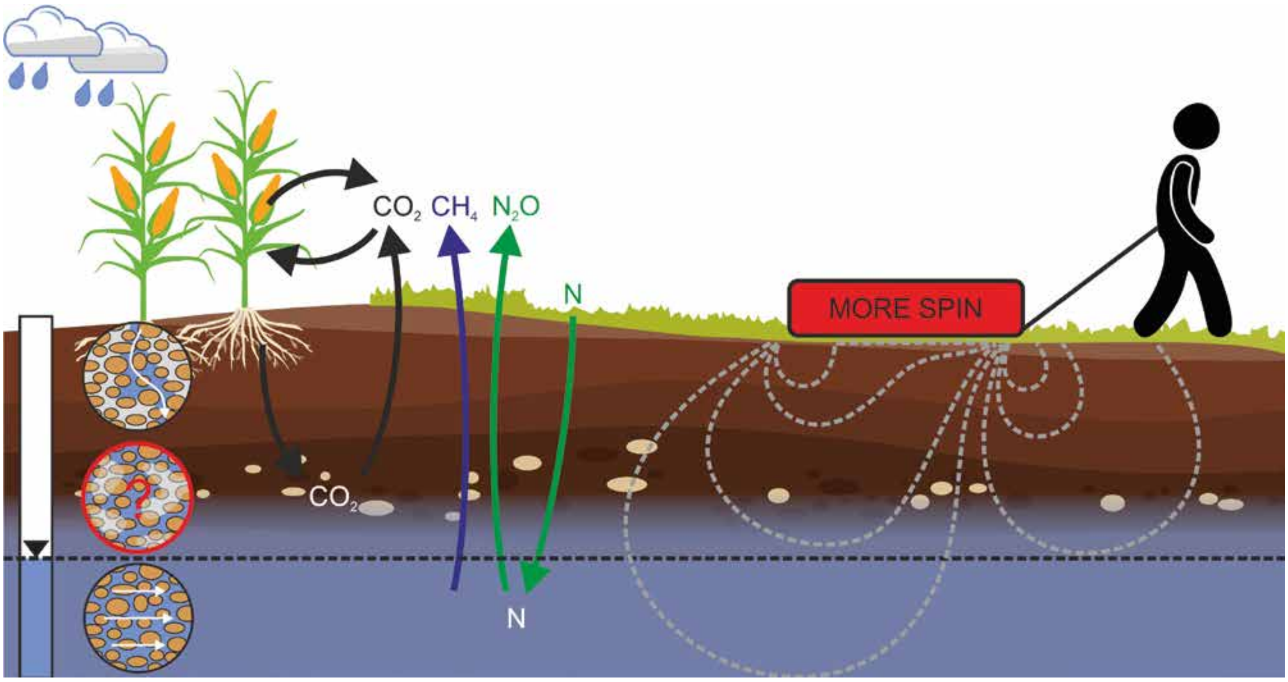
NMR takes advantage of the magnetic properties of the nuclei of hydrogen atoms. Because a molecule of water, H_2O, contains two hydrogen atoms, NMR can be used to measure water – such as in the human body in the case of MRI, or underground in the field of geophysics.

The NMR method for detecting groundwater involves setting up large loops of cable on the ground surface. An electrical current is then sent through these loops, which generates an external magnetic field. This magnetic field causes the hydrogen nuclei in the underground water to become 'excited' as they align themselves with the field.

After the field is switched off, the hydrogen nuclei 'relax' back to their equilibrium states, orienting themselves roughly in the direction of Earth's weak magnetic field. As they relax, the hydrogen nuclei release radio signals, which the NMR equipment can detect.

CREDIT: A. Weitze (LBEG)

The intensity of these radio signals is related to the number of hydrogen nuclei present, so the technique can therefore be used to estimate the amount of water present in the rock and soil below. Other information about the water's surroundings can also be derived from these signals, as



hydrogen nuclei relax in slightly different ways depending on their environment. Geophysical research in this field is focused on improving our ability to create three-dimensional maps of underground water from all of this information.

However, one drawback when using NMR is the presence of electromagnetic 'noise', which interferes with the signals. This noise is highest when NMR measurements are taken near electrical equipment, such as power lines and wind turbines, which generate their own electromagnetic fields that interfere with the relaxation signals. In these situations, the signal-to-noise ratios of NMR measurements can be extremely low, making it difficult for geophysicists to discriminate the signals from the background noise.

Furthermore, in many situations it is not possible to use large loops when conducting geophysical NMR measurements, such as inside a tunnel. In this scenario, small loops must be used, leading to weaker signals, and an even poorer signal-to-noise ratio. 'When applying NMR to soil moisture measurements or inside a tunnel we have to use very small loops and the noise problem becomes our greatest issue,' says Mike Müller-Petke, of the Leibniz Institute for Applied Geophysics.

Overcoming Noise

To help overcome this noise interference, Dr Müller-Petke and his team have adopted the 'pre-polarisation' technique, which is standard in medical MRI laboratories but very difficult to apply in NMR for groundwater detection. Using this technique, Dr Müller-Petke can amplify the NMR signals coming from underground water, so that these signals become much more intense than the background noise. This technology has the potential to expand the use of NMR for high resolution subsurface water detection in areas where the noise strength is often too high compared to the signal intensity. This includes applications for identifying contaminant transport in urban soils and for ensuring the safety of mining and underground building work.
Dr Stephan Costabel, at the Federal Institute for Geosciences and Natural Resources, has also been focusing on improving NMR technology for the detection of underground water. Like Dr Müller-Petke, Dr Costabel has made significant progress in improving signal quality, but using a different approach. His method involves the use of noise cancellation to reduce the strength of the background noise, which allows the NMR signals to be more easily detected and analysed, greatly improving measurements of underground water.

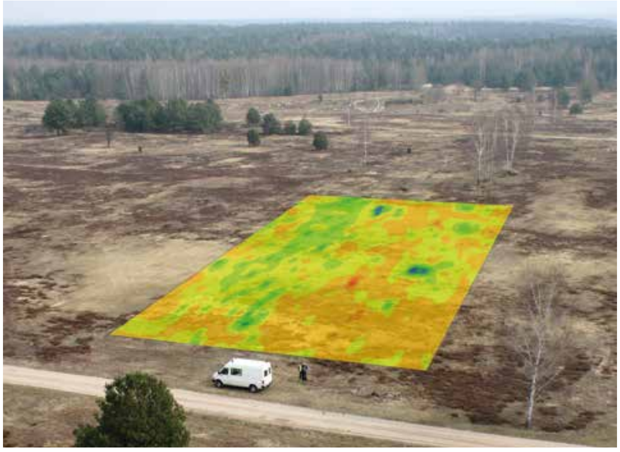
Dr Costabel and Dr Müller-Petke have worked in collaboration for many years, despite working at different research institutions. 'Mike and I first got in touch at the Berlin University of Technology in 2005/2006, where both of us had started our PhD research,' reflects Dr Costabel. 'Our theses were technically quite close – different aspects of magnetic resonance.'

Using Pre-Polarisation to Amplify Signals

Dr Müller-Petke's pre-polarisation technique involves the use of electrical pulses, which are applied before the main magnetic excitation field is switched on, to increase the magnetisation of hydrogen nuclei in groundwater. This increased magnetisation leads to stronger NMR signals that can more easily be distinguished from noise.

The pre-polarisation pulses are generated by sending short pulses of DC electrical current through the coils used in the standard NMR method for detecting groundwater. These pulses generate short bursts of magnetic field, before the main AC electric current is passed through the coils. When the NMR equipment detects the radio signals from hydrogen nuclei, they are greatly amplified with respect to the noise.

CREDIT: M. Sack (BGR)



CREDIT: M. Sack (BGR)

The team's technique then uses software to account for the DC pulses, in order to accurately process the measurements. After this step, calculating the most-accurate image of the distribution of surrounding water is much less challenging.

Using a new NMR instrument, Dr Müller-Petke and his colleagues tested their method by carrying out field measurements on the frozen surface of a water reservoir, located in an area of high noise levels in Shaoguo, China. Prior to this field study, the pre-polarisation method had only been tested in the laboratory. In their tests, the team used their NMR measurements to create a model of the reservoir, and then compared this to physical measurements of the reservoir to see how accurate their new method was.

The pre-polarisation method resulted in data that were in good agreement with physical measurements of the liquid water beneath the frozen surface, despite it being located in an area of high noise. This makes the team's technique a highly promising solution to the problems associated with low signal-to-noise ratios associated with NMR measurements of groundwater.

In addition to this successful outcome, the team also developed new ways to process their data to obtain further invaluable information. 'Besides imaging the distribution of water, we continuously develop new data processing schemes that improve our ability to image the ability of water to move in the subsurface,' says Dr Müller-Petke. 'This involves measuring a parameter referred to as the hydraulic conductivity – a key parameter for understanding water movement.'

Noise Cancellation

A recent study by Dr Costabel took a different approach to the same problem. Rather than amplifying the signals, he looked at ways to significantly reduce the noise in NMR measurements of underground water. Using his method, the environmental noise interference can be predicted and subsequently subtracted from the NMR measurements, in order to produce a far better signal-to-noise ratio.

After investigating several methods of noise cancellation, Dr Costabel determined that a technique called 'reference-based noise cancellation', or 'RNC', was the most effective for reducing noise levels in the NMR measurements, without damaging the useful signals.

His RNC method takes measurements of noise in different directions to best approximate its characteristics. These measurements are combined to become the so-called 'reference noise', which can be easily subtracted from the NMR signals.

Dr Costabel assessed the noise reduction produced by the RNC method in the rock laboratory of Mont Terri in Switzerland, an underground research facility located at a depth of 280 metres below ground. Using RNC, he was able to show that potential NMR signals from dangerous water deposits inside the rock could be identified if they existed, which is luckily not the case in Mont Terri. Dr Costabel further verified the technique by carrying out additional experiments using an artificial water reservoir in an urban area, where there was substantial noise interference.

Future Directions

In the near future, Dr Müller-Petke would like to further improve his team's pre-polarisation technique, in order to broaden its scope for use in the detection of underground water in tunnels and mines, where noise can often be a critical issue. In addition to optimising the instrument design, he also hopes to further amplify the pre-polarisation pulse, which will lead to further amplification of the NMR signals.

Dr Costabel would now like to focus on improving the ability to take groundwater NMR measurements from inside underground mining tunnels. The steel reinforcements used for tunnel support have a tendency to cause significant distortions of the Earth's magnetic field and thus corrupt the NMR measurement, which remains a pertinent problem that Dr Costabel would like to overcome.

Meet the researchers

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Dr Mike Müller-Petke was awarded his PhD in 2009 from the University of Technology Berlin, Germany. Upon graduating, he worked as a postdoctoral researcher at the Leibniz Institute for Applied Geophysics (LIAG), in Hannover, Germany, while also beginning a lectureship at the University of Technology Berlin. In 2015, he completed these positions and then went on to become the head of the department of 'Geoelectrics and Electromagnetics', at LIAG, and professor at the Leibniz University Hannover. His research focuses on improving magnetic resonance technology for geophysical near-surface applications, including the use of pre-polarisation as a way of amplifying signals detected using magnetic resonance.

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Dr Stephan Costabel earned his PhD at the Berlin University of Technology, Germany, in 2011. He has since worked as a senior research fellow at the Federal Institute for Geosciences and Natural Resources (BGR). He is currently researching and improving the use of magnetic resonance as a means of detecting underground water. Among his current research focuses is the development of effective filter techniques to reduce unwanted background interference for signals detected using magnetic resonance. Notable highlights of Dr Costabel's career include being project partner and principle investigator for groundwater and mineral exploration, and moisture detection using magnetic resonance.

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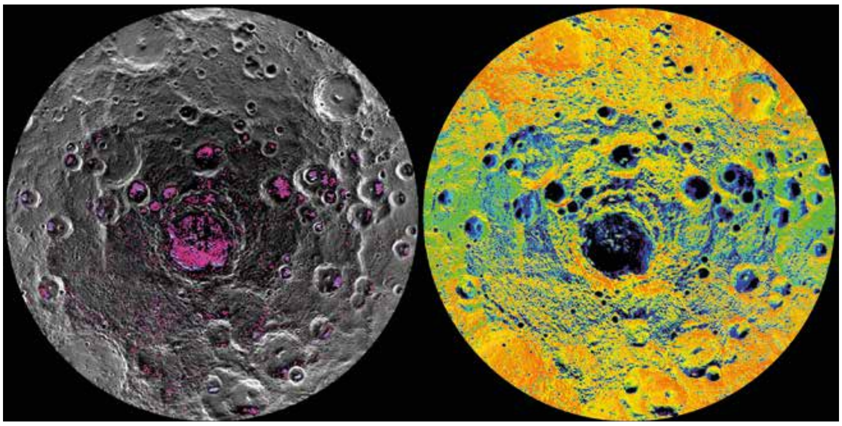
LIAG Leibniz Institute for Applied Geophysics

BGR

ICY DISCOVERIES ON OUR INNERMOST PLANET

The location of water in our solar system may hold the key to understanding how the planets evolved, and indicate other potential places to find life away from Earth. **Dr Nancy Chabot** and **Dr Carolyn Ernst** of Johns Hopkins University Applied Physics Laboratory, and **Ariel Deutsch** at Brown University, use data from NASA's MESSENGER mission to understand how much ice exists on Mercury and how it may have arrived there.



Mercury's south polar region, with Arecibo radar data in pink indicating the locations of ice, and a colourised map of illumination conditions, showing regions of permanent shadow in black

The Search for Water

The question of whether we are alone in the Universe has fuelled humanity's curiosity with space since we first looked up to the stars. From our perspective, Earth is the perfect habitable planet – it has a rocky surface with an atmosphere and liquid water to support life. By looking for evidence of water on other planets, scientists can start to understand how our solar system evolved and find clues for where to search for life in the wider universe.

In the early 1990s, radar images of Mercury's surface taken from Earth identified highly reflective radar-bright areas representing deposits of ice. Dr Nancy Chabot and Dr Carolyn Ernst of Johns Hopkins University Applied Physics Laboratory, and Ariel Deutsch at Brown University study the details of ice on Mercury using data collected from NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft.

NASA's MESSENGER Mission

The MESSENGER mission was the first to visit Mercury since the Mariner 10 flybys in the mid-1970s, and the first mission ever to orbit the planet. MESSENGER orbited the planet between 2011 and 2015, providing an in-depth look at this hostile world. Mercury is the closest planet to the Sun, and experiences temperatures of up to 430°C. These extremely high temperatures, combined with Mercury's lack of atmosphere, would normally mean that no water could condense on the planet's surface.

Mercury rotates almost vertically on its axis. Mercury's vertical rotation means that locations at the planet's cratered poles are permanently in shade. In this shade, where direct sunlight never reaches, the temperatures can be very low, reaching −160°C where ice can be stable.

The MESSENGER spacecraft was equipped with a narrow-angle camera and a wide-angle filtered camera, and the combined instrument was called the Mercury Dual Imaging System (MDIS). This camera could image the surface of Mercury, including within the permanently shadowed polar regions. 'We obtained the first images that successfully revealed what the surfaces of the ice deposits looked like,' recalls Dr Chabot. 'This was a really challenging observation, as we were trying to take images of surfaces that are always in shadow! We used settings on MESSENGER's camera that let the

‘Our continuing analysis of Mercury’s ice deposits suggests that Mercury’s ice is fairly young and perhaps delivered by a large comet or asteroid impacting Mercury within the last tens of millions of years or so.’

Impact crater Hokusai, located on Mercury at a latitude of 58°N, showing impressive system of rays

extremely low levels of light that were reflected into the area from nearby crater walls and other surface features provide enough light to image the surface.’

In a study led by Deutsch, the team utilised over 16,000 images of Mercury’s north pole area to map the locations of permanent shadow, and combined these images taken by MDIS with MESSENGER’s Mercury Laser Altimeter (MLA) measurements. MESSENGER’s MLA measured the amount of time it takes for a laser pulse to travel to the surface and reflect back again, providing key information about the topography of the planet.

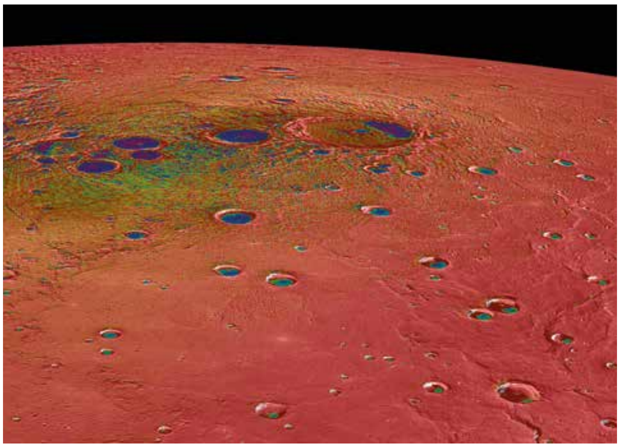
The team confirmed that the water ice signals detected by the Earth-based radar are located in the shadowed craters at the north pole. They then used MDIS images to see within the shadowed craters, revealing images showing that much of the ice is covered with an insulating layer of dark material and not loose rock. The dark material is speculated to be organic-rich volatile compounds. There have been various calculated estimates of the ice thickness, but the current best estimate of its maximum thickness is 15 metres. ‘Data from NASA’s MESSENGER mission, the first spacecraft to ever orbit the planet Mercury, have revolutionised our understanding of Mercury, including the ice in its polar regions,’ states Deutsch.

Detailed Features

During the final year of its mission, the orbit of the MESSENGER spacecraft brought it closer to Mercury’s surface than before, reaching altitudes below 200 kilometres across the north polar region. This provided the team with an opportunity to gather more detailed images of the shadowed craters and ice deposits.

When the team analysed the MDIS data, they discovered that the ice deposits are not uniform, but rather have variations in their surface brightness. They noticed that there can even be quite a lot of variation within the same crater, such as the Desprez crater. At 47 kilometres wide, this is one of the largest shadowed craters imaged during MESSENGER’s low altitude orbit.

The team found that the variations in brightness matched the modelled variations in temperature across the Desprez crater, suggesting that the hypothesised organic compounds covering the ice varied with the location’s maximum surface



Mercury's north polar region, coloured by the maximum biannual surface temperature, which ranges from more than 400 K (red) to 50 K (purple)

temperature. At room temperature on Earth, these types of organic compounds will rapidly evaporate. However, under the extreme cold conditions in the shaded craters on Mercury, these compounds are stable and can act as an insulating cover on the water ice.

Comparing North and South Poles

NASA's MESSENGER mission was able to provide high-resolution images of Mercury's north pole due to the spacecraft's eccentric orbit. This orbit meant that MESSENGER passed over the south pole at a far higher altitude – over 10,000 kilometres above the planet's surface. While this meant that MESSENGER's MLA instrument could not take measurements over the south pole, the mission still provided MDIS images for the team to analyse. These were a combination of standard and long exposure images that covered a large area of the south pole.

The team combined these images with new radar observations from the Arecibo Observatory in Puerto Rico to study the shadowed craters of Mercury's south pole. They found that the locations of permanently shadowed craters in the south pole matched the locations of radar-bright deposits observed from Earth. There is around double the area of radar-bright deposits in permanently shadowed areas at the south pole compared to the north pole.

Where Did Mercury's Ice Come From?

There are distinctive features of the ice deposits on Mercury, which have given the team clues as to their relative age. 'The images showed very sharp boundaries between the shadowed ice deposits and neighbouring sunlit rock, providing strong evidence that the ice on Mercury must be fairly young to have such well-defined boundaries,' explains Dr Ernst.

Other celestial bodies, such as comets and asteroids, frequently impact Mercury's surface. When these impacts occur, they mix up the surface materials, causing the edges of features to appear irregular. As the ice deposit boundary edges have not yet been mixed up, it is likely that the ice was deposited either recently (within geological timescales) or that the ice and associated blanket of organic compounds are constantly renewed as part of an ongoing planetary process, such as outgassing or micro-meteorite bombardment.

The researchers have noted that not every permanently shadowed region at Mercury's north and south poles has ice. This uneven distribution of ice, observed on both hemispheres, may also give clues as to how the ice came to be on Mercury. 'Our continuing analysis of Mercury's ice deposits suggests that Mercury's ice is fairly young and perhaps delivered by a large comet or asteroid impacting Mercury within the last tens of millions of years or so,' says Dr Chabot. Since the postulated organic compounds covering Mercury's ice are similar to those found on comets, this further supports the idea that the ice was delivered by a large and relatively recent impact on Mercury.

In a recent study led by Dr Ernst, the team was able to identify the geologically young Hokusai crater as the most likely impact crater produced from a celestial body capable of delivering the ice. By studying the shape and characteristics of the crater and its ejecta, the team was able to estimate the mass of water that may have been delivered to Mercury by the impact. They calculated that a large projectile of up to 31 kilometres in diameter, travelling at over 100,000 kilometres per hour, could deliver a large amount of water that matches the estimated volume of water locked in the ice at Mercury's poles.

What's Next?

The research completed by Dr Chabot, Dr Ernst, Deutsch and their colleagues into the origins of water ice on Mercury is an important piece in the puzzle of understanding where the water in our solar system came from. During the early evolution of the rocky inner planets, it was too hot for water to condense on Earth. The fact that Mercury's ice may have been successfully delivered by a comet or asteroid impact suggests that the water on Earth may also have this distant origin. NASA has found exoplanets (planets beyond our solar system) in the early stages of formation that are undergoing a similar bombardment by primitive asteroids and comets that could be delivering water to their surfaces, in the same way that it was likely delivered to Earth.

While the mission for the MESSENGER spacecraft may be over, the research team's mapping of Mercury's poles will help to guide the next mission to Mercury. The European Space Agency and the Japan Aerospace Exploration Agency together are working on the BepiColombo spacecraft. Building on the discoveries of the MESSENGER mission, BepiColombo will orbit Mercury in 2025 for at least one Earth year, providing scientists with even more data about one of the solar system's most mysterious planets.

Meet the researchers

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Dr Nancy Chabot is a planetary scientist at the Johns Hopkins University Applied Physics Laboratory. After gaining her PhD from the University of Arizona, she became involved with the NASA MESSENGER mission as the Instrument Scientist for MDIS, as well as chairing the Geology Discipline Group. Since 2016, Dr Chabot has continued to research the rocky planetary bodies in our solar system as Coordination Lead for NASA's DART mission and as Deputy PI for the MEGANE instrument on the JAXA MMX mission. Dr Chabot is a fellow of the Meteoritical Society and also has an asteroid named after her: Asteroid 6899 Nancychabot.

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Dr Ernst is a planetary scientist at the Johns Hopkins University Applied Physics Laboratory. She earned her PhD from Brown University, and her research investigates the processes and effects of impact cratering and the surface evolution of planetary bodies. She worked on the MESSENGER mission as Deputy Instrument Scientist of the Mercury Laser Altimeter, and is currently working on NASA's Europa Clipper and DART missions. She is also a Participating Scientist on the Japan Aerospace Exploration Agency Hayabusa2 mission. Dr Ernst also has an asteroid named after her: Asteroid 11008 Ernst.

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Ariel Deutsch is a PhD candidate at Brown University and a NASA Graduate Fellow at NASA Goddard Space Flight Center. Between 2013 and 2015 she worked with Dr Chabot and Dr Ernst in the MESSENGER Science Operations Center as a NASA/Applied Physics Laboratory Intern. At Brown, she is continuing to research Mercury's polar deposits as one component of her doctoral thesis. She is particularly interested in the evolution of planetary bodies and in using remote sensing and geophysical techniques to understand their geological history.

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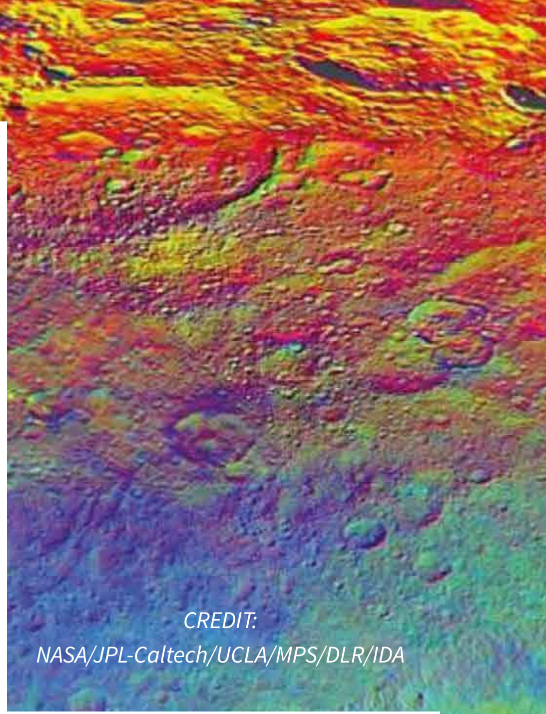
THE DAWN MISSION: CASTING NEW LIGHT ON CERES



CREDIT: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

The dwarf planet Ceres is just a fraction of the size of Pluto, yet it holds valuable information about the evolution of our solar system. As a member of the Dawn mission team, **Dr Scott King** at Virginia Tech has been using data gathered by NASA's Dawn spacecraft to explore the interior structure of Ceres.

A Primitive Planetary Body

Our solar system is not just planets orbiting around a star. There are many celestial bodies that we are continually discovering and exploring, such as asteroids, comets, moons and dwarf planets. Dwarf planets are particularly interesting objects, which offer scientists the opportunity to study worlds very different to Earth and provide clues about the evolution of our solar system.

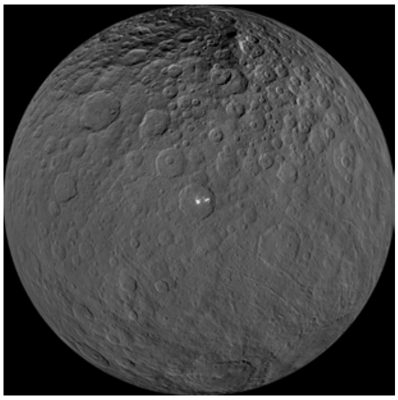
The Dawn mission provided an exciting opportunity for scientists to study the dwarf planet Ceres in much greater detail than ever before. Very little is known about Ceres, particularly details of its internal structure, but scientists are very interested in its evolution because there is a significant proportion of water ice within its crust.

The search for water is closely linked to the search for extra-terrestrial life, but learning how Ceres evolved also gives clues about the early history of our solar system. Ceres is a primitive planetary body, which formed at a similar time to the other planets, but was never finished due to its close proximity to Jupiter. The pull of Jupiter's gravity was so strong that material could not coalesce to continue forming Ceres as it did for the other rocky planets. Therefore, Ceres provides an exciting opportunity to study a planetary body that may be similar to the early Earth. Alongside his collaborators, Dr Scott King of Virginia Tech studies images and measurements of the surface of Ceres taken by the Dawn spacecraft during its Ceres orbit between 2015 and 2018. By combining this with computer simulations and models, they have been able to explore the internal structure of Ceres, and theorise how this mysterious world evolved.

Clues on Ceres's Icy Surface

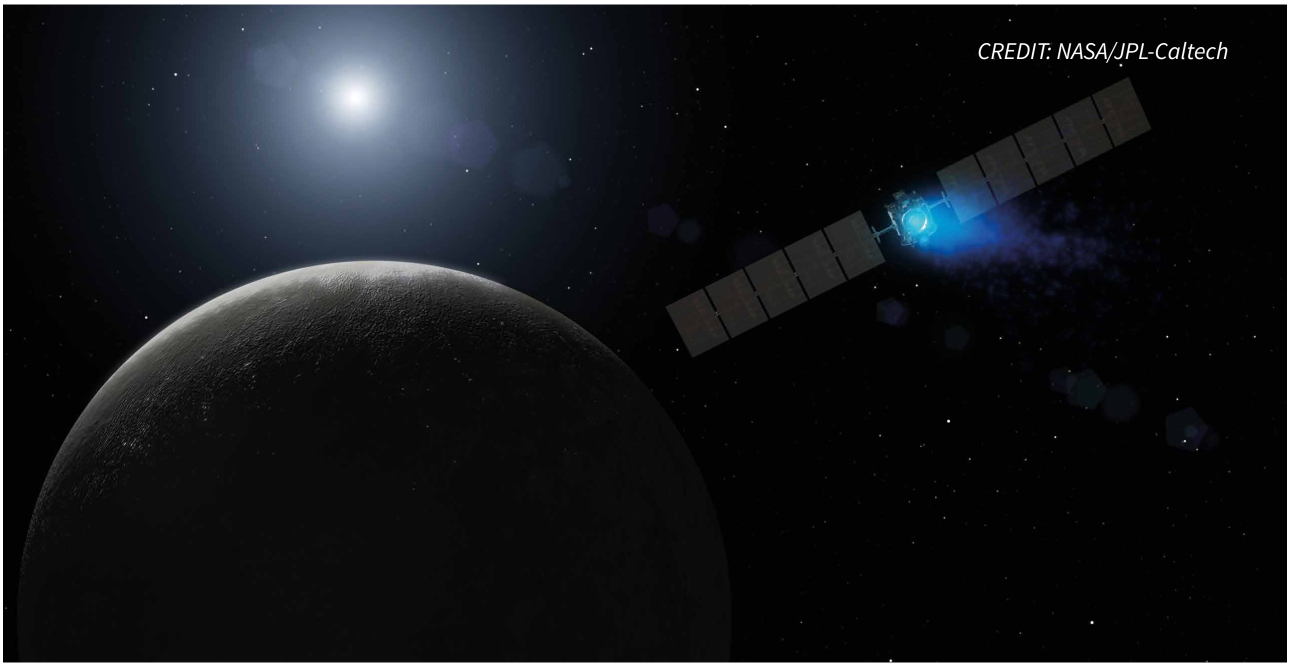
Ceres lies within the asteroid belt between Mars and Jupiter. For many years, it was considered to be an asteroid, but was re-classified as a dwarf planet in 2006, as it is much larger and rounder than the rocky asteroids around it. Ceres has a radius of 476 kilometres, and is thought to have a layered internal structure similar to that of the rocky inner planets. Early telescopic observations by scientists showed that up to 25% of its mass is likely to be made up of water ice, predominantly found in the crust.

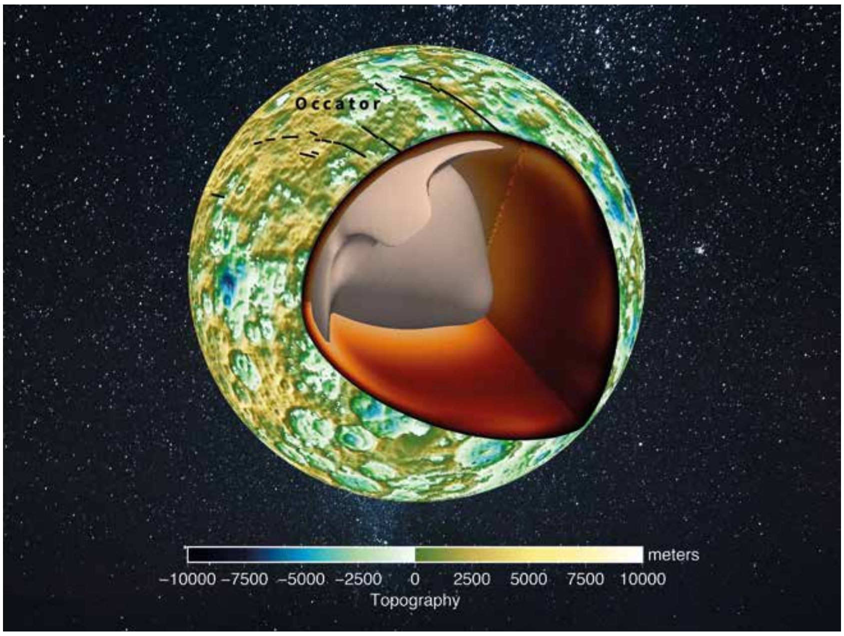
Ceres has a highly cratered surface; however, the absence of very large craters suggests that some process may have reworked the original surface, which has intrigued scientists. The dwarf planet's location means that many large asteroids would have hit it during its lifetime. This has led to the suggestion that an icy subsurface could be erasing evidence of craters due to its slow, viscous flow.



Ceres as seen by NASA's Dawn spacecraft. The projection is centred on the Occator Crater, home to the brightest area on Ceres. Occator is centred at 20 degrees north latitude, 239 degrees east longitude. CREDIT: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

The Dawn spacecraft carried a framing camera, and by employing a technique known as stereophotogrammetry, the Dawn team was able to map the depths of the largest craters on Ceres, creating a digital terrain model. The researchers then applied a numerical simulation to discover how much crater walls have sunk, or 'relaxed', over billion-year timescales. Dr King describes how important computer simulations are for understanding the evolution of a planetary body. He suggests that computer simulations can use the observations of planetary bodies scientists make in the present, such as measuring heat signatures or the movement of tectonic plates, to model how specific aspects of that planet have changed over millions of years.





A cutaway view of Ceres' surface topography (in colour shading) with a superimposed temperature isosurface from one of Dr King's 3D convection models. The hot plume (in tan) is shown rising beneath the high plateau (Hanami Planum), and the black lines represent the interpreted extensional faults, or Samhain Catenae (pit chains). Occator crater sits on the high plateau.

The Dawn team discovered that most of the large craters on Ceres are several kilometres deep, which would suggest that a slow slumping or relaxation of the crater walls has not yet occurred. This means that the crust on Ceres must be made of a material that is at least 1,000 times more viscous than water ice for impact craters to remain this deep over millions of years. Dr King suggests that there can be no more than 30–40% ice in the crust, and that this is mixed with rock material, salts, carbonates and possibly even clathrates (compounds where one molecule is trapped within the crystal structure of another). This combination would make the surface of Ceres much more viscous and consistent with the crater shapes the team observed.

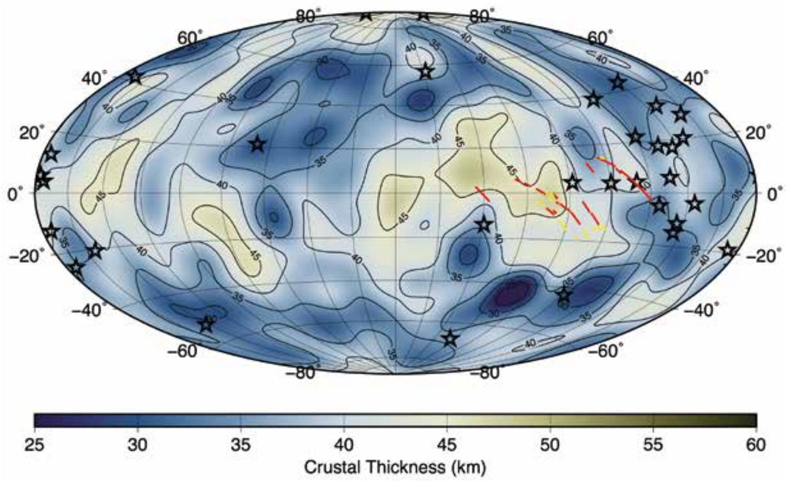
The team did discover some anomalously shallow craters, which suggested there could be some areas of the surface that are more viscous than others. It is possible that the dwarf planet's viscous crust may overlie a subsurface that is more deformable, containing water ice, or possibly even small amounts of liquid water left over from an ancient ocean on Ceres. This may account for the lack of older impact craters.

Understanding the Interior

Dr King and his colleagues used the data provided from the Dawn spacecraft's orbit of Ceres to confirm whether there is an inner core. The early telescopic studies of Ceres provided data from which scientists could estimate the density of Ceres. These studies indicate that the dwarf planet's interior is likely arranged into an outer crust and at least one inner layer. By mapping the topography and features of the surface from images taken by the Dawn spacecraft, scientists have started to understand how internal layering may have evolved.

In a recent publication, Dr King and his colleagues were able to use computer simulations to model the interior of Ceres. By using over a hundred billion models with varying parameters, they

CREDIT: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA



Crustal Thickness map of Ceres. Red/yellow lines are the Samhain Catenae (pit chains). Stars indicate the locations of large domes.

were able to confirm that Ceres has a high-density core. They also discovered that the density of Ceres increases with depth. There is still some discussion as to the exact composition of the core, but Dr King suggests that it could be a combination of dry silicates (rocky minerals containing no water), along with heavier metallic minerals.

The Dawn team created a map of the features on the surface of Ceres, and identified a series of characteristics called pit chains. These are funnel-shaped pits formed by the drainage of impact materials into a subsurface void. These linear features, called the Samhain Catenae, consist of around six pit chains, totalling 1,211 kilometres in length.

The team used the spacing of these features, combined with experimental and computer modelling results, to estimate that the local thickness of the dwarf planet's outer layer is at least 58 kilometres. This is around 14 kilometres greater than the previously calculated average thickness of the outermost layer. The Samhain Catenae are located close to another region with a similar thickness called Hanami Planum. In this location, scientists have also discovered a gravity anomaly – a difference in density between the outer crust and the underlying rock-rich layer.

Evolution of the Interior

Data from the Dawn spacecraft has been vital to understanding the internal structure of Ceres. A core made of denser material compared to that found in the outer crust suggests that Ceres underwent differentiation soon after the dwarf planet formed. Differentiation is a process where materials separate into different layers according to how dense they are. This left a dense core of dry rock and metallic minerals, surrounded by less dense hydrated rock material and a thin crust made of a mixture of low-density materials.

NASA's Dawn mission confirmed that there is a significant amount of water present on Ceres, particularly at the surface, locked within icy deposits and rocky minerals with water in their crystal structure. This supports the theory that Ceres once had a watery ocean, and there are ocean remnants remaining within the crust and shallow subsurface.

Dr King and his colleagues also propose that Ceres might be a dynamic planetary body – a planet where internal processes can affect the surface. There is evidence of convection within the dwarf planet's rocky interior that could have caused some of the variation in topography and thickness of the crust. This is similar to the process within the Earth where hot mantle slowly deforms and over long timescales acts like a viscous liquid even though it is solid.

The small size of Ceres means that unlike the Earth, Mars or even the Moon, Ceres did not have enough heat when it formed to power this viscous motion. Instead, heat was generated by radioactivity over time, gradually warming the interior until it became unstable. This could result in a single large area of upwelling, called a plume. The team proposes that this plume could alter the topography in the outermost crust, resulting in the pit chain formations of Samhain Catenae. It would also account for the thicker crust at Hanami Planum, along with the gravity anomaly that the Dawn spacecraft measured.

The possibility that a dwarf planet such as Ceres might be a dynamic body despite being much smaller than other geologically active bodies in the solar system is an exciting revelation. It was thought that Ceres was too cold for internal convection to occur. Evidence of an upwelling plume, along with the potential presence of liquid water, will help scientists to better understand how early Earth may have evolved. It may also suggest new locations to find liquid water in our solar system and beyond. Liquid water might be present below the surface of Ceres, as the presence of salt lowers the freezing temperature of water. The Dawn mission has provided a wealth of information that scientists continue to analyse in order to further our understanding of the early solar system.

Meet the researcher

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Dr Scott King is Professor of Geophysics at Virginia Tech, with a particular research interest in combining numerical models with topography, gravity and seismic measurements to understand plate tectonics and the internal structure of planetary bodies. He was selected as a Guest Investigator for NASA's Dawn mission to Ceres, but has also worked on the evolution of Mercury, Venus, Earth, and Mars. Since completing his PhD at the California Institute of Technology, Dr King has had an extensive research career resulting in over 80 publications. He is a Fellow of the Geological Society of America and in 2009 received the Alexander von Humboldt Research Award.

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PARTICIPATING INSTITUTES

The Dawn mission is managed by the Jet Propulsion Laboratory for NASA's Science Mission Directorate in Washington. Dawn is a project of the directorate's Discovery Program, which is managed by NASA's Marshall Space Flight Center in Huntsville, Alabama. The University of California at Los Angeles (UCLA) is responsible for overall Dawn mission science. The German Aerospace Center, the Max Planck Institute for Solar System Research, the Italian Space Agency and the Italian National Astrophysical Institute are international partners on the mission team.

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HIGH VELOCITY IMPACTS: A NEW WAY TO COLLECT SAMPLES FROM SPACE

For now, planetary scientists can only dream of getting their hands-on rock samples taken from the surfaces of distant worlds. Achieving these extractions presents a significant set of challenges, but **Dr Robert Winglee** and his colleagues at the University of Washington have made significant strides towards developing feasible techniques for retrieving samples. Through detailed computer design and field experiments, they have now clearly demonstrated that obtaining core samples created during high-velocity impacts with planetary surfaces could one day be a reality.

Exploring Different Worlds

Over the last few decades, a diverse array of planets, moons and asteroids have been imaged in ever more intriguing ways. Photos gathered by the *Curiosity* rover on Mars have revealed a high-resolution, ground-level view of a completely alien landscape. *New Horizons* has provided us with detailed images of Pluto, at the icy fringes of the Solar System. Yet for all the achievements these missions have made, the goal of being able to readily attain a subsurface sample from the many different solar system objects remains elusive. Returning such samples to Earth for further analysis is even more elusive still.

With even the most generous of budgets, every probing mission ever launched has faced a trade-off between the inclusion of many different interesting experiments, and lower launch costs. Before a mission is launched, many different groups of scientists must ultimately battle it out to prove that the data their proposed experiments would collect will be more valuable to science than those of other groups' experiments. Inevitably, such a highly competitive process means that many experiments must be abandoned. If samples could be returned to Earth, then more detailed analysis could be undertaken, greatly increasing the scientific return, especially towards understanding the solar system's evolution and the potential for life beyond the Earth.

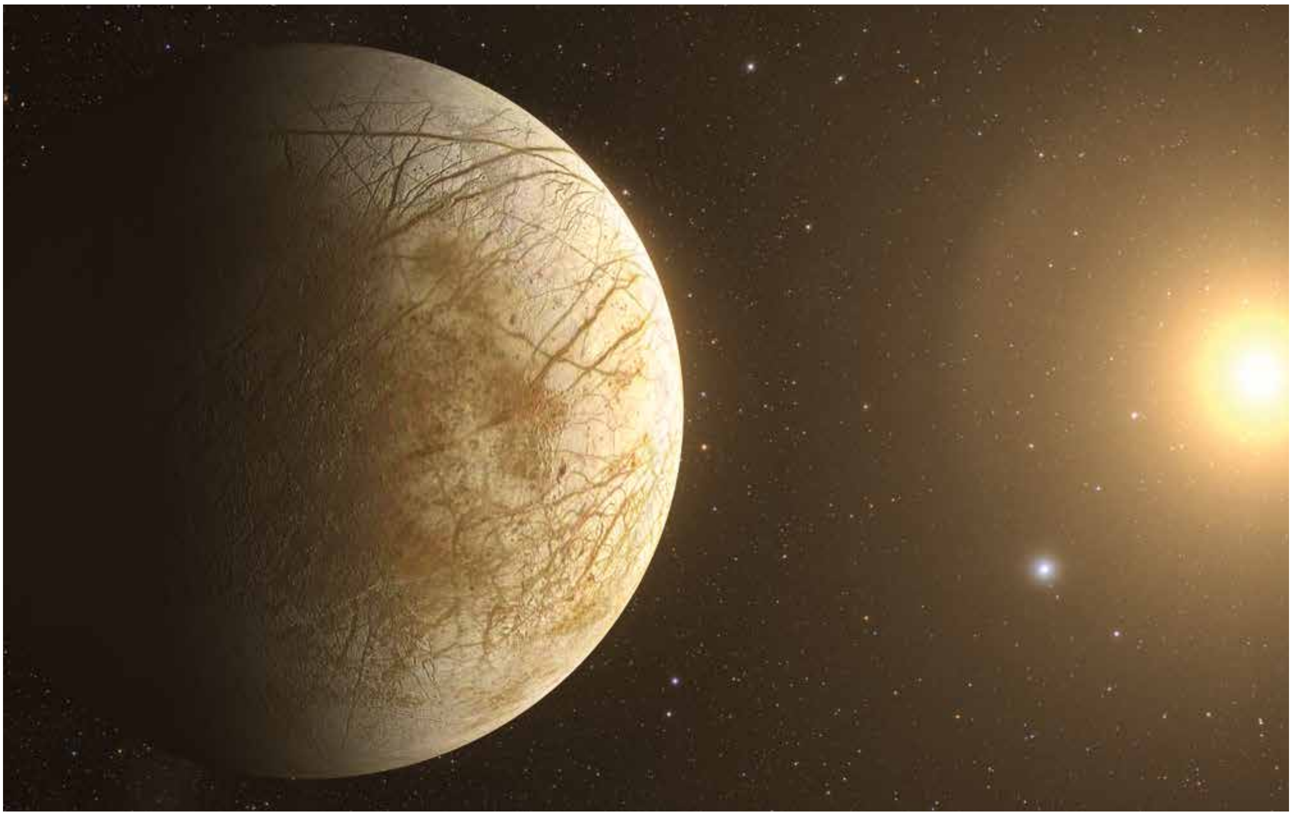
Extracting Samples

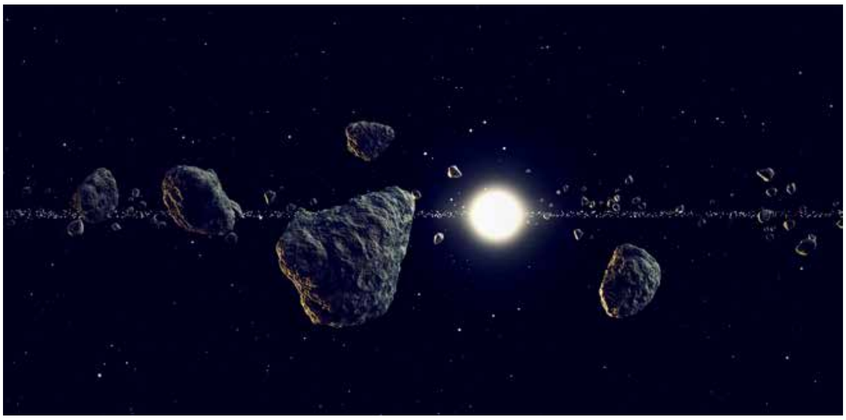
During the Apollo area, slightly more than 380 kilograms of rock were returned to Earth, providing the first direct evidence that the Moon was formed from a giant impact between Earth and another solar system object called Theia. Since the end of the Apollo era, only grams of material have been returned to the Earth from missions such as NASA's Stardust and JAXA's Hayabusa I.

One particularly desirable feat for scientists is to achieve the ability to collect samples from below a planetary body's surface. The reason for this is that surface material has been modified by weathering processes, such as

meteorite impacts and exposure to solar radiation. Reaching below the surface would provide pristine material that would offer insight into processes controlling the formation and evolution of the solar system.

However, the extraction of a subsurface samples is inherently difficult. Getting drilling equipment onto the surface of a planetary body is extremely expensive, while the zero-gravity conditions at asteroids and comets makes





drilling impossible, unless additional mechanisms are developed to firmly attach the drilling equipment to the surface.

Another way to extract a core sample without the need for drilling equipment is to exploit the fact that all spacecraft tend to have substantial velocity relative to their target object. Indeed, braking thrusters need to be used to reach a stable orbit around the object. However, what if this energy could be harnessed instead to release a penetrator that would impact the surface at high speed.

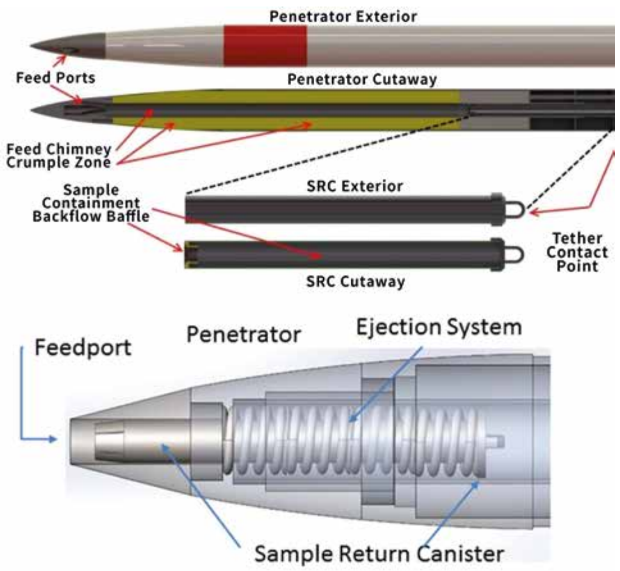
High Velocity Core Samples

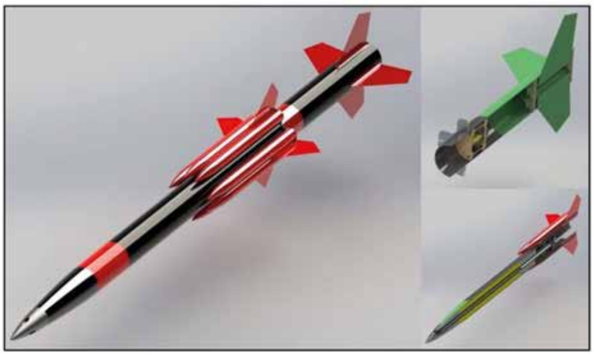
In their research, Dr Robert Winglee and his colleagues at the University of Washington have designed and tested an intriguing solution to the main challenges posed by sample extraction, in the form of a high-speed penetrator device, which is shaped like a giant hollow needle. On impact, the penetrator is buried to depths of several metres, as material is rapidly fed into a canister held inside, through ports in its steel nose cone. Travelling between 1000 and 2000 kilometres per hour (or about 10 times the speed of a car on a freeway), a significant difficulty is to ensure the penetrator survives such a high-speed impact.

The other difficulty is to get the core sample to be ejected from the impact site back into space when the penetrator itself is deeply embedded in the surface of the target. Dr Winglee's group has solved this problem using an internal canister, which is pushed upwards by the reflected energy coming from the impact. When the canister reaches orbit, it is collected by the awaiting spacecraft through a mechanism like an electromagnet. The rock sample is then safely stored within the body of the spacecraft as it travels back to Earth – ready for detailed analysis on its return.

High-Impact Field Tests

To demonstrate the capabilities of this technology, Dr Winglee and his colleagues have tested their penetrator through both computer simulations, and field tests on Earth, in which penetrators are fired into the ground by rockets. The researchers have now carried out three rounds of these flight tests. The first of them demonstrated that even at supersonic impact speeds, the penetrator could survive its collision with the ground and remain mechanically intact.





The second series of tests demonstrated that core samples can indeed be collected by feeding them through the penetrator's nose cone and into the return canister, again without damaging any of its inner parts, and with the sample being ejected back onto the surface for easy pickup. Finally, the third round of testing demonstrated that the sample-carrying return canister containing the electronics can survive the impact. The only element of Dr Winglee's design that has not been tested in this way is the capture of the return canister once it reaches space – a test that would need to be carried out on far larger scales. All the same, the field tests clearly showed that high-impact sample extraction is a perfectly feasible prospect.

Studying the Solar System's Moons

If you think trying to survive an impact at 2000 kilometres per hour is difficult, braking speeds of about 4 kilometres per second are needed to reach the surface of the Europa, one of the icy moons of Jupiter. This moon is a particularly enticing target, as NASA's Galileo mission has recently revealed that a vast liquid ocean could be hidden beneath its icy surface. This ocean could also be heated by the significant tidal forces induced by its host planet – potentially creating a suitable environment for life to evolve.

Because Europa has no atmosphere, using a parachute system to land equipment is not possible. Access to the surface through a rocket landing is possible, but the projected cost is very high. This has been possible for lunar landers, because they only had to decelerate by 1 kilometre per second to reach the surface. For 4 kilometres per second, you have to carry a lot more fuel or the payload has to be substantially reduced.

Throwing Up a Snow Storm

To get around this issue, Dr Winglee and his colleagues propose a simple two-stage landing system, avoiding the need for expensive braking systems. The first stage would involve sending in a separate, initial impactor, shaped like a hollow cylinder. Travelling at hypersonic speeds, this object would penetrate to depths of around 10 metres, throwing up a temporary, cone-shaped cloud of ice and dust particles. The second stage – containing the payload – can then use this dense cloud as a passive braking system, which slows down its speed to ensure that its electronic components can survive.

Dr Winglee and his team have now tested this approach using computer simulations and undertaken a field test in Alaska in mid-winter. They found that if the initial stage has just the right shape, it can slow down the second stage as heavy as 10 kilograms to a safe impact velocity. Softening landings in this way could prove invaluable for a wide variety of space missions, and would be particularly useful for sample extraction. Direct analysis of the geology of the moons of the outer Solar System are likely still a long way off, but if realised, it would transform our understanding of how these worlds were formed, and how they have behaved since then.

A Promising Future

Through further research, the team's proposed sample extraction techniques could one day open up the door to a diverse new range of studies in planetary science. For example, scientists would be better equipped to answer the question of why asteroids appear to join together through cohesive forces, which prevent them from breaking up. This process is thought to underly the formation of every planet, moon and asteroid orbiting the Sun, but for now, remains a mystery.

In addition, scientists would be able to investigate variations in the compositions of different moons and asteroids, solving further mysteries about the formation of the Solar System. For worlds such as Europa, where Galileo has already given us tantalising glimpses of organic molecules, any sample returned to Earth could aid our understanding of the origins of life. For now, Dr Winglee and his colleagues will continue to improve their extraction technique, with these ambitious goals in mind. In the coming years, they will focus on the mechanisms that spacecraft could use to retrieve sample-carrying canisters, without damaging their loads.

Meet the researcher

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Dr Robert Winglee completed his PhD at the University of Sydney in 1985. He has worked at the University of Washington since 1993, where he is now the Director of the Washington NASA Space Grant Consortium, which aims to improve education in science, mathematics, and technology throughout the state. Dr Winglee's main research interests include space plasma physics and engineering, particularly in relation to the environments around the planets of the Solar System. He also studies a variety of areas relating to the dynamics of other planets' aurorae and magnetospheres, with the aim to study how they would interact with our spacecraft.

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UNIVERSITY of WASHINGTON

EXPLORING THE WEATHER OF TITAN AND MARS

The moons and rocky planets of our Solar System may be remote, unfamiliar worlds, but even on the very strangest of them, the weather on those with atmospheres is not wholly unlike our own. **Dr Scot Rafkin**, a planetary scientist at the Southwest Research Institute, believes that the small-scale patterns their atmospheres exhibit are directly comparable with Earth's weather. Based on the results of computer models simulating the atmospheres of Titan and Mars, he argues that these local and regional behaviours are significantly underappreciated in planetary science.

Familiar Yet Foreign Worlds

When we look at images of the moons and rocky planets with atmospheres in our Solar System, they can simultaneously seem completely alien to us, and yet strangely familiar. Clouds of sulphuric acid on Venus, Pluto's neatly layered atmosphere, and Mars' global dust storms are unlike anything we can find on our own planet, but the physical laws that shaped those worlds also apply to Earth. This means that planetary scientists can draw clear parallels between our Earth and the atmospheres of other bodies in the Solar System.

This principle is central to the research of Dr Scot Rafkin, a planetary scientist at the Southwest Research Institute in Boulder, Colorado. 'I study the weather and climate of other worlds using the same computer models, appropriately adapted, used to study and forecast the weather and climate of Earth,' he explains. 'There are many planetary bodies in our solar system with atmospheres overlying a rocky surface – Mars, Venus, Pluto, Titan – that behave in ways that are both familiar and foreign to us.'

Using computer models to study such a diverse range of bodies might seem like a mammoth task at first glance, but as Dr Rafkin explains, the laws of physics are on his side. 'These so-called terrestrial atmospheres are described by and are constrained by the same physics that governs the Earth's terrestrial atmosphere,' he says. 'Therefore, the same modelling framework that allows us to predict the weather and study the climate of Earth can be applied to other terrestrial atmospheres.' In building these models, Dr Rafkin aims to incorporate a crucial element that he believes is missing from many comparable simulations: the small- and regional-scale behaviours of planetary atmospheres.

Zooming into the Details

When simulating the atmospheres of Mars, Venus, Pluto and Titan, the models that most scientists use provide data that is averaged in space and time, removing details that are present at specific locations and times. Furthermore, many of these models are incapable of simulating the small scales, meaning that they fail to highlight potentially important effects. However,

CREDIT: NASA

if meteorologists only ever told us how the Earth's atmosphere was behaving on average, neglecting to mention any smaller-scale weather patterns, the weather forecast would be of very little use to us. Instead of providing local areas with important information about storms, showers and sunny spells, everyone would be subjected to the same, ultimately useless forecast. Dr Rafkin argues that to truly understand how planetary atmospheres work, scientists need to look at these small-scale features.

‘There are many planetary bodies in our solar system with atmospheres overlying a rocky surface – Mars, Venus, Pluto, Titan – that behave in ways that are both familiar and foreign to us.’

‘In the big picture, my work shows that details matter,’ he explains. ‘It is common in the planetary science community to think about how atmospheres behave on the large or global scale, often with little thought to the importance of processes operating at smaller scales. These smaller details can be extremely important, and if you neglect to take their effects into account, you will not fully capture the reality of how terrestrial atmospheres behave.’

Therefore, Dr Rafkin uses his computer models to analyse how local and regional weather patterns behave on different bodies – paying particular attention to how they can affect the properties of their atmospheres as a whole. Two particular worlds have been the subject of several of his recent studies: Saturn’s largest moon, and one of our closer planetary neighbours.

Titan’s Methane Cycle

At first glance, the weather on Saturn’s moon, Titan, appears to be remarkably similar to our own, with clouds, rain and storms, all fuelled by a global patchwork of lakes and seas. Here, however, all traces of water have been frozen as hard as rock, meaning a completely different substance must be cycling between liquid and gas on this world.

‘Titan has a very dense and cold atmosphere composed primarily of nitrogen with a small amount of methane that can condense into liquid or ice,’ says Dr Rafkin. ‘Earth has a similarly dense atmosphere of nitrogen, but it is much warmer, and water rather than methane is the trace gas that condenses. Both atmospheres produce clouds, and both atmospheres support storms.’

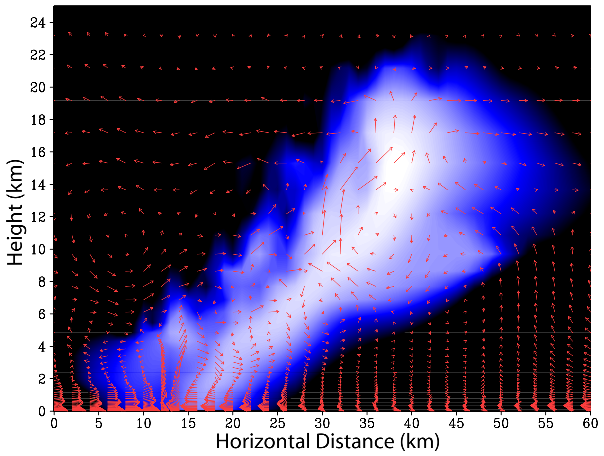
On Earth, storms arise when large amounts of energy are stored in evaporated water, which is rapidly released when the water condenses to produce rain, strong winds, and lightning. Because Titan’s methane cycle appears to be so remarkably similar to the water cycle on Earth, Dr Rafkin modifies the techniques used by more conventional meteorologists who study these violent weather phenomena.

‘By adapting Earth cloud models to Titan, I can understand the conditions under which Titan’s storms form, and importantly, I can learn more about the characteristics and behaviour of the storms than is possible from the very limited observational data,’ he explains. Through these studies, Dr Rafkin has concluded that the very same physical processes responsible for the dynamics, shapes and lifetimes of our own storms can be directly compared with those on Titan.

‘For example, in the absence of strong wind shear, Titan’s storms have a short lifetime and produce heavy rain in a local area,’ he adds. ‘When wind shear increases, the storms evolve into longer-lived and more severe storms similar to those seen on Earth. These storms also produce heavy rain, but it is spread over a larger area along the path of the storm.’

Cold Sea Breezes

In further research, Dr Rafkin and his colleagues studied another Earth-like weather phenomenon visible on Titan: exchanges of vapour and



A simulated Titan storm: the cloud is shown by the shading and the red vectors indicate the circulation and flow of the atmosphere

energy between lakes and seas, and the lower layers of the atmosphere. This process creates a steady wind flowing inland, named a 'sea breeze', which can be impacted by factors including the size and depth of the lake, the strength of the background wind, and the difference in temperature between the lake and the atmosphere.

Since the breezes appear to form on both Earth and Titan, Dr Rafkin could again adapt existing computer models used to study sea breezes on Earth to discover how they behave on Titan. 'Our recent work shows that properly representing the amount of evaporation from Titan's methane lakes requires attention to the details of the local scale circulations,' he says. 'Just like on Earth, Titan's lakes produce sea breezes and marine microclimates of cool and moist air.'

Through these results, Dr Rafkin and his colleagues have shown that smaller-scale weather patterns cannot be ignored when studying planetary atmospheres. 'The circulations and the local marine layer strongly affect the amount of methane evaporated from the lakes, and this, in turn, affects Titan's global methane budget,' explains Dr Rafkin. 'Failure to account for these localised details results in an inaccurate picture of how methane is globally recycled through clouds, rain, and lakes on Titan.' So far, this line of research has already provided scientists with critical insights into how one of the most active terrestrial worlds in the outer Solar System can be properly studied.

Dust Storms on Mars

Closer to home, Dr Rafkin and his colleagues are also studying the atmosphere of Mars, whose mass is now greatly diminished through aeons of gas molecules escaping from the planet's weak gravity, and being stripped away by unshielded solar winds. When looking at images of the planet's desolate surface, especially those gathered by NASA's *Curiosity* rover, it is easy to draw parallels with the more barren parts of our own planet. As Dr Rafkin explains, such comparisons can indeed be useful in studying the Martian atmosphere, though not in an immediately obvious way.

'Mars has enigmatic dust storms,' he says. 'While dust storms occur on Earth too, the characteristics and behaviour of Mars' dust storms is, in many ways, more similar to Earth's thunderstorms, squall lines, and hurricanes. We know this because computer models provide insight into how atmospheres work.'

In recent studies, Dr Rafkin and his team have also used their computer models to interpret data gathered by *Curiosity*, now located in the Gale Crater, to characterise the seasonal changes observed throughout the Martian year. This research has now revealed a complex, small-scale meteorological landscape inside the crater, complete with features including thermal tides, regular flows of dust down the slope of the crater, and atmospheric waves breaking on the surrounding mountain tops. Such discoveries represent crucial advances in our understanding of the Martian atmosphere, and its similarities with our own.

Giant Vertical Plumes

As on Titan, Dr Rafkin argues that these intriguing behaviours play an integral role in the atmosphere on Mars, which cannot be ignored by simply studying the system as a whole. 'The evidence for the importance of small and regional circulations has continued to grow,' he says. 'For example, the dust distribution in the atmosphere of Mars strongly influences the temperature distribution, which then drives pressure gradients and winds.'

One particularly intriguing conclusion Dr Rafkin makes is the influence of deep and vigorous plumes of dust, which come and go in measurable life cycles. As he explains, the results indicate that these coherent, small-scale phenomena are a crucial element of larger patterns in dust dynamics. 'It turns out that small local scale atmospheric circulations are critical to the overall dust cycle,' he says. 'In particular, these atmospheric circulations are capable of rapidly injecting dust high into the atmosphere. The result is enhanced layers of dust at altitude, which cannot be explained by the global scale circulation alone. I've also shown, along with other colleagues, that local and regional dust storms have similar effects.'

Such discoveries are now transforming the ways in which researchers are viewing the moons and terrestrial planets of our Solar System – an advance that would not have been possible with large-scale atmospheric analysis alone. Dr Rafkin's research, therefore, could have a significant impact on the techniques used by planetary scientists in the future, potentially allowing us to study them in unprecedented levels of detail.

CREDIT: Rayna Tedford

Meet the researcher

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Dr Scot Rafkin achieved his PhD in the Department of Atmospheric Science at Colorado State University in 1996. He then worked at the University Corporation for Atmospheric Research and San José State University in collaboration with the NASA Ames Research Center before moving to Southwest Research Institute in Boulder, Colorado in 2003. Here, he is currently Program Director in the Department of Space Studies. Dr Rafkin has extensive experience developing weather and research modelling codes and has applied these to the study of local-scale circulations, clouds, and aerosols for Earth and to several other terrestrial planetary atmospheres. His systems for modelling Mars and Titan are recognised as the premier tools for simulating local and regional atmospheric circulations. Dr Rafkin is a Co-Investigator on the Mars Science Laboratory Rover Curiosity mission and the recently selected New Frontiers Dragonfly mission to Saturn's moon Titan.

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SwRI
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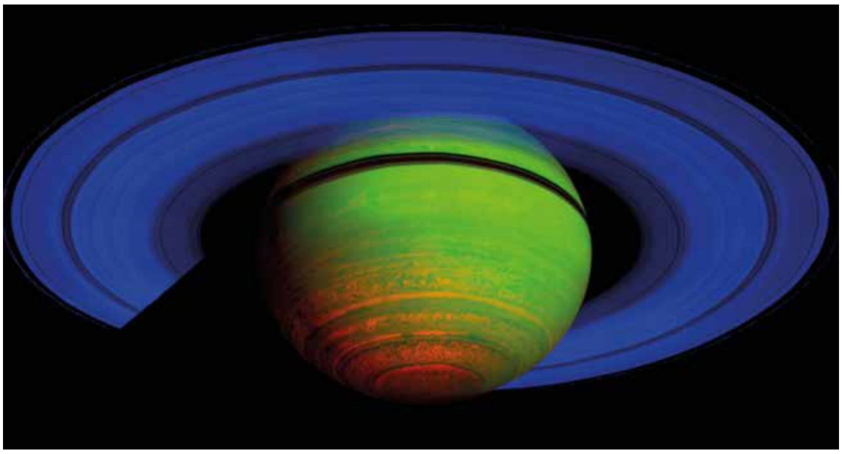
EXPLORING ENERGY FLOW IN PLANETARY ATMOSPHERES

Within the atmospheres of different planets, energy is continually moving around and being converted into different forms. In his research, **Dr Liming Li** at the University of Houston studies how the different worlds of our solar system generate, transfer and convert energy in different ways. Through analysing the atmospheres of Jupiter, Saturn, Titan and Earth, his team has made discoveries that provide new insights both for astronomers and for scientists studying our own changing climate.



Heat (red) emitted from the interior of Saturn shows up in this false-colour image, made from data taken in 2008 by Cassini's visual and infrared mapping spectrometer. CREDIT: NASA/JPL/ASI/University of Arizona.

Flowing Energy

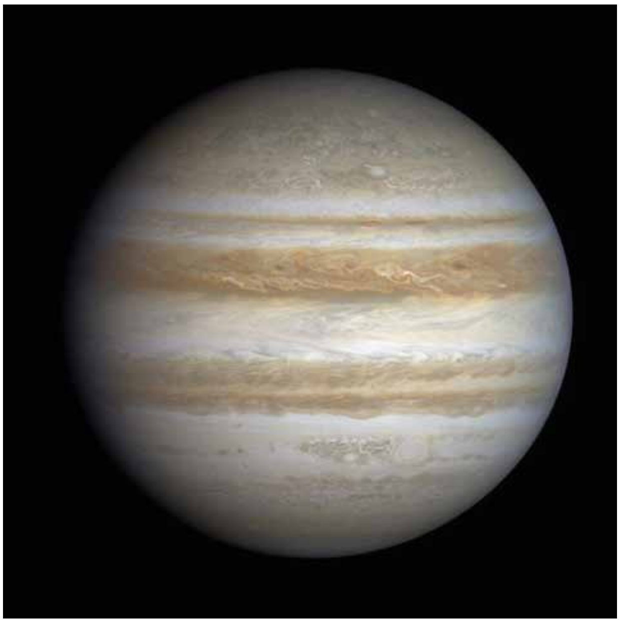
Scientists can draw conclusions about planetary atmospheres from three fundamental properties of the energy flowing within them. Firstly, the 'radiant energy budget' is the balance between the energy that a planet absorbs from the Sun and the energy that the planet emits. The energy from the Sun travels through space in the form of radiation, before interacting with a planet's atmosphere. Once this energy has been absorbed, 'radiative transfer' describes how it moves around – crossing between different systems within the larger planetary system. Finally, this radiant energy can be converted into many different forms, such as mechanical energy.

As Dr Liming Li of the University of Houston describes, these three energy flow properties together have a profound influence over the ways in which atmospheres behave. 'The radiant energy budget and its variation over time influence the thermal structure of these atmospheric systems,' he says. 'Furthermore, the transfer and distribution of radiant energy within these atmospheric systems can generate mechanical energy to drive atmospheric circulation, weather and climate.' Understanding these three aspects is vital for explaining the dynamics of planetary systems as a whole, including our own.

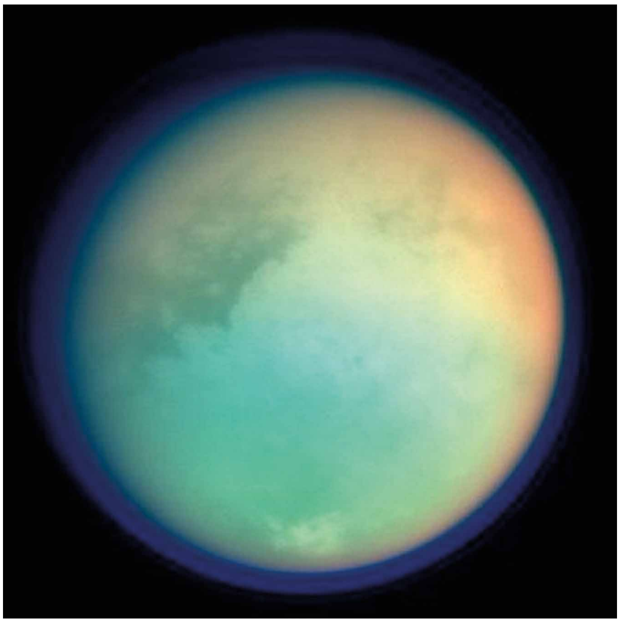
Focus on Four Worlds

Dr Li and his colleagues investigate real observations of the planets and moons of the solar system, each of which displays its own unique behaviour. Within the solar system, there is a diverse range of active worlds to explore, from small, rocky moons to colossal gas giants. Clearly, such a high degree of diversity means that energy budgets, and the rates of energy transfers and conversions, will vary widely between different bodies.

Though it is challenging to study such different systems using the same techniques, Dr Li believes it is hugely beneficial for astronomers and Earth scientists alike. 'For giant planets, the radiant energy budget and the related internal heat also can help understand the evolutionary history of planets,' he explains. 'In recent years, my research group has been exploring the radiant energy budgets and mechanical energy cycles for the atmospheric systems of the gas giant planets, including Jupiter and Saturn, and some rocky bodies, including Earth and Titan.'



Jupiter's visible image, recorded with the Cassini Imaging Science Subsystem. CREDIT: NASA/JPL/SSI/Color composite by Gordan Ugarkovic.



Multi-spectra image of Titan. CREDIT: NASA/JPL/Space Science Institute – NASA planetary photojournal, prepared by Alfred McEwen.

These four worlds each present their own unique set of challenges for astronomers and Earth scientists exploring the flow of energy within their atmospheres. Yet despite their differences, studies of such planets and moons can yield important insights into Earth's atmosphere. At a time when the atmospheric energy budget is severely disrupting the climate on our home planet, these insights are now critically important.

Jupiter's Energy Budget and Internal Heat

The solar system's largest planet has been mystifying astronomers for centuries, with its endlessly swirling clouds masking a deeply complex set of underlying behaviours. One of the biggest uncertainties about Jupiter is the reflectivity of its gases – a value that is strongly linked to its energy budget. From data gathered by the Pioneer and Voyager missions, which each flew past Jupiter in the 1970s, astronomers had estimated that the planet reflected just 30% of the Sun's light back into space.

In their work, Dr Li and his colleagues used updated data on Jupiter, gathered by the Cassini spacecraft, which made its closest approach to the planet in 2000. Using data on reflected light gathered by the spacecraft, the researchers concluded that Jupiter reflects around 50% of the sunlight that it initially absorbs. In addition, they found that Jupiter generates more heat in its interior than previously thought.
Dr Li believes that the new findings will help us to better understand the formation and evolution of planets in our solar system. 'Based on the observations from the Cassini spacecraft, we conducted the best measurements of Jupiter's radiant energy budget and internal heat,' he summarises. 'The new measurements significantly improve previous estimates and have wide applications and impacts in planetary science, meteorology and astronomy.'

Saturn's Emitted Power

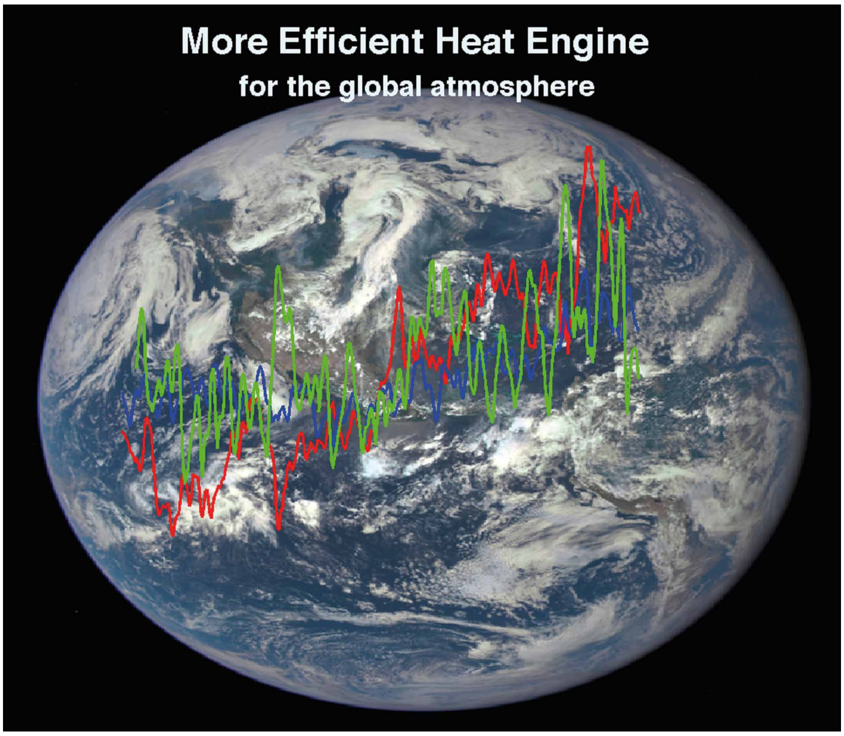
Cassini also provided Dr Li's team with useful data about Saturn – the end point of the mission. After the craft began orbiting Saturn in 2004, its infrared spectrometer collected consistent data on the energy emitted from the planet's surface. The data revealed that Saturn's southern hemisphere was emitting more energy than its northern one – a result that was consistent with the gas giant's distinctive systems. More mysteriously, however, the data also showed that the planet as a whole cooled for several years before 2009, before beginning to heat up again.

In 2010, astronomers observed a violent storm on Saturn, which increased the global power emitted from its surface by around 2%. Similar violent storms could be a regular occurrence on this planet, reappearing once every Saturnian year – the equivalent of around 30 Earth years. If this is the case, storm clouds could be periodically affecting Saturn's radiant energy budget and hence atmospheric evolution.

'We examined the temporal variations of Saturn's emitted energy for the first time,' Dr Li summarises. 'Our studies suggest that seasonal cycle and the 2010 great white spot – the largest storm ever discovered on Saturn – both play important roles in Saturn's radiant energy budget.'

Titan's Energy Budget

As the only moon in the solar system with a thick atmosphere, Saturn's largest moon, Titan, is a particularly intriguing subject of study due to its similarities with Earth. Comparable to the water cycle on Earth, Titan's atmosphere is able to support lakes and seas of liquid methane, which evaporates to form clouds and rainstorms. Therefore, studying Titan's energy



The background image of Earth was obtained by NASA's Earth Polychromatic Imaging Camera aboard NOAA's Deep Space Climate Observatory. The curves are the time series of the dissipation of the total kinetic energy, which is used to measure the efficiency of the global atmosphere as a heat engine during the modern satellite era (1979–2013).

budget could tell us more about that of Earth's atmosphere.

Again, using observations made by the infrared spectrometer on board Cassini, the researchers compared how much of the Sun's energy was absorbed by Titan, with how much was emitted back into space. They concluded that Titan is in a rough equilibrium even though a small energy imbalance is possible.

'Our analyses suggest that Titan does not have a large energy imbalance between the absorbed solar energy and emitted thermal energy discovered on its mother planet, Saturn, but it possibly has a small energy imbalance,' Dr Li comments. His discoveries offer important insights into Earth's atmospheric system, which is currently experiencing a small energy imbalance and related changes in climate.

Earth's Lorenz Energy Cycle

On our home planet, scientists describe the flow of energy throughout the atmosphere using the 'Lorenz energy cycle', which describes how much mechanical energy is generated, how much of it is converted into different forms, and how much is dissipated.

Dr Li's team studied the long-term variations in the cycle, which had not been particularly well studied in the past. To explore them, they analysed three independent meteorological data sets over several decades. 'We updated the classical picture of the energy cycle of Earth's global atmosphere based on modern-time satellite-based datasets,' Dr Li describes.

The researchers discovered that while the total mechanical energy of the Earth's atmosphere has remained relatively constant over time, it is also converting heat into mechanical energy more efficiently. In other words, its performance as a thermodynamic heat engine is improving over time. Ultimately, this means that as the climate warms, Earth's atmosphere is becoming increasingly turbulent, as energy is being converted and dissipated more quickly.

This type of approach to studying climate change is often overlooked by scientists, but as Dr Li concludes, it is crucially needed to fully understand its effects on our atmosphere. 'Our exploration of the temporal variations of the energy cycle suggests that the efficiency of the global atmosphere as a heat engine increased during the modern satellite era,' he says. 'These studies are helping us better understand climate change and storm activities on Earth.'

Preparing for the Future

In studying the flow of energy throughout planetary atmospheres, Dr Li and his colleagues have provided astronomers with potential answers to a variety of problems. These insights are invaluable to the field of planetary astronomy, but they also come at a critical stage for our own planet, as our atmosphere experiences changes in its energy flow that have not been carefully examined in its history.

By gaining a more sophisticated understanding of the atmosphere's performance as a heat engine, climate scientists will be better equipped to understand the extent to which the climate is changing, and to predict how it could transform in the future.

In addition to Jupiter, Saturn, Titan and Earth, Dr Li's team is also exploring other planets and moons in our solar system. In particular, they are working on the radiant energy budgets and internal heat of the two ice giant planets – Uranus and Neptune. They are also developing an instrument with a possible space mission to better measure the radiant energy budgets and internal heat of the two ice planets. Such an instrument could be used to explore the radiant energy budgets and internal heat of other planets and moons.

Meet the researcher

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Dr Liming Li completed his PhD in Planetary Sciences at Caltech in 2006. Upon graduating, he worked as a Research Associate in the Department of Astronomy of Cornell University, before moving to the University of Houston. Here, Dr Li is now an Associate Professor in the Department of Physics, where he has worked since 2009. His research group is interested in exploring the planetary atmospheres of giant planets, rocky planets and moons by combining observations, theories and numerical models. Recently, his group is mainly working on two space missions – Cassini and Juno.

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UNIVERSITY of HOUSTON

THE ROYAL ASTRONOMICAL SOCIETY

Established almost two centuries ago, the Royal Astronomical Society (RAS) is the UK's learned society dedicated to facilitating and promoting the study of astronomy, solar-system science and geophysics. In this exclusive interview, we speak with the Society's President, **Professor Mike Cruise**, who tells us all about the RAS and its exciting and varied activities. He also describes some of the latest advances in the world of astronomical research, and discusses the future of this fascinating field.

To begin, please tell us a little bit about the history of the RAS. When and why was the Society established?

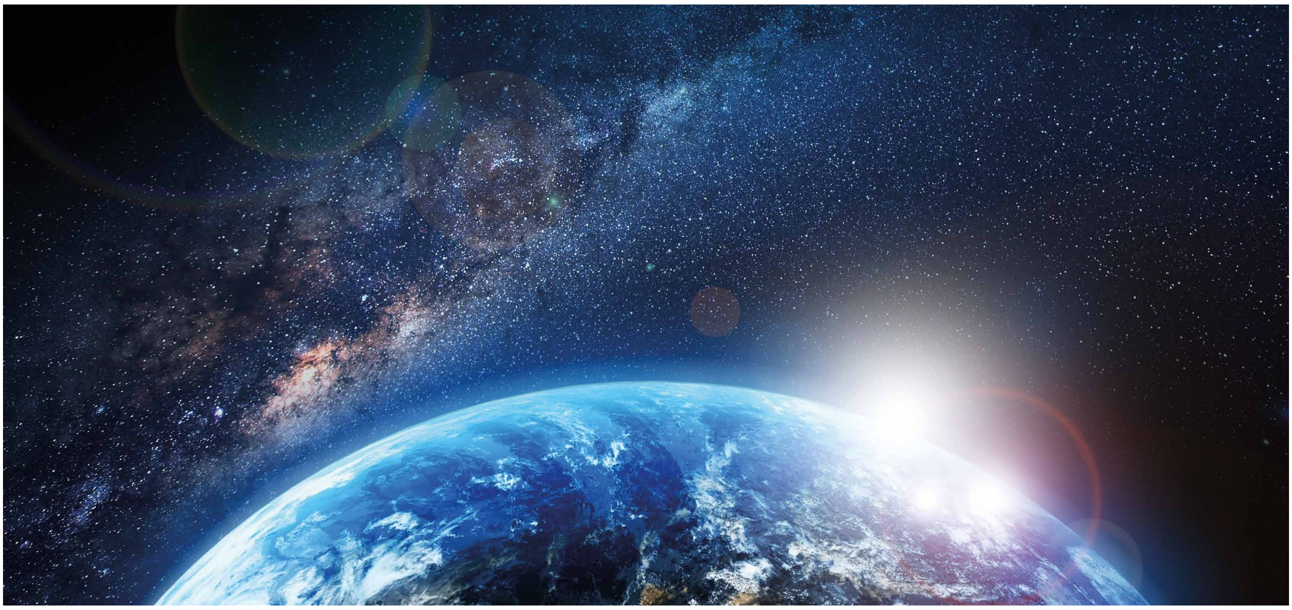
The RAS began life as the Astronomical Society of London and the idea for forming it arose at a dinner on January 12th 1820 in the Freemason's Tavern in London. The dinner was attended by a group of distinguished amateur astronomers and scientists. In 1831 the Society received the Royal Charter and became the Royal Astronomical Society. The original aim was to organise scientific meetings in London for the members to attend and discuss the latest results. Quite soon a library of astronomical works was started and the formal publication of scientific papers on astronomy was also initiated.

What are the Society's aims, and how do you work to achieve these?

The aims of the RAS are 'Encouraging the development of Astronomy and Geophysics and related sciences such as Space Science'. Geophysics is part of the RAS subject area, recognising that when we study planets, we also need to study solid earth processes such as vulcanism, plate tectonics and seismology to compare with what we observe elsewhere in the Solar System.

One of the most significant ways that the RAS facilitates collaboration amongst scientists is through its meetings and conferences, the largest of which is the National Astronomy Meeting. In your opinion, what were the research highlights from last year's meeting, and what are you most looking forward to this year?

One persistent problem that astronomers are trying to solve is the nature of Dark Matter. This is a component of the universe that seems only to interact via the gravitational force, quite unlike the normal forms of matter we meet in everyday life.



A new result announced at the National Astronomy Meeting concerned a remarkable galaxy in the cluster Abell 3827 which previous observations suggested had become disconnected from its cloud of Dark Matter, indicating some other form of interaction – perhaps in a galaxy collision. This raised hopes of some new insight into Dark Matter, but the new results shown at the Meeting indicated that, with better resolution, the Dark Matter halo is really present. And so, the puzzle continues.

An excellent example of the power of new space data was presented at the National Astronomy Meeting using solar observations. The Sun is very much an ordinary star and the only one we can study in extreme detail. A group of scientists from across Europe had observed 'Solar Tornados' with new techniques which permit the construction of 3D images of these vast structures. They found that, despite their name, these Solar Tornados are not swirling vortices of hot gas but more stationary structures at the foot of larger solar eruptions. The name tornado arose because, viewed only in 2 dimensions, they do have a similar shape to tornados on Earth, but we now know that this name is really misleading.

The National Astronomy Meeting in 2019 is certain to produce a wide range of new observations and new ideas from the closest planets to the far reaches of the cosmos. The Meeting is the UK's showcase for the continuing advances of modern astronomy.

In what other ways does the RAS support astronomy and geophysics research in the UK and internationally?

The RAS awards medals and prizes to recognise major achievements in our science and these are highly valued the world over. We give travel grants to enable post-graduate students to travel to conferences and present papers, often for the first time in their career. We also have a student summer bursary scheme which funds undergraduates joining a research group for 8–10 weeks in the vacation to experience research at first hand.

During the academic year from October to May, the RAS organises scientific meetings both in London and around the UK. Much of our resource is focused on early career scientists, helping them get a good start to their career.

How does the RAS engage the public to become interested and involved in astronomy and geophysics research?

The RAS has developed its outreach activities a great deal in the past ten years, mostly in response to the incredible public interest in astronomy and geophysics. A contributing factor has also been the change in the public attitude to charities, which are now required to deliver public benefit as well as benefit for the membership. Happily, these two trends are exactly aligned and the RAS has responded by assigning more resource to this important activity. Our outreach teams visit schools and arrange talks for the general public and many of our members deliver these at sites across the UK. These talks are often so popular that the audience size is limited by the size of the venue.

Explain what RAS200 Sky & Earth is all about.

Several years ago, the Council of the RAS decided to start a rather new outreach scheme, one aiming to bring the excitement of astronomy and geophysics to people who might not normally experience it. Recognising that our bi-centenary will arrive in 2020, the project was named RAS200. We then

went out to the wide community of organisations involved in helping various disadvantaged sectors of society and sought their ideas as to how to achieve these aims. The project was started well before 2020 so that during the bi-centenary we could talk about what we had actually achieved and not just our aspirations.

RAS200 has touched the lives of many corners of society where people were perhaps unaware of how an interest in science might encourage and inspire them to look beyond their immediate difficulties. We have run projects with carers, prisoners, minority language speakers, football fans, people on the autism spectrum, girl guides and communities located far from London and other major centres. The response has been immensely positive and nearly 8000 individuals have so far been involved. This is an innovative programme that the RAS is very proud to have initiated.

The RAS is committed to promoting diversity and equality in the fields of astronomy and geoscience. Detail some of the ways in which the Society is working to achieve this.

The unspoken ethical basis for science has been that we value and respect our colleagues for their scientific knowledge and achievements completely independently of their gender, racial background, nationality, sexual orientation, politics or other world views. For some years the RAS has responded to the need to be more explicit in showing support for such ideals. We now have a written code of conduct defining what is regarded as acceptable behaviour and we run special sessions on diversity and equality during our National Astronomy Meeting each year. We have also allocated staff time to promote and encourage diversity and equality in all we try to achieve.

Finally, your area of expertise is gravitational wave astronomy, and your research team was involved in the recent discovery of gravitational waves at LIGO. What are you most excited about for the future of this field, and how is the RAS involved?

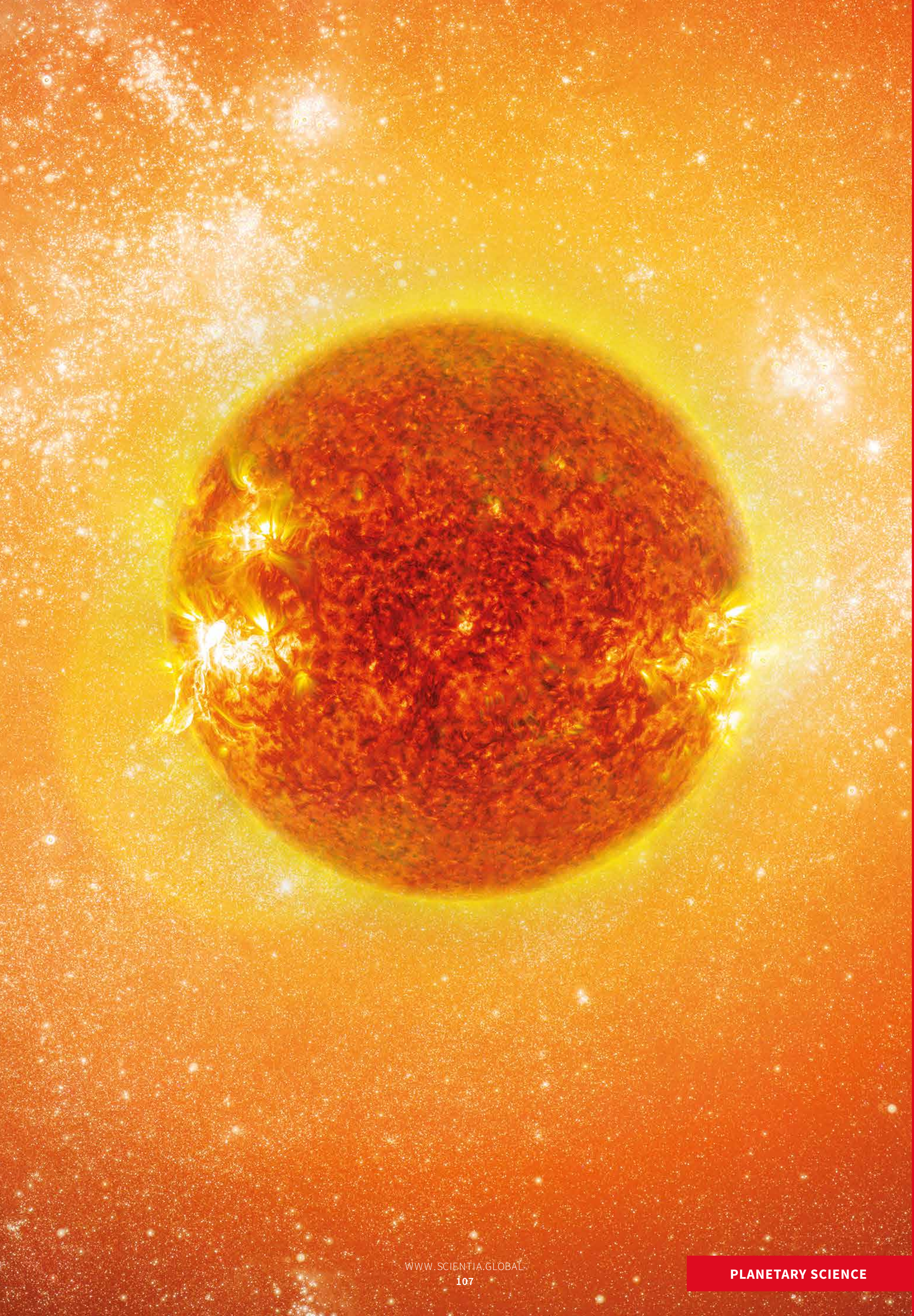
The impact of the detection of gravitational waves in 2015 has been enormous, both for the scientists involved in producing and analysing the data and their colleagues in other branches of astronomy who now benefit from the knowledge gained. I set up the gravitational wave group in Birmingham when I moved there in 1995 and was extremely proud of their significant role in the first detection, although I had retired by then.

As with every other situation where scientists can measure something new, the data from LIGO is expanding our knowledge of the world around us. In this case we are learning about Black Holes and the routes by which they are created, knowledge we could not gather from any other source. Rather surprisingly, we are also learning how the heavy elements like gold and silver are created when neutron stars collide, solving a long running puzzle.

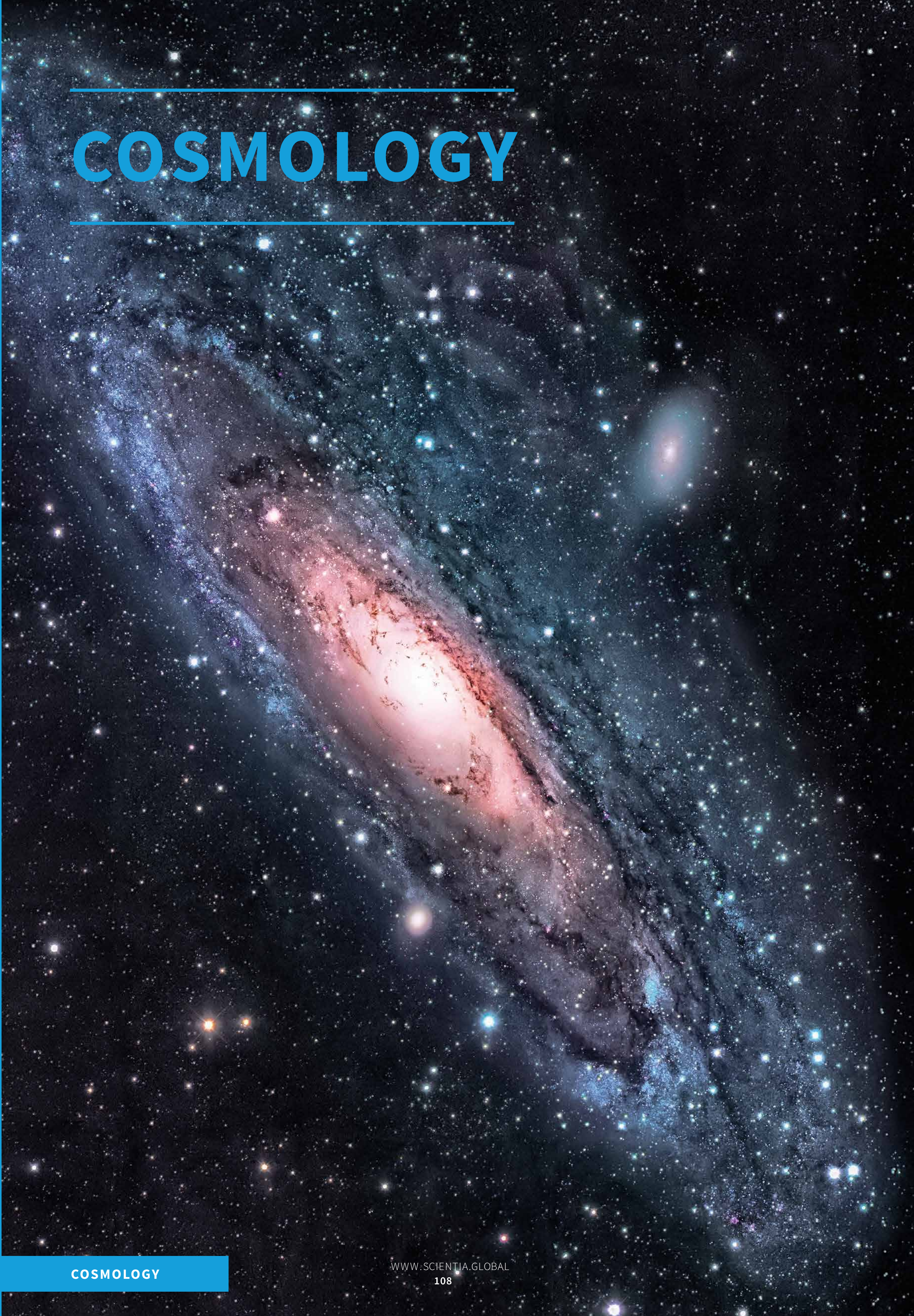
The RAS was fortunate to have scheduled a talk from one of the LIGO team the day after the discovery was made public and as the subject matures, I am sure we will have many more exciting scientific announcements concerning gravitational waves, and other branches of astronomy and geophysics, at the RAS meetings.

www.ras.ac.uk

Royal Astronomical Society
Advancing Astronomy and Geophysics



COSMOLOGY



ASTRONOMICAL ADVANCES IN COSMOLOGY RESEARCH

In the final section of this edition, we showcase some of the most fascinating research in the fields of cosmology and astrophysics, with a particular focus on the formation and evolution of stars and other large objects in the universe.

Scientists understand quite a lot about fully-formed stars, such as our Sun, but many aspects of star formation remain shrouded in mystery. In the first article of this captivating section, we introduce Dr Philip Myers of the Center for Astrophysics, Harvard and Smithsonian, who has been observing and interpreting stellar formation using a range of sophisticated telescopes and theoretical models. We discuss his pioneering work over the past four decades, before introducing his most recent research into uncovering the mysteries of 'fragmentation' – the process whereby molecular clouds break down into ever-smaller fragments, which then collapse to form new-born stars.

Next, we meet Dr Reinhard Genzel and Dr Linda Tacconi at the Max Planck Institute for Extraterrestrial Physics, and Dr Karl-Friedrich Schuster at the Institute for Millimetre Radio Astronomy, who have also been exploring how stars and galaxies form and evolve over time. Using the Northern Extended Millimetre Array (NOEMA) in France, and the 30-metre single dish telescope in Spain, the team has studied galaxies of different ages to assess how their ratios of gas to stars evolves over time. Their findings have significantly advanced our understanding of how stars form inside galaxies of different ages, and the timescales involved.

As well as investigating star formation, our next featured researcher studies the formation of other massive objects that form as material collapses in on itself under its own gravity. Through a combination of physical theories and the latest computer simulations, Dr Shantanu Basu at the University of Western Ontario in Canada is offering intriguing new insights into how various massive structures originate – from bodies that are too small to become stars, to the vast, all-devouring black holes that reside in the centres of galaxies.

Following these fascinating investigations into the formation of stars and other astronomical objects, our final article of this section focuses on one of the biggest questions in cosmology: are we alone in the universe? In the hope that intelligent life forms on planets orbiting other stars might generate radio signals that we can detect, a group of astronomers launched the Search for Extra-Terrestrial Intelligence (SETI) institute in the 1960s.

In an exciting new initiative at the SETI Institute, called the Earthling project, composer Felipe Pérez has been charged with the task of creating collaborative musical compositions that represent us as humans. Then, with the help of world-renowned astronomer Dr Jill Tarter, these compositions will be launched into space, as a single unified voice that epitomises humanity. To close this mind-blowing edition, we speak with Mr Pérez Santiago, as the artistic director of the project, who gives us an overview of this ambitious venture, and what he hopes it will achieve.

A FAMILY AFFAIR: EXPLORING EARLY STAR FORMATION

A star-forming filament harbouring dense cores in the Taurus molecular cloud complex. CREDIT: ESO.

We know much about fully-formed stars, such as our Sun, but the very earliest processes of star formation are still a mysterious area of astrophysical research. The original idea that a single new-born star (or 'protostar') forms within a single molecular cloud core has been dispelled by the discovery of new-born pairs, triplets, or even larger groups of protostars in cores. **Dr Philip Myers** of the Center for Astrophysics | Harvard and Smithsonian has been observing and interpreting protostar formation for many years using a range of sophisticated telescopes and theoretical models.

Star Birth and Evolution

On a clear night, we can stand on the Earth's surface and gaze into a night sky full of bright stars. In our galaxy alone, there are around 250 billion stars, which is just a mere fraction of the number of stars in the universe. Stars have their own particular lifecycle that varies in length depending on their mass. For example, our Sun, a relatively low-mass star, is already around 4.6 billion years old – about halfway through its lifecycle.

Stars are the powerhouses of our galaxy, spreading heavier elements such as carbon and oxygen into the planetary systems that form around them, and providing the light and heat required to support life. A star emits light due to the ongoing fusion reaction in its centre, where hydrogen is converted into helium. However, a star's life begins long before it starts to shine.

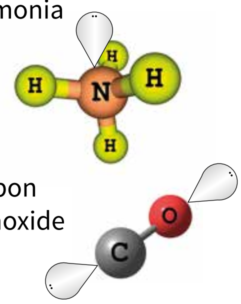
Clouds of gas and dust, known as molecular clouds, are found throughout our galaxy and beyond. It is within these molecular clouds that protostellar objects, or protostars (the earliest stage of a star) are formed. 'Stars and their planet-forming circumstellar disks form in "dense cores", or regions of increased density in an interstellar molecular cloud,' describes astrophysicist Dr Philip Myers of the Smithsonian Astrophysical Observatory, who studies the complex processes behind the early formation of stars.

Gravitational attraction causes this gas and dust to begin to draw together. As the material continues to collapse, it rotates, causing the densest gas to flatten into a disk-like shape. The material at the centre begins to heat up, forming a protostar surrounded by a disk of gas and dust that may eventually form orbiting planets.

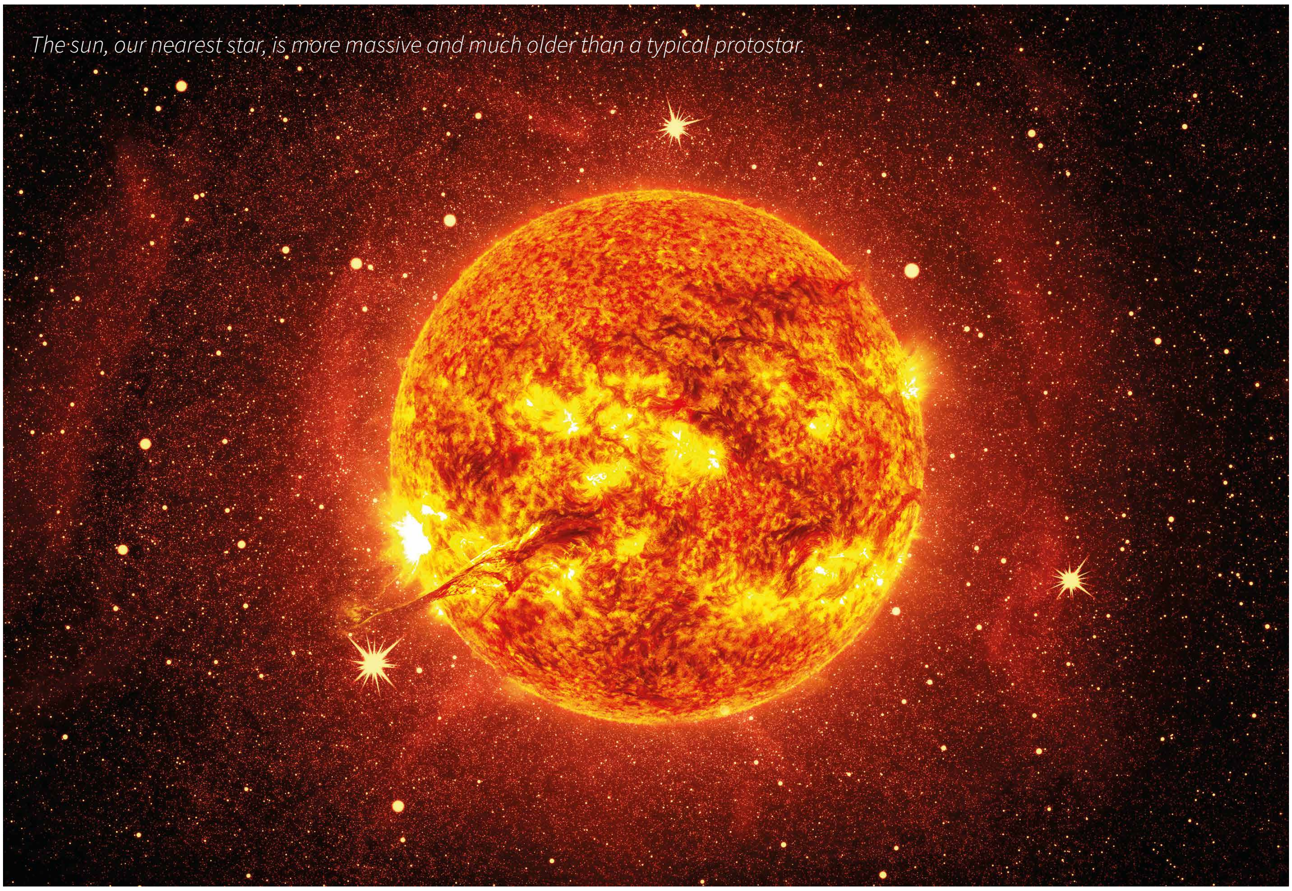
Observing Protostars

Although nuclear fusion has not yet kick-started in a protostar, it still emits visible light, generated due to heating as the protostar contracts. However, this light is absorbed by the surrounding molecular cloud, which reradiates it as lower-energy radiation at infrared and submillimeter wavelengths. This means that we cannot see protostellar objects using normal optical telescopes.

Protostars were first studied in depth during the 1980s using new observation techniques that could measure this low-energy radiation. Specific molecules such as carbon monoxide and ammonia within the molecular clouds emit characteristic frequencies



Key molecules for studies of star-forming gas.



The sun, our nearest star, is more massive and much older than a typical protostar.

of radiation, allowing scientists to figure out exactly which molecules are present in clouds millions of kilometres away. The properties of this radiation also provide information about the density, temperature, and internal motions of the star-forming gas.

Using telescopes that can create images from this low-energy radiation, Dr Myers and his colleagues made observations of dense cores within dark molecular clouds, in their hunt for clues about early star formation. By studying the locations, masses, and stability of cores in the Taurus-Auriga dark cloud complex, they were able to predict that most, if not all of these cores would eventually form stars. This was one of the first times scientists had identified protostar-forming conditions within a molecular cloud.

In 1986, Dr Myers and his team were able to complete a survey of dense cores in nearby star-forming regions, using the Infrared Astronomical Satellite (IRAS). This was the first survey of its kind in the hunt to identify a protostar, as no previous search had the sensitivity to detect such cold, faint objects embedded in molecular clouds.

The team found that over one-third of molecular cloud cores in known stellar nurseries contained an infrared source that was a newly-formed star. They determined that the sources were embedded deep in the molecular cloud surrounded by cold shells of material and still in the very earliest accretion stages.

Brothers and Sisters

For many years, researchers relied on simple models where a spherical dense core undergoes gravitational collapse to form a single protostar at its centre. However, during the late 1990s, new observations led to some new ideas about protostar formation. Scientists studying dark molecular clouds known as Bok globules found clear evidence of multiple neighbouring protostars.

When scientists first imaged these Bok globules using infrared telescopes, they identified single protostars by their infrared emission and by their outflowing streams of gas, detected in spectral lines of the carbon monoxide (CO) molecule. However, more detailed observations soon showed that some of these protostars have near neighbours in the same dense core. 'These discoveries opened the door to studies of protostar multiplicity, with recent surveys of star-forming regions revealing many systems of carbon monoxide outflow from binary or triple protostars,' says Dr Myers.

Spitzer and Herschel

More recently, Dr Myers and his colleagues have focussed on dense cores that contain small groups of young stars. As telescopes have improved in sensitivity and image resolution, the team has been able to identify areas containing young star clusters. However, the early formation conditions of cores harbouring such protostar groups were still poorly understood.

NASA's Spitzer Space Telescope. CREDIT: NASA/JPL-Caltech

The Submillimeter Array atop Mauna Kea

In a recent 2019 study, Dr Myers and the team reported key features of protostars using infrared observations by NASA's Spitzer Space Telescope. They surveyed the Gould Belt region, which is home to well-studied molecular clouds that contain the majority of currently forming stars closest to our Sun. From the survey data, the team identified 32 protostellar groups, five of which are extremely young, since they exclusively contain protostellar objects and no older objects. This study revealed new properties of these young groups, including their number, diameter, and surface density.

They then combined this information with a survey of the same areas completed by the Herschel Space Observatory. Run by the European Space Agency, this Observatory contained the largest mirror ever built for a space telescope mission. The telescope collected infrared radiation at longer wavelengths than did the Spitzer Space Telescope, allowing it to observe the gas and dust in extremely cold regions with greater sensitivity than did the Spitzer Space Telescope.

Dr Myers and his colleagues used these data to study the relationship between the protostellar objects and the density of the gas formed around them. The team determined that the groups showing both high protostellar surface density and high gas density are undergoing vigorous star formation. This identifies them as excellent targets for future studies investigating the formation processes of protostars.

Fragmentation

The discovery that multiple protostars form together casts doubt on the traditional view that gravitational collapse of a spherical core leads to the creation of a single star. Instead, the well-known process of fragmentation appears increasingly important. During this process, molecular clouds break down into ever-smaller fragments, which then collapse to form protostars.

'We now see more evidence of fragmentation – gravitational, magnetic, and turbulent processes in a dense region which create multiple centres of gravity rather than just one,' says Dr Myers. He and his colleagues used new observations of the Perseus molecular cloud to study the process of fragmentation. They used a combination of previous observations from surveys completed by telescopes including the Spitzer Space Telescope along with new data taken from the MASSES project (Mass Assembly of Stellar Systems and Their Evolution with the Sub Millimetre Array).

The team identified a hierarchical structure of nested fragments within the cloud that covered five different size scales. The largest is the cloud itself, whose diameter is more than one million times the distance between the Earth and Sun. Clouds contain smaller clumps, which in turn house filaments. These filaments are much smaller but are still about three trillion kilometres in length. Inside filaments, there are much smaller fragments of molecular cloud, known as cores and envelopes. It is inside these envelopes that protostellar disks and stars are formed.

The team's study, published in 2018, was the first of its kind to look in detail at the fragmentation structures within a single molecular cloud, paving the way for future research into cloud structure and the distribution of protostar masses.

Advancing the Field

To help fellow researchers in illuminating the mysteries of star formation, Dr Myers and his team have released the MASSES survey data as a publicly available dataset. The survey has imaged the 74 confirmed protostars within the Perseus molecular cloud, and it offers an enormous amount of information on the dust and gas around each protostar, including its structure and multiplicity of condensations, its chemical composition, its CO outflows, and the energy in its internal motions. Databases such as these are vital for collaborative research, and aid scientists across the globe as they shine a light into one of the most mysterious processes in our universe.

Meet the researcher

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After completing a PhD in physics at the Massachusetts Institute of Technology, Dr Philip Myers joined the physics faculty there, before moving to Harvard University and the Smithsonian Astrophysical Observatory (SAO). His successful research career has led to over 200 publications, and he has been the recipient of many research awards. Dr Myers' particular research focus is on stars and the processes driving their formation, combining observations with theoretical studies. He has also held Visiting Professor positions at numerous international universities, including the University of Leeds in the UK, the Lorentz Centre at Leiden University in the Netherlands, and the University of California, Berkeley. During his career, he has supported and supervised many early career scientists, who have themselves gone on to successful research careers in astrophysics.

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SAO
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INVESTIGATING THE EVOLUTION OF STAR FORMATION WITH MILLIMETRE WAVE ASTRONOMY

Astronomers have much to learn from the giant clouds of gas and dust that occupy the vast spaces between stars. These conglomerates of dense, cool interstellar matter provide the food needed for star formation in galaxies. Over the past decade, **Dr Reinhard Genzel** and **Dr Linda Tacconi** at the Max Planck Institute for Extraterrestrial Physics and **Dr Karl-Friedrich Schuster** at the Institute for Millimetre Radio Astronomy have used the Northern Extended Millimetre Array (NOEMA) near Grenoble, France and the 30-metre single dish telescope near Granada, Spain to observe characteristic radio signals from interstellar gas and dust in galaxies. Their work has gained fundamental insights into how stars and galaxies form and evolve over time.

Galactic Carbon Monoxide

Giant interstellar molecular clouds consist mostly of hydrogen molecules (H_2), with a sprinkle of helium and heavier elements. By virtue of their symmetrical shape, H_2 molecules do not emit much electromagnetic radiation, making them very hard to detect. Instead, as a proxy of H_2, astronomers observe the emissions of carbon monoxide (CO) molecules, as H_2 and CO tend to exist in almost the same ratio in all molecular clouds.

CO may be deadly to humans, but this gas has proven to be very useful for radio astronomers who study physical properties of the interstellar medium and star formation in galaxies. Molecules of CO not only comprise a significant proportion of interstellar gas – they also give off bright radio signals with characteristic frequencies.

By mapping the positions in the sky where emissions at these frequencies are observed, astronomers can precisely locate the regions where large numbers of CO molecules reside. They can then measure the masses, densities, temperatures and motions of this gas, thereby probing the properties of interstellar gas and dust clouds with impressive accuracy. Such observations show that interstellar material can contract under its own gravity, eventually collapsing to form new stars. Thus, CO signals reveal the birth sites of young stars.

Since 2003, Drs Reinhard Genzel, Linda Tacconi, Karl-Friedrich Schuster and their co-workers have been using the **N**orthern **E**xtended **M**illimetre **A**rray (NOEMA) near Grenoble, France and the 30-metre single dish telescope facilities near Granada, Spain in several major observing programs to explore how the ratio between the masses of interstellar gases and stars (the gas-to-star mass ratio) changes as galaxies evolve over billions of years.

Previous studies with the Hubble Space Telescope and the Infrared Space Observatory had suggested that the star formation rate for a given galaxy mass was larger in the past than in the current Universe. In the most active period of star and galaxy formation about 10 billion years ago, and about 3 billion years after the Big Bang, star formation rates were about 20 times greater than today.
The key question was whether this faster galaxy growth rate occurred because gas was turned into stars more efficiently then, or whether galaxies simply contained more gas.

The Horse Head and Flame Nebula

By quantifying the interstellar gas-to-star mass ratio in galaxies of different ages and masses, one can hope to empirically differentiate between these possibilities and thus uncover the basic physics of galaxy growth.

To observe galaxies of different ages, astronomers over several decades have exploited a fundamental law in cosmology: the 'redshift' of distant galaxies is directly proportional to their distance from us. This phenomenon was first observed by Edwin Hubble in the 1920s. It arises due to the fact that the farther a galaxy is from us, the faster it is moving away from us – as a consequence of the Big Bang.

Because of this, the light we observe from galaxies is 'Doppler shifted' to lower frequencies to varying degrees depending on their distance from us, making them appear redder. Also, due to the finite speed at which light travels, the light we observe from more distant, 'redshifted' galaxies provides us with a useful glimpse of the younger universe.

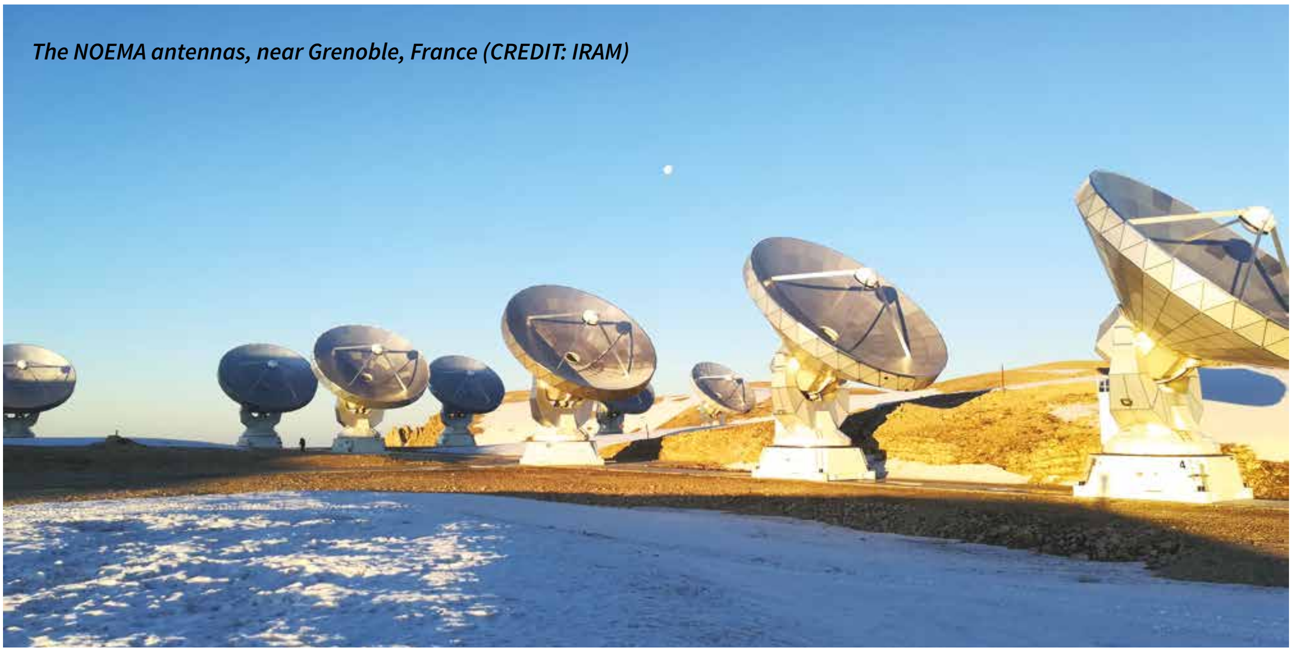
In their research, Drs Genzel, Schuster and Tacconi have used this effect to measure how gas contents have changed in galaxies as the universe has evolved.

Observing High-Redshift Star-Forming Galaxies

Over the past 15 years, the team's progress in this endeavour has been enabled by the remarkable improvements in sensitivity of the NOEMA and 30-metre facilities, especially in terms of their radiation sensors (receivers).

In the first phase of NOEMA between 2002 and 2008, it was just possible to observe a few of the rarest and brightest high-redshift, star-forming galaxies. These so-called 'submillimetre' galaxies had been previously discovered on the basis of their unusually high broad-band luminosities from warm dust emissions in the submillimetre range (light with wavelengths between a few hundred micrometres to a millimetre). With NOEMA, the team was able to spatially resolve CO emissions and infer how the gas moves around within these particular galaxies by investigating spatial changes in the Doppler shift.

The team's observations revealed that these extreme systems are often so-called 'galaxy mergers', which arise when galaxies collide to form a disturbed and more massive system. In the process of such a collision, extreme, short-lived star-forming events occur – coined 'starbursts' by astronomers. These galaxy mergers were much more common in the young, dense Universe than they are today and probably produced many of the massive 'elliptical galaxies' that we observe today.



The NOEMA antennas, near Grenoble, France (CREDIT: IRAM)

Surveying Normal Star-Forming Galaxies

In the second phase, Dr Genzel, Dr Tacconi, Dr Schuster and their co-workers took advantage of further improvements in the capabilities of NOEMA to survey ever larger samples of galaxies. In this research, they included more normal 'rotating disk galaxies', which make up the majority of the star-forming galaxy population at high redshift.

Because of improved statistical methods, the team was now able to determine how gas mass, the ratio of gas mass to stellar mass, and the ratio of gas mass to star formation rate vary with stellar mass, redshift and star formation rate. In the team's so-called PHIBSS1 survey (2009–2013), it became ever clearer that star-forming galaxies in the young Universe were indeed much richer in interstellar gas, leading to higher star formation rates. The researchers also confirmed that the efficiency of star formation changed more modestly over the past 10 billion years.

Confirming Mass Scaling Relationships

In their latest study (PHIBSS2, 2013–2017), Dr Genzel, Dr Tacconi and their colleagues aimed to further confirm the relationships that influence star formation rates by including additional methods to complement their observations of CO emissions. From a sample of 1,444 galaxies representing a variety of redshifts, including those observed in the 30-metre telescope xCOLDGASS survey of local galaxies (led by Drs Kauffmann and Saintonge), the researchers used two further techniques to determine molecular gas masses over time.

The first of these was a technique that uses the broad-band far-infrared light emitted by cold dust. Secondly, the team used 'dust photometry', which measures the dim millimetre emission given off by interstellar dust. Reassuringly, the CO and dust techniques yielded comparable results, thus increasing the robustness and reliability of the team's conclusions.

The findings of Dr Genzel and Dr Tacconi and their colleagues have significantly advanced our understanding of how stars form inside galaxies of different ages. They have also shed light on the timescales involved when interstellar gas and dust collapse to form stars, even across galaxies with different overall masses. Over the last decade, these observations have been critical for establishing a 'standard model' of galaxy evolution.

The Role of Dark Matter

While the Universe as a whole is expanding, local concentrations of (predominantly) dark matter, along with observable molecular gas, can reverse this expansion, collapsing to form gravitationally-bound structures or 'halos'. Normal (baryonic) matter in these dark matter halos falls toward the halo centres and forms the first early small galaxies.

In the next epoch, which is the one observed by Dr Genzel, Dr Tacconi and their co-workers, these proto-galaxies grew rapidly in mass by being steadily supplied with additional gas from the intergalactic medium. Near the centre, the gas cooled and then formed stars. Over cosmic time, the rate of gas inflows decreased steadily because of the expansion of the Universe, thus explaining the decrease in star formation and gas fractions over the last 10 billion years.

In the near future, Dr Schuster and his team at IRAM plan to further expand NOEMA from the current ten antennas to twelve antennas by 2020. With the upgraded NOEMA array in the northern hemisphere, future studies may further unlock the mysteries surrounding formation and evolution of galaxies throughout the Universe.

Meet the researchers

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Dr Reinhard Genzel completed his PhD in Physics at the Max Planck Institute for Radioastronomy in 1978. He has since held a variety of esteemed positions in Astrophysics both in Germany and the US – becoming the Director at the Max Planck Institute for Extraterrestrial Physics in 1986. Dr Genzel's research interests include the cosmological formation and evolution of galaxies, massive black holes, and developments of infrared instrumentation for ground-based space telescopes.

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Dr Linda Tacconi completed her PhD in Astronomy at the University of Massachusetts in 1988. She has worked at the Max Planck Institute for Extraterrestrial Physics since 1991, becoming a Senior Astronomer and Deputy Director of the Infrared/Submillimetre Group at the institute in 1999. Dr Tacconi's principal research interests include galaxy formation and evolution, millimetre and submillimetre interferometry, and star formation and massive black holes in galaxies.

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Dr Karl-Friedrich Schuster completed a PhD in Physics at Ludwig-Maximilians University in 1993, before becoming a research scientist at IRAM. He has worked at the institute since; becoming the leader of the Northern Extended Millimetre Array (NOEMA) project in 2005 and IRAM's director in 2013. Elsewhere, Dr Schuster has contributed to several projects in millimetre astronomy, including his position as co-investigator of the HIFI instrument for the Herschel-Space-Observatory.

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EXPLORING THE FORMATION OF GRAVITATIONALLY BOUND OBJECTS ACROSS THE UNIVERSE

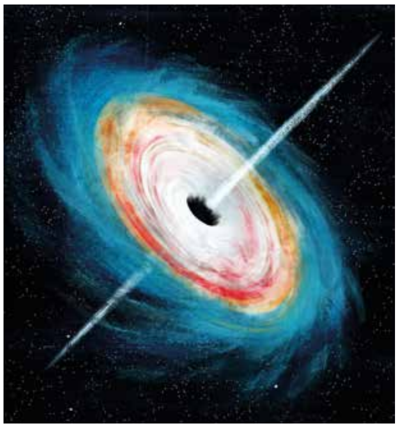
From brown dwarfs to supermassive black holes, many of the strangest objects known to astronomers are formed as material collapses in on itself under its own gravity. Through a combination of physical theories and the latest computer simulations, **Dr Shantanu Basu** at the University of Western Ontario in Canada is offering intriguing new insights into how these structures originate. His theories could help astronomers to understand the very earliest stages of bodies ranging from those too small to become stars, to the vast, all-devouring heavyweights that reside in the centres of galaxies.

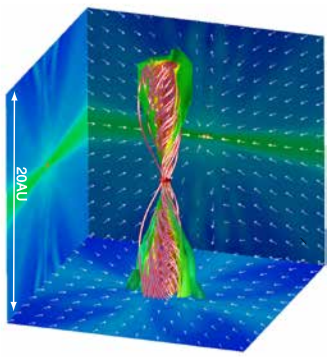
From Brown Dwarfs to Black Holes

Gravity may be the weakest of the universe's four fundamental forces, but it is nonetheless critical in shaping the landscape of the universe. In patches of space where the densities of gas, dust and other interstellar material become high enough, the force will inevitably pull it all together to form larger structures. The physical theories surrounding these processes may have been around since they were first described by Newton, but much remains to be discovered about the diverse array of bodies they can form.

This is where Dr Shantanu Basu at the University of Western Ontario comes in. 'My overall research program is to understand the assembly of gravitationally-bound objects in the universe, whether they are stars that form in the present-day or early universe, planets or brown dwarfs that form in circumstellar disks, or supermassive black holes that form through direct collapse in the early universe,' he explains.

Due to the sheer complexity of these scenarios, traditional calculations alone are not enough to explore them in detail. Instead, Dr Basu combines them with the capabilities of the latest simulation techniques. 'Through the use of large computer simulations, or analytic insight where possible, our group has discovered many features of the assembly of these objects,' he continues. With these techniques, Dr Basu and his colleagues have drawn new insights into the formation of structures including ordinary stars, bodies too small to become stars, and the very heaviest black holes in the universe.





3D view of outflowing gas (green and yellow surfaces) and magnetic field lines (red lines) in the vicinity of a newly formed protostar. CREDIT: Masahiro Machida, Shantanu Basu.

A Star is Born

Having observed them in meticulous detail for many centuries, astronomers are now able to predict the life cycles of many types of star – from red dwarfs to blue supergiants – with high degrees of certainty. However, the very earliest stages of star formation still remain shrouded in mystery. The most widely accepted theories predict that the process occurs as interstellar material collapses, forming structures called 'protostars', which are too small and well hidden to observe directly.

Building on these theories, astronomers including Dr Basu use simulations to study how small, dense lumps can transform into bodies hot enough to fuse hydrogen in their cores. As Dr Basu explains: 'Stars have been found to form through a highly episodic mass assembly process, during which a protostar can for a time brighten dramatically.' He concludes that this process is strongly influenced by doughnut-shaped clouds of material surrounding new protostars.

Furthermore, Dr Basu proposes that some of the material in these 'circumstellar' disks will go on to influence planet formation, while some of it may escape the system entirely. 'We have found that circumstellar disks can form protostellar or protoplanetary embryos that then migrate through the disk and can either fall into the central protostar, be ejected to form free-floating bodies, or carve out a gap in the disk and settle into a stable orbit,' he continues.

In his research, Dr Basu explores these behaviours in further detail by accounting for the magnetic behaviours of fluids that conduct electricity – as is the case for circumstellar disks.

Shutting Down Braking

In our own solar system, the process of 'magnetic braking' is a well-studied phenomenon. It occurs as electrically charged material captured by the Sun's magnetic field rotates at the same speed as the Sun. Eventually, the material will escape, carrying with it some of the Sun's angular momentum – subsequently slowing down its spin.

Dr Basu proposes that this same effect can be seen in the environments surrounding early protostars, and initially prevents circumstellar disks from forming.

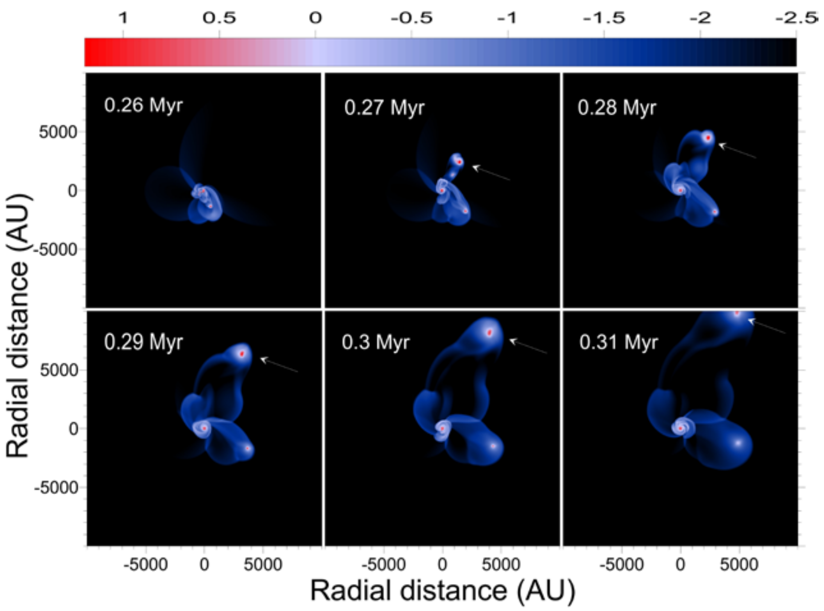
To allow disks to form, Dr Basu's simulations suggest that this braking is shut off as the surrounding magnetic field dissipates. Furthermore, the loss in angular momentum during braking allows a hydrogen-burning stellar core to form within the disk.

'Large scale magnetic fields are found throughout the universe, and our work shows that their removal during protostar assembly allows the formation of circumstellar disks, while also driving powerful jets and outflows of material from these regions,' he explains.

In one of his latest studies, Dr Basu and his colleague used their simulations to follow the subsequent dynamics over the first 2,000 years after the formation of a protostar. They have now concluded that the circumstellar disk is never absent over this period; instead, it grows and its density will increase, and spiral arms will form due to gravitational instabilities. As this happens, the disk will transfer mass to the central protostar, allowing it to grow. In turn, some material flows out from the system, inducing effects including highly time-variable jets, cavities within the disk, and structures called knots and bow shocks.

Forming Failed Stars

Dr Basu also proposes that this process could explain the origins of another long-standing astronomical mystery: brown dwarfs. Typically having masses between 13 and 80 times heavier than Jupiter in our solar system, these cold objects are too large to be classed as planets, but too small to become hot enough for sustained nuclear fusion to occur. Since their initial discovery in the mid-1990s, several hundred brown dwarfs have now been observed directly. Multiple previous theories have suggested that brown dwarfs are



Gas surface density distribution. The arrow identifies a proto-brown-dwarf that is ejected from the circumstellar disk surrounding a young protostar.
CREDIT: Eduard Vorobyov, Shantanu Basu.

formed as interstellar clouds collapse in on themselves directly, but currently, they disagree on the exact mechanisms by which this occurs.

As an alternative theory, Dr Basu and his colleague suggested in a 2012 study that brown dwarfs originate within circumstellar disks around protostars, in the very earliest stages of star formation. Over time, fragments of the disk will form large, dense clumps, which interact with each other through their mutual gravitational attraction. Ultimately, these dynamics will cause some fragments to gain speeds high enough to escape into interstellar space, where they finally collapse to form brown dwarfs. If this theory is correct, it would likely explain why many of the objects appear to cluster closely around young stars.

Mysteriously Colossal Structures

On far larger scales, Dr Basu has also explored the formation of the enigmatic black holes found within many galactic centres – including that of our own Milky Way. Typically, black holes are known to form when the most massive stars collapse in immense explosions called supernovae, leaving behind remnants so dense that not even light can escape from them. In the most extreme cases, these remnants can be many tens of times heavier than our Sun. However, the masses of the largest black holes known to astronomers – dubbed 'supermassive' black holes – are far greater, sometimes as much as a billion times heavier than the Sun.

Even accounting for how black holes will accrete mass from their surrounding environments after their formation, the laws of physics need to be stretched to allow such large structures to form at the early times in the universe's history at which they are observed. In addition, astronomers currently remain in the dark as to why quasars – supermassive black holes with extremely bright jets originating from their poles – are so varied in their apparent brightness. Clearly, an updated physical theory is sorely needed.

Bypassing Stellar Remnants

In his latest research, Dr Basu and his student suggest that the origins of these mysterious structures don't follow the deaths of stars, but instead lie within the universe's earliest stages: less than 800 million years after the Big Bang. During this period, Dr Basu's model shows that there could have been a brief era in the early universe when massive black holes formed in a way that bypassed the supernova stage entirely, instead forming directly due to the collapse of vast amounts of interstellar material under gravity. Moreover, the number of these direct collapse black holes would have been increasing rapidly during this era.

If correct, this theory could reliably explain some features of quasars, as astronomers observe them today. 'Quasars are supermassive black holes that are swallowing prodigious amounts of material, and our work has shown that the direct collapse scenario can explain their observed luminosity distribution, and has constrained the rate and duration of their formation in the early universe,' Dr Basu describes. 'Using this approach, we have also been able to understand the features of the observed quasar luminosity function.'

Dr Basu's new theory could help pinpoint the time and rate at which quasars formed in the universe. If correct, this insight would have profound implications for our knowledge of the evolution of the universe as we know it, and could be applied to understanding many of its observed features.

Understanding Gravitationally Bound Objects

As the instruments used by astronomers to observe the universe become increasingly accurate, new findings are continuing to surprise them, and throw unending curveballs towards long-established physical theories.

Yet in the face of these challenges, Dr Basu and his colleagues are pushing our understanding of the universe ever further. If their conclusions become widely accepted, astronomers could soon become far better equipped to explain the origins of the universe's bewildering array of gravitationally bound objects.

Meet the researcher

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Dr Shantanu Basu completed his PhD in Physics at the University of Illinois at Urbana-Champaign in 1993. He has now worked at Western since 1999, where he became a Professor in the Department of Physics and Astronomy in 2010. Dr Basu's research interests include the physics of gravitationally bound objects: from collapsing stars and discs, to the formation of supermassive black holes in the early universe. He has made significant contributions to theories including the roles played by magnetic fields and angular momentum in gravitational collapse and star formation, as well as luminosity bursts from young stellar objects. Outside of his research, Dr Basu has demonstrated a strong involvement in international education, and has organised a number of diversity and equity-related projects in recent years.

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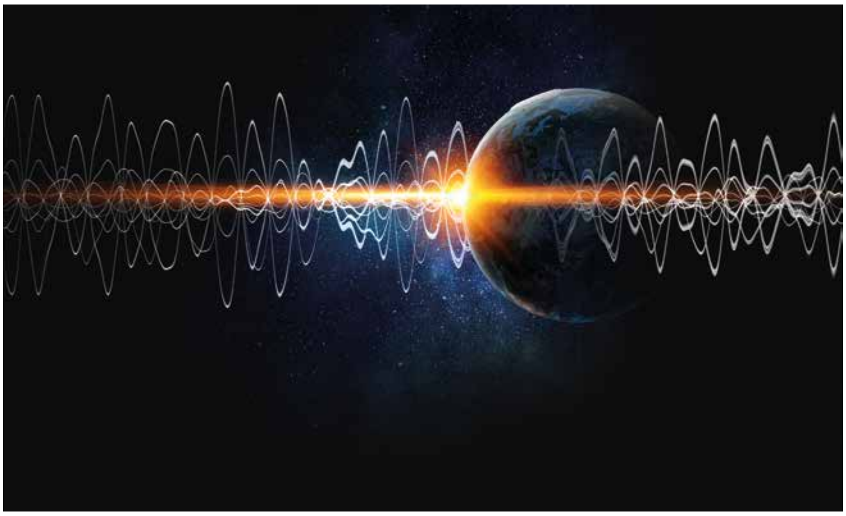
THE SETI INSTITUTE'S EARTHLING PROJECT

An exciting new endeavour at the SETI Institute, the Earthling project, aims to connect humans around the world through the universal language of music. Charged with the task of creating music that represents us as humans, composer Felipe Pérez Santiago aims to foster collaborative musical compositions that bridge ethnicity, race, culture and geography. Then, with the help of world-renowned astronomer Dr Jill Tarter, these compositions will be launched into space, as a single unified voice that epitomises humanity. In this exclusive interview, we speak with Mr Pérez Santiago, as the artistic director of the project, who gives us an overview of this ambitious venture.



To begin, please explain how you first became involved with the SETI Institute. How was the Earthling project conceived?

I got to know via the internet (and a series of very fortunate coincidences) about the SETI Artist in Residence Program. After calling and asking for information I received an e-mail from Charles Lindsay, Director of the program, who asked me to connect through Skype. We talked for a while and exchanged some ideas and that's how everything started.

Tell us a bit about the project, its timeline and the key people involved.

The project consists of creating a global sonic message through online collective compositions that represents us as human beings in this moment of our history. We are still studying the possibilities for launching this message into space, as a representation of who we are as a species. From this moment to the completion of the whole process will take approximately four years divided in four stages.

The main people involved are of course myself, Dr Jill Tarter (the world-leading astronomer and Co-founder of the SETI Institute) and Charles Lindsay (Founder and Director of the SETI Artists in Residence Program). Other key people include Ola Kowalewsky (technology and impact), Robert Baker (system architect and developer), Víctor Hernández and David Cueva (platform developers), Julio Morales (graphic designer), Patricia Carrera (PR and IP) and Omar Roldán (press and promotion).

And we are also closing partnerships with people in Mexico, the US, Germany, Denmark and Colombia. The idea of the project is, once we launch it, to have collaborators from all over the world.

Describe the 'collective compositions' that you plan to create. Who will contribute and how?

The idea is to invite people from all over the world to use the online platform that is being built specifically for this project. This will allow everybody with an internet connection to record their voices in the first stage and then to create collaborative music based

‘Can you imagine thousands of people creating music together that represents us as human beings, as earthlings? I think is an amazing dream that I truly hope we can make true.’

on that material. I will of course take the lead as a ‘musical director’ to give shape and structure to the music, but we are hoping that musicians and non-musicians from several countries will join this initiative.

Many animals produce noises that sound like music, for both known and unknown reasons, but whether such ‘music’ is created for enjoyment or aesthetic reasons is still debated. Do you believe that music is unique to humans? Would this mean that an advanced alien civilization might find it difficult to identify and interpret music?

I think animals, nature and physical phenomena all have natural implicit musical elements such as pulse and pitch, for example. Yet music as itself is a way of organising all those elements that I believe is – so far – specific to humans. We can of course enjoy the singing of birds or the sounds of thunder or the pulse of waves in the oceans, but that is sound, not music.

Whether an alien civilization may identify it as music, well, honestly, I don’t know. We don’t even know if they have the senses to listen the way we do. But if there is a human language that could be universal, that is definitely music.

How will Earthling differ from previous attempts to make contact with intelligent alien life?

The most important part of the Earthling project is the creation of the message itself. So far, we don’t know with certainty about intelligent alien civilisations and therefore we cannot send a message to a specific location and/or receiver. Of course, the idea of sending a message into space is very exciting, and who knows? Maybe someone will actually receive it and reply, but the idea of creating collectively a kind of musical missive that involves the collaboration of people from all over the world is fantastic.

If the project does not lead to contact with an advanced alien civilization, please tell us what you hope it will achieve for humankind here on Earth.

Sending music into space is a romantic and beautiful act, but since we don’t know for sure where or to whom we are sending it, it’s really about creating the message.

Music – and art in general – is a way of showing some of the best of our species, and if someone out there ‘listens’, it is a great presentation card.

Can you imagine thousands of people creating music together that represents us as human beings, as earthlings? I think is an amazing dream that I truly hope we can make true.

www.earthlingproject.com

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