Scientia

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HIGHLIGHTS:

- How Stable is the West Antarctic Ice Sheet?
- Knowing What We Face in an Uncertain Climate
- Exploring How the Lower Atmosphere Influences Space Weather
- Creating Radio Maps of the Universe

EXCLUSIVE:

- Sigma Xi – The Scientific Research Honor Society

Issue: #116

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WELCOME...

It is my great pleasure to introduce this compelling edition of Scientia, where we showcase a diverse collection of research projects, on topics ranging from climate change to galaxy evolution.

To kick-start the edition, we have had the opportunity to speak with Dr John Nemeth, former Executive Director and CEO of Sigma Xi – the Scientific Research Honor Society. In this exclusive interview, Dr Nemeth discusses the Society's rich history, and the ways that its members have been working to encourage scientific integrity, promote science education, and much more.

Following this introduction, the first section of the magazine deals with the greatest challenge of our time – anthropogenic climate change. To predict and hopefully mitigate the most deleterious effects of climate change, thousands of scientists across the globe are working to accurately quantify its effects on sea levels, storm severity, flooding and drought. This type of research is vital, as it allows us to make the best possible evidence-based decisions to ensure a sustainable future for ourselves and countless other species.

Next, in our planetary science section, we take a wider look at our home planet, and even venture deeper into the solar system. Here, we highlight several exciting projects, on themes ranging from how fractures develop deep within the Earth, to asteroid mining and investigating water on the Moon. We also meet a team of researchers who are developing technologies to help astronauts carry out spacecraft repairs on their way to Mars.

In our final section of the edition, we are plunged into the realms of cosmology and astronomy. Here, we meet four dedicated research teams, each striving to unravel the mysteries of the cosmos – how it came to be and what the future holds. From recreating the iconic Eagle Nebula Pillars in a laboratory, to simulating how the Universe evolved from the Big Bang until today, what better way is there to conclude this fascinating edition of Scientia.

Science Diffusion

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Published in the UK, by
Science Diffusion ltd

ISSN 2059-8971 (print)
ISSN 2059-898X (online)

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SIGMA XI: THE SCIENTIFIC RESEARCH HONOR SOCIETY

Founded in 1886 at Cornell University, Sigma Xi is an international community of scientists and engineers dedicated to promoting excellence in research, enhancing public engagement with science, and fostering the next generation of researchers. Here, we have had the pleasure of speaking with John C. Nemeth, PhD, former Executive Director and Chief Executive Officer of Sigma Xi, who tells us about the Society's rich history, and the ways that it has been working to encourage scientific integrity, promote science education, and much more.

Please start by giving us an introduction to Sigma Xi – tell us a bit about the organisation's rich history.

For 130 years, Sigma Xi has been the beacon of research, the clarion for scientific integrity, and the standard for quality performance. Our ranks include over 200 Nobel Prize winners. From Albert Einstein to a sophomore from East Plano High school, we encompass the total breadth of scientific research endeavour and the full array of all ages and stages of recognised professional achievement.

Sigma Xi was founded in 1886 at Cornell University by a group of engineering students and a junior faculty member, Frank Van Vleck. From the beginning, the founders emphasised that the new scientific honour society would be broad in its outlook, devoted to all of science and engineering. Sigma Xi was designed to reward excellence in scientific research and to encourage a sense of companionship and cooperation among scientists in all fields. In selecting a name and motto for the new honour society, the founders chose a combination of Greek letters – Sigma Xi – not being used by any other group.

By 1887, Sigma Xi was holding 'regular meetings for the discussion of scientific subjects', and the following year, the group elected five women to full membership, which both promoted the interests of women and made their research more available to the scientific community. By that time, chapters had been established at Rensselaer Polytechnic Institute, Union College, Stevens Institute of Technology, and Rutgers College, as well as at Cornell.

SIGMA XI
THE SCIENTIFIC RESEARCH HONOR SOCIETY

www.sigmaxi.org

‘We are a band of sisters and brothers in membership and chapters doing and promoting research – research that is the tangible foundation for a sustainable future’

At its quarter-century anniversary in 1911, Sigma Xi had about 2,000 active members in 28 chapters. Two years later, former Sigma Xi president Samuel W. Williston urged the establishment of a ‘Quarterly Bulletin’, which would, he argued, ‘create further interest in the Society and increase its usefulness’. This publication would later become known as *American Scientist*, which today is a bimonthly, illustrated magazine that communicates the latest developments in science and technology.

As Sigma Xi grew, it came to play a prominent role in scientific affairs. In 1916, the newly-formed National Research Council asked Sigma Xi’s ‘cooperation…in organising…research facilities’ in preparation for the country’s expected entry into World War I, and the Society enthusiastically agreed. By 1927, Sigma Xi had firmly committed itself to a program (which continues today) of awarding small grants to young scientists through the Grants-in-Aid of Research Program to help advance their careers.

Sigma Xi chartered its 100th chapter in 1948, and by 1950, it boasted about 42,000 active members. In 1947, a group of Sigma Xi members formed the Scientific Research Society of America (RESA) to encourage research in government and industrial laboratories, in the same way that Sigma Xi encouraged research in the academic community. In 1974, RESA merged with Sigma Xi, under the name of Sigma Xi, The Scientific Research Society of North America.

Sigma Xi’s Centennial in 1986 provided an opportunity to address issues of importance to science and society in the decades ahead. With support from the National Science Foundation, Sigma Xi sought to develop ‘A New Agenda for Science’, a project that identified seven important areas for ongoing consideration: public understanding of science, science in the policy development process, interdisciplinary research, science education, the international dimension, cooperation-not competition-in science and technology, and ethical issues involving science and technology.

In response, Sigma Xi adopted an expanded mission statement in 1989: to honour scientific accomplishments, to encourage and to enhance the worldwide appreciation and support of original investigation in science and technology, and to foster worldwide a creative and dynamic interaction among science, technology and society.

Today, Sigma Xi has over 100,000 living inductees in over 500 chapters in the US, Canada and other countries, including Georgia, Switzerland, Thailand, Lebanon, New Zealand and Australia. Sigma Xi chapters are found wherever scientific research is undertaken in universities, colleges, industrial research facilities and government laboratories.

Sigma Xi’s mission is very simple. Sigma Xi encourages, actively promotes, and directly supports performance of research at the highest degree of integrity and quality. Sigma Xi, the largest research honour society in the world, that is our inducted membership, is dedicated to enhancing and protecting the science and engineering research enterprise in all its facets. To reflect our true nature, we added ‘Honor’ to the name in 2016.

You have had quite a varied career working as an environmental consultant, and more recently as the vice president of Oak Ridge Associated Universities. What motivated you to join Sigma Xi as the Executive Director?

Through the various stops along the way, one constant has been paying my annual Sigma Xi dues. I was first in my family to even attend college, much less achieve the PhD, thus upon my 1969 induction to Sigma Xi at NC State University, the honour was strong, strong enough to last a career, for the pride and aura of zealous companionship has never left. Real scientists had invited me into their ranks! The meaning to me, even as an unproven researcher, was that I was now considered by others to be a scientist! At that point, I launched a very successful and rewarding career in environmental consulting, and came home to education and research for the longest segment of my career on the faculty at The Georgia Institute of Technology, appointed in three schools and as a Laboratory Director in GTRI. Just as background, before graduate school beckoned, I taught high school biology and chemistry, and coached American football and track. After 'retiring' from Georgia Tech in 1998, I became VP in charge of the country's largest science-based consortium of research universities – Oak Ridge Associated Universities, 'retiring' yet again in 2009.

Fast forwarding to October of 2015, I was asked to come out of retirement to assume the position of Executive Director and CEO for 6 to 9 months, and I agreed. The Society, like many such organisations, was experiencing some membership slippage and related issues. While happily working on a set of challenges and seeking a new permanent CEO, I was asked to remain for another year through to June 2017. Now, after a really enjoyable and hopefully productive tenure, I'm seeking to replace myself and retire once more. We have accomplished much and set a good heading into the future, and, naturally, I will involve myself in some way.

So, why? I love Sigma Xi, The Scientific Research Honor Society. Everything about it from the initial honour of having thousands of outstanding *Companions in Zealous Research*, to my current position, the Society feeds my passion for serving the creativity and innovation that is research.

Considering that the US is a world-leader in scientific research, why do you think scientific literacy amongst Americans is so low? Please tell us how Sigma Xi is striving to improve this situation.

Wow, if I knew this answer I would be an even busier person. A friend contends that the literacy deficit, period, is a shrunken attention span due to 'gadget communication'. Certainly, a changing way of life factors in, but there is more, and if it is true that busy thumbs have resulted in a decline in teenage drug use, why can't they be learning something with those digits? I suspect that our people have a lifestyle that detracts from day to day realities until that point in life when responsibility actually sinks in. I know this was the case for me. Having a baby on the way got all of my attention, and, thankfully for me, the truly great thing about our educational system, with all its flaws, fits, and starts, is that it allows comebacks – it offers laggards another chance.

As a scientist and an ordinary consumer of 'the news', I am suspicious of shallow analyses, ill-conceived premises, or just plain bogus statistical analyses and arm-chair sensationalism. All this normal confusion is compounded by the embarrassing failure of the pollsters, the undermining of educational content and pedagogy by legislators and other uninformed or special interest groups, and the advent of the astounding fake news phenomenon – in sum make for an altogether dangerous brew. You see, besides all the evidence that engenders my suspicions, I was once an 18-year old jokester that answered 'yes' on a personality test about whether someone was following me. Serious and personal calculation – thinking things through – and analysis without group-thinking is probably the best way forward for us all. That takes personal introspection and work. The broad-brush proclamations about the poor quality of our total educational enterprise and its products or our scientific literacy are not necessarily to be trusted out of hand… I'm just saying, sort of like Yogi Berra, a famous baseball player, who once held that, 'if you look around, you can see a lot'.

So, contrived man-on-the street interviews about science can be fun, but maybe not so informative, certainly not controlled experiments that produce truly evidence-based information. Unsubstantiated feelings, all forms of prejudice, and stereotypical characterisations are damaging, not fun. For now, I judge, as does the rest of the world, that the level of technological skill, innovation, and creativity in the United States competes very nicely anywhere. So, while we still may lag in many ways at some stages of an individual's scientific development, and it is true that opportunity, inclusivity and fairness are meted out unevenly, I see that individuals are not left out entirely nor are they tested out at early age as in many other cultures. A large proportion of our children and adults have a chance to catch up, to work hard, and to succeed. I see that through it all, we produce really world-class scientists, engineers, technologists, and mathematicians and that this cadre still represents the global gold standard. The thing is we need more gold, and the world must have an uninterrupted flow of investment and communication past obstacles confronting us in so many places and in so many ways.

The prism through which I see our young and aspiring scientists and engineers is at conferences and poster sessions at science fairs. These young people are terrific. And so, I infer that their peers, passionate about other areas, are similarly improved over my pals that chose other paths in life. In sum, I don't buy the whole pie that the scientific literacy of our people, young to old, is all that low. I do agree that it can be much better. If it is low, the reason might be most attributable to people so often uninformed about educational process, who control educational content and investment. This does not generally include teachers. My friend Norm Augustine, Sigma Xi's inaugural Gold Key awardee in 2016, and his panel on this subject a few years back did a wonderful job of defining and then recommending the path forward for STEM education. The Nation has failed to follow that advice and institute a national, broad-based, consistent, well-funded, or sustainable STEM education movement. Inadequate science literacy and spurious notions like opposition to vaccination or claims that man rode around on dinosaurs and other equally spurious ideas come from widely and sometimes surprising sources, but my community of science deserves special criticism for not speaking out more often and for not being more visible to the larger society.

Many people would say that the most visible way Sigma Xi improves the public understanding of science is through the publication of *American Scientist* – the finest science magazine in the world, I might add. Even so, Sigma Xi is a member-based organisation. The good ideas and the energy and the promotion of research is member driven through the activities of our 500+ chapters. With the support from headquarters, chapter-based initiatives achieve public understanding of science through promoting Grant In Aid Research, STEM education, Science Cafés, our KeyedIn Blog, distinguished lecturers, our newsletter, ScienceDebate.org, the Coalition for Human Rights, Sigma Xi Speaks, student research showcases, and much more in our value proposition. Finally, we work hand-in-glove with sister organisations to present the clearest state of the art information available across all of scientific research.

Explain how Sigma Xi works to prepare scientists to communicate their research more clearly and effectively. What are the major benefits that this initiative is likely to bring?

I would say that we accomplish much of this part of our value proposition for members and contribution to research overall through:

- organising science cafes to provide a forum for engaging the public and for gaining experience with public speaking.
- offering communication workshops during the annual meeting designed to educate members about the latest tools and techniques for communicating science. In recent years, we have focused on the use of social media for engaging public audiences. We are planning a major expansion of this sort of professional development programming.
- regularly publishing articles in *American Scientist* that explain best practices for communicating science. We recently launched Science Communication, a column dedicated to effective dissemination of research.
- providing communication support services through a new Research Communication Initiative that give scientists access to editorial and graphic design assistance that transforms very dense, sometimes difficult subject matter into much more easily understood and enjoyable content . We also provide platforms, including Sigma Xi's publications, social media, and newsletters, for disseminating research to a broad audience.

The major benefit…a communication-savvy population of science researchers and educators properly armed to present a robust voice for science.

Does the Society also encourage scientists to act as advocates for public policy in support of science?

It is fair to say that our whole organisation is dedicated to the promotion and protection of the research enterprise through totally apolitical and nonpartisan means. As a 501c3, we do not, cannot lobby specific legislation. In recent times, we have not as a whole been very active in the public limelight, preferring to hold meetings on important issues, write reports and conduct symposia, support distinguished lectures, and so on. All wonderfully useful pursuits; however, it is our duty and stated mission to promote and assure the highest possible ethical behaviour in research and to attain the highest possible quality research results; all conveyed in a full-throated voice.

Recently, I have sought to actively partner with like-minded organisations, such as AAAS, Research!America, and AAU, helping add the backing of our 110,000 inducted members to issues of importance to research.

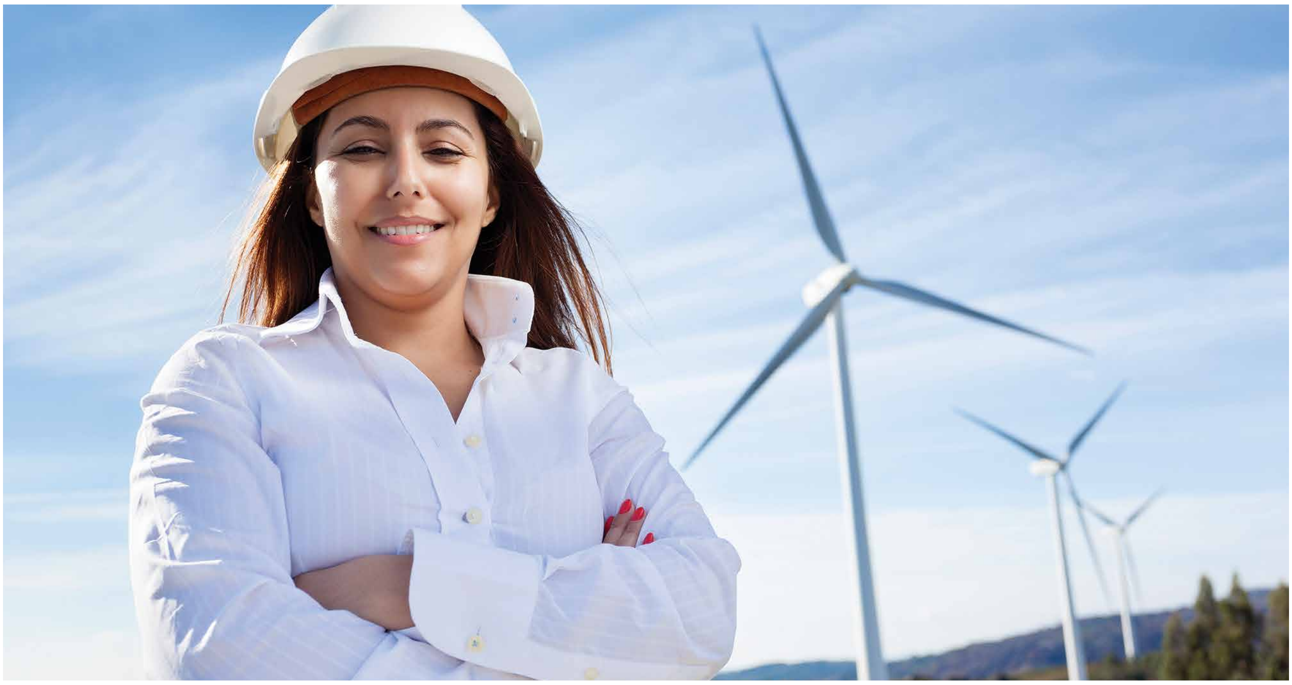
We have continued the traditional effort of assisting new administrations in finding the highest quality individuals for appointments to research positions in government, many of which remain unfilled, as well as providing fact-based information to decision-makers. However, rising concerns over such issues as the CURES initiative, rights for Turkish scientists and now our own researchers, including travel restrictions, a dumbfounding erosion of public trust in science, and declining research investment have wakened us and have mobilised Sigma Xi to increased and visible action.

On January 26, 2017, Sigma Xi sent a letter of concern to the White House over federal communications restrictions. The letter urged the Administration to move quickly to enable the rapid dissemination of information to the public. Then, on February 1, 2017, we issued a statement on the Presidential Executive Orders Establishing Temporary Travel Bans. The statement expressed our fervent desire that the President rescind the order and restore America's role as a trusted leader and partner to the rest of the world. This matter and others continue to be disquieting.

We released the following statement in part from Sigma Xi, The Scientific Research Honor Society on March 17, 2017.

Executive Director and CEO John Nemeth released comments on President Trump's Budget Proposal – President Trump has released his budget proposal for fiscal year 2018. If adopted by Congress, this financial

'Sigma Xi was designed to reward excellence in scientific research and to encourage a sense of companionship and cooperation among scientists in all fields'



blueprint would do harm to the American scientific enterprise, abruptly and dangerously curtail progress in scientific research and choke off the productivity needed for economic growth and technological leadership. The ability of the United States to effectively and efficiently protect its citizens from disease and disability, external threats, economic stagnation, and natural and man-made disasters depends on a robust scientific community.

See more at: https://www.sigmaxi.org/news/article/2017/03/18/statement-from-sigma-xi-the-scientific-research-honor-society-executive-director-and-ceo-john-nemeth-on-president-trump's-budget-proposal#sthash.h2mdOkFK.dpuf

In the days to come and foreseeable future, Sigma Xi will continue to weigh in on all science research issues that impact the welfare and growth of the human condition. Look for them.

Now, for me, one of the most exciting and heartening events since the first Earth Day is in the offing – the March for Science. Sigma Xi was the first scientific organisation to step up and partner with the march organisers. We have assisted in every way we are able to help these wonderful young people carry a positive, nonpartisan and apolitical torch that illuminates a positive, passionate message of support for science, one that is against no one or anything. We are working fervently to match as many of our Chapters as possible with the organisers of satellite marches across the country. To my unending pride and appreciation, the Board of Directors of Sigma Xi offered to fiscally sponsor satellite marches through the use of our 501(c) 3 status. To date, New York City, Chicago, Columbus, OH, San Diego, and San Francisco are taking advantage of this service. Many Chapters are working in their communities to lines up buses to attend the marches in DC and other cities. We are sending a bus from our headquarters.

How prevalent do you believe scientific misconduct is in the research community today? By what means does Sigma Xi encourage scientific integrity?

First, let me rely on a forbearer:

'The honour in being elected to Sigma Xi is inextricably coupled with responsibility, to use the knowledge that you have to better the lot of humanity. And this is the hallmark of Sigma Xi in the 21st Century.' – Thomas F. Malone, Sigma Xi President 1988–1989.

Charlatans exist in every aspect of human endeavour. Ethical behaviour and the highest standards of research are not just a part of our vision and mission statements. These core principles are life blood to Sigma Xi. These tenets are what we swear to when inducted. Through career training and across all we do, scientific integrity is at the forefront. As an example, Sigma Xi recently started, through *OpenStax*, contributing an ethics and integrity sidebar in each chapter of scientific textbooks. We will be doing more of that in the future, most notably in Advanced Placement texts for high schoolers.

Since its founding in 1886, Sigma Xi has emphasised that integrity is vital to science. But for busy researchers, ethical practices are often taken for granted until something bad happens – perhaps a resignation, a retraction, or an authorship dispute. But, the research enterprise armed with peer-review does identify, correct, and enforce accountability upon those that fall from the responsibility tree.

As an honour society, Sigma Xi aims to foster the highest professionalism among its members. This means cultivating a keen awareness of ethical issues and a proactive approach to research integrity as it applies to each stage of the research process.

When scientists uphold ethical best practices in these and other areas, they contribute to an accurate scientific record, public trust in science, and efficient use of research funds.

Finally, one of the biggest scientific challenges of our generation is anthropogenic climate change – please tell us about some of the many ways that Sigma Xi is striving to mitigate a global climate disaster, and working towards a sustainable future.

Sometimes they are fairly direct. For example, we sponsored a reception for the James Hansen climate change lecture at the Virginia Tech hosted Appalachian Studies Association Conference in March. In truth, there is no way I can list the events directed at this subject through our 500+ chapters all over North America and the world. It will have to suffice to say that issues such as Climate/Global Change, pro-vaccination, population control, national research investment policy, and environmental quality… name a subject...we are the 'Scientific Research Honor Society'. Every aspect of research falls within the purview of our very diverse, eclectic membership, and they act through their professional endeavours and their voices as citizens.

We have been and continue to be a leader in laying the research foundation for the fact of global climate change, disaster if you wish. We portray the evidence-based facts as we know them about global change. How? We are 110,000 plus living, inducted members composed overwhelmingly of researchers that not only perform the research to establish founding principles, but we also write, speak, and teach in classrooms and elsewhere about the already undeniable case that human activity contributes to global warming significantly and in a seriously large magnitude. That said, we are also a huge portion of the research workforce that is seeking ways and means to mitigate the already evident damaging effects of global warming and the technologies to halt the production of greenhouse gases through the replacement of fossil fuels with already competitive, emerging clean energy sources and infrastructure. Should you point to any research facility or clean energy business – science, engineering, technology, or math based – you will find members of Sigma Xi at the core and leading. The examples are legion, but I will point again to our inaugural Gold Key Awardee, Norman Augustine, Lockheed-Martin and multi-faceted contributor to STEM education and national defence, and so much more, or to Jim Goodnight, Founder and CEO of SAS, a leader in corporate conduct and employee welfare and advancement of STEM education.

You see, Sigma Xi is not about headquarters or officers, although we try to provide some form and function. We are a band of sisters and brothers in membership and chapters doing and promoting research – research that is the tangible foundation for a sustainable future.

CLIMATE CHANGE

PREDICTING OUR PLANET'S PRECARIOUS FUTURE

Our first section in this edition deals with the greatest challenge of our generation, and arguably, one of the greatest challenges our species has ever faced – anthropogenic climate change.

Although our carbon dioxide emissions had levelled off between the years of 2013 and 2016, offering hope that a downward trend would ensue, they now appear to be on the rise once again. This is according to recent calculations from the Global Carbon Project – an international group of researchers that quantify global carbon emissions – who estimate that our carbon emissions increased by approximately 2% in 2017.

This goes to show that recent efforts to curb greenhouse gas emissions have failed. Furthermore, with the current atmospheric concentration of carbon dioxide at a record high (~408 ppm), this high level will persist for a long time even if our emissions were drastically reduced tomorrow. Thus, continued warming of the planet is inevitable, leading to increasingly severe effects. The degree of severity, however, is still a topic of debate.

For example, the timescale and magnitude of future sea-level rises are extremely difficult to predict, even if we make assumptions about the levels of greenhouse gases in the atmosphere over the next few decades. With further uncertainty regarding the severity and frequency of future droughts, wildfires and storms, scientists must continue to study our delicate climate systems, and further improve our modelling capabilities and observation technologies, so that we can make the best possible decisions to protect our planet, and all of its inhabitants.

One major unknown of crucial importance is the precise impact of climate change on the interior of the Antarctic ice sheet. This is vital to understand, because if the West Antarctic Ice Sheet were to completely melt, this would contribute to a rise in sea level of a whopping five metres. To reduce this worrying uncertainty, three scientists from the University of Edinburgh and Northumbria University have combined their complementary expertise to understand the stability of the West Antarctic Ice Sheet during our planet's history. In this section, we discuss the team's new evidence, which shows how this ice sheet has behaved in the past, enabling modellers to better predict the degree of ice melt and thus sea-level rise in the future.

Next, we feature the work of two dedicated researchers also wishing to increase the amount of observational evidence we have on our climate, so that we can better predict the future and make the best possible decisions. Dr Roger Cooke of Resources for the Future and Dr Bruce Wielicki of the NASA Langley Research Center propose the development of an advanced international climate observation system, and have estimated that such a system would be worth US$10 trillion to the global economy.

While developing the best sensing and imaging tools to probe the Earth's climate is vital, there is also a great need to make the information these systems collect available to decision-making organisations, such as government bodies and environmental groups. Next, we introduce the work of Vanessa Escobar and Dr Molly Brown, who are tailoring NASA's satellite data into usable products to support major decision makers across the world.

Also passionate about building a sustainable future is Dr Vladimir Strezov and his team at Macquarie University. Just like Dr Roger Cooke and Dr Bruce Wielicki, Dr Strezov is also interested in the interplay between the global economy as it relates to industrial processes and the environmental impacts of those processes. Here, we showcase his team's work in developing strategies and technologies to reduce our environmental impacts through improving the energy efficiency of industrial processes, reducing emissions and integrating renewable energy technologies.

From here, we move on to feature the work of Dr Robert Allen and his team at the University of California, Riverside, who use both ground and satellite observations along with a suite of global climate models to determine how climate change is going to affect atmospheric circulation into the future, with a particular focus on California. Contrary to conventional thought, Dr Allen and his colleagues have found that California may actually become wetter, not drier, as a result of climate change.

As we've seen from Dr Allen's projections, and how they conflict with most predictions, many of the consequences of climate change are still highly uncertain. Although we can hope for the advanced international climate observation system proposed by Dr Wielicki and Dr Cooke, in the meantime, we must be sure to make the best possible decisions regarding our climate, as there is far too much at stake.

So, how do we plan ahead for a future that is so uncertain? Here's where the work of Dr Robert Lempert at RAND Corporation comes in. To help manage such deeply uncertain challenges, Dr Lempert and his team have developed a strategy called 'Robust Decision Making' (RDM). Instead of focusing on trying to improve prediction, they use analytics to try to improve decisions when the future is unclear. By using analytics to systematically expand the vast range of possible futures, sift through a multiplicity of scenarios and test the consequences of myriad assumptions, RDM is a new way to use data to best inform evidence-based decisions.

Despite the immediacy of climate change, the vast majority of people do not view it as a serious problem, with most people ranking war, food insecurity and disease epidemics as far greater threats. However, climate change is poised to increase the likelihood of war, harm our food supplies through drought and flooding and facilitate the spread of disease due to warmer temperatures. Therefore, in order to tackle global climate change, one of the primary hurdles to overcome is changing the public's misperceptions of the risks and immediacy of the problem.

To overcome this, Dr Edward Maibach and his colleagues embarked on a project called Climate Matters, which empowers local weathercasters to become beacons of public education for climate change. In the final article of this section, we tell the story of how Climate Matters came to be, and how it has already shown great success in educating Americans about humanity's greatest challenge.

HOW STABLE IS THE WEST ANTARCTIC ICE SHEET?

Professor David Sugden, Dr Andrew Hein and **Professor John Woodward** have combined their complementary expertise to shed light on the stability of the West Antarctic Ice Sheet during previous interglacial periods. Knowing how ice sheets have behaved in the past enables us to better predict the degree of ice melt and sea-level rise in the future.

Ice Sheets in the Antarctic Interior

The dramatic loss of ice from floating ice shelves, due to the warming waters of the Pacific Ocean, has been the subject of much recent study. However, the precise impact of global warming on the interior of Antarctica is a major unknown. This is important to understand, because if the West Antarctic Ice Sheet were to completely melt it would contribute directly to a rise in sea level of around five metres.

To gain insight into the past behaviour of this massive ice sheet, Professor David Sugden, Dr Andrew Hein and Professor John Woodward, and their teams at the Universities of Edinburgh and Northumbria, gathered evidence from three locations in the southern Ellsworth Mountains. The team's data served to determine if the West Antarctic Ice Sheet, half of which flows into the Weddell Sea, remained relatively stable or retreated significantly during past interglacial periods, such as at 130,000 and 205,000 years ago, when the world was warmer than at present.

To measure past fluctuations in the West Antarctic Ice Sheet, the team went into the field to date surface boulders and landscapes carved by glaciers. They used geomorphological field observations linked to a technique that calculates how long rocks had been free from ice cover, to track changes in ice flow during ice age cycles, over millions of years. This new data complemented that obtained from satellites, climate modelling, models of past and future ice sheet evolution, and marine biological evidence suggesting the possibility of interglacial seaways in West Antarctica during interglacial periods.

'I walked on a glacier in Norway at the age of 16 and was hooked on glaciers and the magnificent landscapes they create. I became a Physical Geographer at that point,' says Professor Sugden, of the University of Edinburgh. 'I have worked in different parts of Antarctica for 15 seasons. It is humbling but magnificent to see mountains as far as the Earth's curvature allows, to see the changing light as the sun dips and circles round the sky in 24-hour daylight, and to hear the silence of a world with no running water or people.'

'The preservation of old rock surfaces is testimony to the stability of at least the central parts of the Antarctic Ice Sheet – but we are still very concerned over other parts of Antarctica amid climate change' – Professor Sugden

His colleague Dr Hein manages the Cosmogenic Nuclide Laboratory at Edinburgh University, and brought field and laboratory experience of exposure dating techniques to the team. 'Mountains protruding through the ice are used as dipsticks of changing ice surface elevation. We mapped the distribution of boulders dropped by the ice on the mountains and dated them using cosmogenic

‘West Antarctica has undergone complex changes since the last Ice Age, and it quickly became unstable – similar processes may dominate the future of the region in a warmer world’ – Dr Hein

isotope dating,’ explains Dr Hein. ‘Cosmic rays bombard the earth surface, leading to the accumulation of cosmogenic isotopes in surface rocks. Measure this and you can show how long a boulder has been exposed and sometimes how long it has subsequently been buried by ice.’ By measuring different isotopes of several rare nuclides in exposed rocks, the team are able to reconstruct a detailed history of ice elevation changes.

A Professor of Physical Geography at Northumbria University, Professor Woodward is a specialist in glaciology and an expert in the use of radar to study glaciers. One of his key research interests is the use of glaciological and geophysical evidence to investigate subglacial lakes and ice/sediment/water interactions at the glacier bed. The West Antarctic Ice Sheet is potentially vulnerable because its 2,000-metre-high central ice dome overlies a marine basin with a depth of 1,500 metres below sea level. The risk is that, as warming oceans melt the floating margins and the ice sheet thins and retreats, the interior ice sheet will be affected above this marine basin. ‘It is possible that the ice sheet has passed the point of no return and, if so, the big question is how much will go and how much will sea levels rise,’ says Professor Woodward.

Extreme Camping

The team of scientists reached their field camp, in the southernmost edge of the Ellsworth Mountains, in a Twin Otter aircraft flown from the British Antarctic Survey’s Rothera Research Station. Once in the mountains, they spent two-and-a-half months in small tents, while collecting data using skidoos to get around – the furthest field site being a gruelling 40 km round trip. One trip back to Rothera took two days, stopping off at a half-way runway due to changing weather conditions.

‘There is something about living in a tent surrounded by such splendour, and potential danger, and reliant on your own capabilities and those of your companions. I have been so fortunate to be able to combine such experiences with my university life,’ Professor Sugden tells Scientia.

In a paper published in *Nature Communications* in February 2016, Professor Sugden, Dr Hein, Professor Woodward, and their colleagues, reported the first field evidence to be used to constrain models of the West Antarctic Ice Sheet during previous warm interglacial climates. ‘Our findings suggest that in the southern Ellsworth Mountains katabatic winds have been blowing down the ice sheet surface persistently for 1.4 million years,’ explains Dr Hein. ‘This means that an upland ice sheet has been present continuously for at least this time and survived previous interglacial periods when the world was warmer than present.’

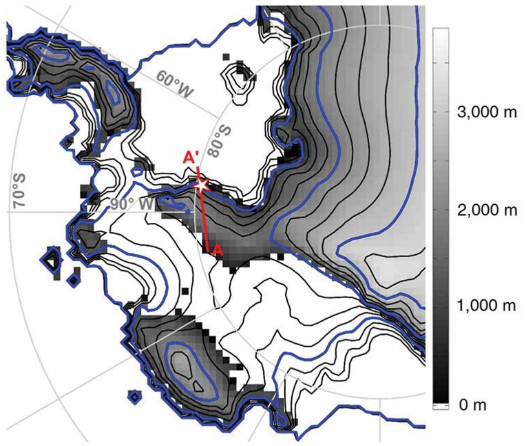
Evidence from the Blue-Ice Moraines

The team focused on blue-ice moraines, created by strong downslope winds, where boulders and other debris (moraine) have been bought to the surface. These blue-ice moraines were studied through geomorphological methods, such as 3-D laser scanning, Differential Global Positioning Surveys (DGPS), and ground-penetrating radar, to determine ice thickness, and the exposure-age dating of boulders.

‘The study of ice-sheet evolution is like a detective story,’ says Professor Sugden. ‘You compare observations on the ground with theory and painstakingly build up a narrative of how the ice sheet has evolved to its present state. Each field campaign takes you further but raises more questions. Our focus on blue-ice moraines is such an example.’

According to Professor Sugden, blue-ice moraines are somewhat of an enigma. As snow accumulates on the ice sheet surface, rock debris should become buried. However, blue-ice zones occur where downslope katabatic winds have eroded the surface snow, and ice has migrated upwards to compensate for this loss, bringing debris

‘It is possible that the ice sheet has passed the point of no return and, if so, the big question is how much will go and how much will sea levels rise’ – Professor Woodward



Minimum interglacial extent of ice compatible with the evidence from blue-ice moraines

to the surface. Since some of this debris has been at the surface for millions of years, its study can open a deep window into the history of an ice sheet.

Another paper from the team, published in *Nature Communications* in August 2016, focused on what their field data revealed about the thinning of the ice sheet in the southern Ellsworth Mountains during the most recent Ice Age, peaking some 21,000 years ago. The team found that as the Earth warmed, the West Antarctic Ice Sheet close to the Weddell Sea remained covered with ice long after other parts of the Earth were emerging from the Ice Age. Eventually, a tipping point was reached, after which it thinned relatively quickly, losing 400 metres of thickness in 3,000 years, causing global sea levels to rise by up to two metres.

‘West Antarctica has undergone complex changes since the last Ice Age, and it quickly became unstable – similar processes may dominate the future of the region in a warmer world,’ Dr Hein says.

Ice Melt and Sea-Level Rise

In addition to blue-ice moraines, the team’s other main focus was looking at how glaciers have cut into the landscape, to leave an erosional trimline (a sort of high-tide mark) in the exposed peaks of the Ellsworth Mountain range. These glaciated surfaces can be dated where they are overlain with surface deposits. ‘We have discovered a much longer history than we expected at the outset; indeed, some ice-scratched surfaces may be 14 million years old,’ believes Professor Sugden.

In a paper published in *Earth and Planetary Science Letters* in 2017, the team presented evidence showing how the glacial trimline evolved up to 14 million years ago – when the Earth was 20°C warmer than present and vegetation grew in the Ellsworth Mountains, in a climate that would have been similar to that seen in Greenland or Patagonia today. This study was among the first to find evidence of how the ice sheet would have looked at this time in West Antarctica. The extreme age of the elevated trimline suggests that subsequent fluctuations in ice thickness have progressively been confined to lower elevations, as a result of deep troughs being eroded beneath the glacier, lowering the ice surface relative to the mountains.

Field evidence collected by the team over several seasons showed that during warmer interglacial periods, the West Antarctic Ice Sheet retreated, but at its lowest point it formed regional ice sheets on three mountain blocks, of which the Ellsworth Mountains were one, with marine seaways in between. Although the team found no evidence for complete deglaciation (and therefore sea level rises of at least 5 metres), the most likely scenario is that the considerable melting of this ice sheet would have raised sea levels by around 3.3 metres. Therefore, the team suggest that we should be planning for an additional 3 metres of sea level rise from the West Antarctic Ice Sheet alone if global temperatures keep climbing unchecked, with considerable implications for coastal populations around the world.

‘These findings help us understand how the Antarctic Ice Sheet has evolved, and to fine-tune our models and predict its future,’ concludes Professor Sugden. ‘The preservation of old rock surfaces is testimony to the stability of at least the central parts of the Antarctic Ice Sheet – but we are still very concerned over other parts of Antarctica amid climate change.’

‘It is important to know what is going on in the quarter of the Antarctic Ice Sheet that drains into the Weddell Sea,’ says Professor Sugden, as he explains the next steps for the team’s research. ‘This means we need to understand how the big outlet glaciers from the East Antarctic Ice Sheet interact with the West Antarctic Ice Sheet. Then we would learn more about the behaviour and resilience of the Antarctic Ice Sheet as a whole. A clear next step is to carry out a detailed study of blue-ice moraines from major outlet glaciers from East Antarctica, such as those bounding the Shackleton Range.’

Meet the researchers

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After receiving his DPhil from the University of Oxford in 1965, Professor David Sugden worked for the British Antarctic Survey and held Lectureship positions at several universities, including the University of Colorado and the University of Aberdeen. At the University of Edinburgh, UK, he has been Head of Geography (1987–1992, 1997–2000), Head of the School of GeoSciences (2003–2006), and is currently Professor Emeritus. His research interest is to understand how ice sheets behave and interact with the Earth's systems, by linking glaciology with landscape studies in geomorphology/geology and exploring the role of geomorphology in shaping the evolution of the Antarctic Ice Sheet.

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FUNDING

UK Natural Environment Research Council

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KNOWING WHAT WE FACE IN AN UNCERTAIN CLIMATE

Dr Roger Cooke of the non-profit Resources for the Future and **Dr Bruce Wielicki** of the NASA Langley Research Center have been researching the challenges, costs and benefits of a proposed international climate observation system capable of providing the highly valuable information needed for managing our climate.

A Decisive Moment

The significance of Earth's climate to our lives is impossible to overstate – climate is the medium in which we live. Climate issues are wide-ranging, and include sea-level rise, droughts, floods, heat warming events, and the availability of food and fresh water. Agriculture is of course heavily tied in with these factors, and the effect of climate change on our infrastructure is also alarming – buildings, electricity generation, transportation and water delivery systems are all impacted by the climate.

Earth's climate has multiple parts, including the atmosphere, ocean, land and cryosphere. In addition to the variables intrinsic to these areas, the changing climate is also heavily interdependent with many social, economic and political variables.

Dr Roger Cooke of Resources for the Future and Dr Bruce Wielicki of the NASA Langley Research Center propose that climate change should be examined as if it were an economic ultimatum of global proportions. Through their research, they have found that decision making in this area has very quantifiable consequences. 'We will be managing the Earth's climate system as long as humans remain on this planet,' says Dr Wielicki. 'The stakes are high and we better get it right.'

The economic benefits of climate science not only impact the immediate future – the repercussions of any decisions regarding climate change expand exponentially into future decades. This necessitates a new climate observation system capable of providing the information needed for sophisticated emerging models.

The seriousness of climate change makes it a major risk to modern society. Drs Cooke and Wielicki's research suggests, however, that switching from 'business as usual emissions' to reduced emissions once an established limit has been exceeded could greatly reduce worldwide damages. Knowing as much as possible about these growing pressures is fundamental to our success in managing the effects of climate change into the future.

A Lucrative Investment

The information derived from climate observing systems and improved environmental regulation is now being quantified as tangible economic value. This 'value of information' (VOI) is increasingly relevant to the world's economies and has been shown to be consistently valuable in many different scenarios. Dr Wielicki and his colleagues recently wrote a review article citing that an advanced international climate observation system is worth US$10 trillion to the global economy. Thus, there are significant local and economic benefits to such a system.

Current investment in climate observation amounts to US$4 billion per year. Tripling the investment in such a system would mean approximately 50 times the monetary return, as verified by an independent analysis published in 2015. In their review, Dr Wielicki and his colleagues note that few investments offer such a massive return, and that it would be a cost-effective approach to a stable economic future, offering a return on investment ranging from 25:1 to 100:1.

Conversely, the economic costs of climate damage by continuing our 'business as usual' practices between the years 2050 and 2100 have been calculated to be

somewhere between 0.5% and 5% of GDP per year, depending on climate sensitivity. Two studies carried out in 2014 and 2016 by Dr Cooke estimated that the cost of delaying an advanced observation system would range from US$250 to $570 billion per year.

Drs Cooke and Wielicki use models established by the US government for monetising the damages of greenhouse gas emissions. These integrated assessment models help to establish the relationship between emissions, temperature rise and climate damages. They combine simple climate, carbon cycle and economic models with assumptions about population growth, income growth, technological change and public policies.

‘We will be managing the Earth’s climate system as long as humans remain on this planet. The stakes are high and we better get it right.’

The ‘Social Cost of Carbon’ (SCC) is an estimate that is commonly used to evaluate the economic impacts of climate change. Rather than solving a problem, however, the SCC is typically calculated for the purpose of simply estimating cost in the form of environmental damages. VOI builds on this and calculates the damages that better observation systems would actually avoid. Thus, VOI techniques can convert the value of future observing systems into hard cash, and this can have a further payoff in terms of designing better observing systems to maximise their cash value.

Managing Uncertainty

Dr Cooke notes that the current climate debate is hampered by a cognitive illusion which he calls the Confidence Trap. ‘Faced with a sequence of uncertain events, most people successively choose the most likely outcome of each event, and then treat those outcomes as if they were certain,’ he says. ‘The confidence trap consists of ignoring these cascading uncertainties.’ In the current political climate, elected officials put all the burden of proof on those claiming that climate change is real and humans are responsible. These officials do not call for proof that climate change is NOT happening. The confidence trap lures some scientists into accepting this lopsided proof burden. If things are really uncertain, then whoever gets stuck with the proof burden loses.

Our climate future is uncertain, and our collective decision making must take the full range of uncertainties into account. The parties to the climate debate should be sharing instead of shifting the proof burden.

Dr Cooke says that using uncertainty as a justification for inaction is reckless, as the worst course of action is to assume that there are no risks. The urgency of action on climate change outweighs the desire for having all the facts available, which may not come in time to respond. This is why early learning can have great value. ‘Learning about risks by suffering their consequences is a luxury that humankind can no longer afford,’ says Dr Cooke. The timeframe for an advanced system to provide the data necessary for long term policy making ranges from 10 to 40 years, and the timescales of the predictions afforded range from seasons to centuries. As such, we have to prepare for multiple futures.

Dr Cooke stresses that the public needs a better understanding of the nature of science. Science advances in certainty and confidence as results are confirmed from independent observations, models and analyses. During this process of reducing uncertainty, scientific debate and disagreements are at the heart of advancing understanding. Care is also needed to separate science from politics as much as possible – the ‘Aryan Physics’ movement in Nazi Germany provides a cautionary example.

There are a number of ways to reduce scientific uncertainty – observations of climate processes such as clouds can be used to develop improved prediction models, while long term climate change observations can be used to test how well the new models can predict future climate change. Dr Wielicki emphasises that both scientists and society look at climate change through three fuzzy lenses: the noise of climate natural variability, uncertainties in observations, and uncertainty in climate model predictions. Science cannot eliminate natural variability, but it can work to greatly improve the clarity of the observation and modelling lenses through which we view and plan our climate future.

A further area of uncertainty is that the SCC is not comprehensive – it does not incorporate the costs of political instability, ocean acidification, species loss or ecosystem services. It also struggles to incorporate

the costs of low likelihood but very high impact changes that might arise due to larger than expected releases of methane and carbon dioxide from the warming arctic, or faster than expected melting of the Greenland and Antarctic ice sheets.

In SCC calculations, the uncertainty range of equilibrium climate sensitivity is a critical factor. This is because in integrated assessment models, climate change economic damages are fundamentally an expression of the capacity of the global temperature to change. The amount of future global temperature change in turn is strongly driven by climate sensitivity. If the climate sensitivity uncertainty range is a factor of 4 with 90% confidence, then the uncertainty range in economic impacts is a factor of 16. In his 2013 paper, Dr Wielicki says that these uncertainties can be greatly reduced in the future by using higher accuracy and more complete climate observations.

SCC estimates will need to be continually updated to reflect changes, particularly in areas such as policy and economic changes, which tend to be difficult to predict. Despite the complexity of societal decisions, which are impacted by long term policy intricacies, results show that the predictions of imperfect models are preferable to none. Agreement on the level of uncertainty relating to uncertain factors, such as ice sheets, would assist in the mathematical refinement of the models used. A greater number of uncertain inputs is always beneficial – the more information the better.

Old Designs, New Challenges

Historically, climate change has been approached as a scientific problem. Drs Cooke and Wielicki argue that it needs to be thought of as having an importance to society that is as tangible as anything else. Therefore, a more comprehensive, coordinated approach is required. The pair points out that if climate observation systems had some of the qualities of international weather observation systems, such as continuity and robust international commitments, they would be greatly enhanced. But they also need to go well beyond weather observing systems, as they need to measure ten times as many variables at ten times the accuracy of weather observations. As Dr Wielicki says, 'We are perfectly fine with a temperature accuracy of 1 degree centigrade on tomorrow's weather forecast, but observations of climate change over decades requires much better than 0.1 degrees accuracy.'

An international observation system for joint social and scientific climate problems has never been developed before, and current observation systems were not planned to meet emerging needs. The past inadequacy of observation systems, which has severely hindered advancements in our understanding, means that there is a need for a significantly expanded system. Many observation systems were not designed specifically for climate observation and this has limited the usefulness of the data they collect. Datasets must be relevant for the long term, and records dating from decades ago are sometimes inadequate in facilitating predictions of natural variability and global changes. Drs Cooke and Wielicki have called for a need for more advanced observation not only for present decisions, but for all future ones too.

Improvements that Facts Demand

Planning an international climate observing system takes a combination of expertise in climate science and economics. Currently, there is an effort to synergise the data from multiple projects: the NASA CLARREO Climate Accuracy Framework (2013), the Interagency Memo on Social Cost of Carbon (2010) and the DICE Integrated Climate/Economic Model (2009). The CLARREO mission (Climate Absolute Radiance and Refractivity Observatory), of which Dr Wielicki is the science team lead, is set for launch on the International Space Station in 2022, and will operate for 1 to 2 years. CLARREO will be focused on demonstrating climate change observations that will be 5 to 10 times more accurate than current observations.

Approaches to address climate change include mitigation (including greenhouse gas reduction and reversing or stopping deforestation), adaptation and responses such as geo-engineering. Existing observation systems will also need to be augmented where beneficial. Technology is more than adequate for the development of a more advanced system – it is essentially a question of funding.

Observation systems need to be classified according to the roles they serve for observation and society. Further, it is important to use climate models to help determine which observations are most critical to improving the accuracy of future climate model predictions. Such activities bridge the research worlds of climate modelling and climate observation, and can help prioritise future observations. Finally, having a more accurate and complete observing system would reduce the amount of time needed to observe climate trends. Because of this, if we are to understand climate change as rapidly as is required, we must develop high accuracy in our observational systems.

The Integrated Future of Observation

Managing our climate is simply a reality that we have to face and live with now. The future offers multiple areas in which the economic value of climate observations can be investigated. Relevant areas that Drs Cooke and Wielicki point to include cloud and carbon cycle feedbacks, aerosol forcing, sea-level rise, ocean acidification and ice sheet and glacier changes.

It is impossible to delay a decision when delaying is itself a decision. Imperfect information is the only basis for any path we can take, and as such, our only option is to maximise the quality of that information.

Meet the researchers

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Dr Roger Cooke's early work focused on the foundations of quantum mechanics and probability. He received his PhD from Yale University in mathematics and philosophy in 1975. He is currently the Chauncey Starr Senior Fellow at Resources for the Future, Washington DC, and also works on the value of information of Earth Observation Missions for NASA Langley. He consults for expert judgment studies on invasive species (NOAA), food borne diseases (WHO), The National Institute for Aerospace, efficacy of public health measures (Robert Wood Johnson, CDDEP) and nitrogen loading in the Chesapeake Bay (EPA).

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RESOURCES FOR THE FUTURE

Langley Research Center

HOW NASA'S SATELLITES ARE MAPPING THE WAY FOR GLOBAL POLICY

NASA's satellite technologies have provided a wealth of data about the planet, and can be tailored into usable products to support major decision makers across the world. **Vanessa M. Escobar** and **Molly E. Brown** are working to bring these data products to decision-making organisations, to help them reach their goals, while also supporting the sustainability of our delicate planet.

Major initiatives have recently been put in place to monitor the changing behaviour of the Earth – erratic air masses, receding ice sheets, shifting soils and the unbalanced global exchange of carbon. By observing our home planet, we can piece together a picture of how different parts of the Earth interact, and identify the key drivers of environmental change.

Of particular importance, is the study of human-induced climate change. Perhaps the greatest challenge of our time, climate change motivates scientists to keep a close eye on the planet, and encourages institutions across the world to meet their sustainability goals. The European Union and United Nations have already defined ambitious plans to reduce global carbon emissions and seek sustainable solutions, so that we can hopefully mitigate the most damaging effects of climate change in years to come.

Remote sensing technologies such as satellites provide us with a wealth of information about the Earth – whether it is data on the oceans, air, forests or ice sheets. Satellites use different wavelengths of light to measure the planet's health, including visible light to observe disturbances caused by people across land, radar (radio-frequency) for assessing the height of foliage, or infrared light for identifying bodies of water that lie below thick forest canopies.

Although there has been an enormous amount of effort dedicated to developing remote sensing and imaging tools to probe the environment, there is a need for more work to translate the information they offer over to the organisations that define policies for environmental management, or set sustainability goals, for example. These organisations may be government bodies, environmental groups or commercial users, who can use these data to enhance their existing tools to make better-informed policy decisions, or develop new and improved management systems.

NASA's Applied Sciences Program

Vanessa M. Escobar of NASA Headquarters and Molly E. Brown of the University of Maryland are finding ways to connect Earth science data with policy makers through the NASA Earth Sciences Division and the *NASA Applied Sciences Program*. While the *NASA Earth Sciences Division* seeks to understand our Earth and its key changes, the purpose of the *NASA Applied Sciences Program* (ASP) is to find effective ways of giving the global community access to Earth science knowledge.

'The impact and value of the science needs to be tailored to individual communities and this translation must be reflective of the organisation's culture and policies,' explains Escobar. 'Thus, a focused concentration on the user and the user's culture is as important as the expertise of the science products themselves.'

The team is continuously working to develop methods to help users interpret, access and apply NASA Earth science data, which can then be provided to organisations that can truly benefit from them. The team is achieving this by networking with institutions across multiple countries, organising thematically tailored communication strategies and workshops, while implementing new NASA guidelines for focusing future satellite project efforts to engage with users during the development of the satellite. This is to ensure that after launch, the feedback for the user community is reflected in the products and the applications are more streamlined for operational uses and decision support processes.

'The most recent and most important change for application s of Earth science data at NASA has been the development of the Flight and Applied Science Mission Application Guidelines,' says Escobar. These guidelines, which the team worked on for four years, are now an official policy that encourages scientists to take users' feedback and needs into account when designing satellite missions and satellite derived products.
By involving user organisations' goals, needs and uses of science data in their operations, Escobar and Brown are increasing the value and potential impact of NASA's satellite missions, while raising awareness of the environment and the impact of human-induced climate change. With the information NASA offers, and the products they develop, institutions such as governments, councils, commercial, non-profits and environmental groups will possess vastly greater knowledge about the planet, and will therefore be in a position to make better-informed decisions.

‘Concentration on the user and the user’s culture is as important as the expertise of the science products themselves’ – Escobar

Early Adopters: Involving Users at an Early Stage

The ASP initiatives are targeted towards all potential users of the information, including ‘Early Adopters’ – individuals who volunteer to test mission project’s products, and work to determine how the data can benefit their organisations. By providing key feedback to the missions, Early Adopters can have an active role in ensuring that NASA science data products are continuously developed and improved upon. Escobar and Brown have shown that engaging with users at an early stage in their mission not only improves the team’s data prototypes, but also provides enhanced knowledge bases for the users. This is a win-win situation, where both the scientists and the organisations benefit from knowledge sharing over time. Brown emphasises that ‘early engagement with science data users results in much more rapid and meaningful use of new satellite data products’.

While the quantity of Earth science data collected by NASA satellites is vast, the diverse users of the team’s products each have their own unique objectives. As such, the ASP Early Adopters initiative is divided into satellite mission-focused programs. These comprise strategies that focus on the global monitoring of soil, ice, water, air and carbon exchange.

The Soil Moisture Active Passive Mission

NASA’s Soil Moisture Active Passive (SMAP) mission uses satellite microwave technology to present soil moisture maps that help identify variations of soil moisture content around the world at the earth’s surface as well as identifying frozen or thawed soil at the Earth higher latitudes. This information can be used to guide policy decisions for crop production and even preserve our safety through predicting droughts and floods.

SMAP makes global soil moisture and freeze thaw measurements from space, providing data on the weather, climate, flooding, agriculture and human health. With this information about soil moisture and freeze/thaw we can improve weather forecast and better prepare for droughts and flooding. SMAP’s products are currently being used by several monitoring agencies, such as the National Drought Mitigation Center, who use soil moisture maps to assess drought risks and their potential impacts across the US. These products are also being used by the US Forest Service to monitor the risk of wildfire occurring across the North Carolina Coastal plain, along with the NOAA National Weather Forecasting Center, USDA National Agricultural Statistics Service and Canadian Weather-Environment Canada.

Launched in January of 2015, SMAP was the first NASA missions to design and implement an Early Adopter Program. Escobar and Brown worked with SMAP to design formal application strategies and the Early Adopters starting in 2009 and have been guiding the mission ever since. Through the Early Adopters and the translation of mission science to the user community, the SMAP mission has been helping bring the mission data into the hands of major decision-making organisations.

Although called an ‘active–passive mission’, the active part of the satellite (the radar), unfortunately failed after the first 10 weeks of data collection. The passive part of the mission (the radiometer) has exceeded the performance and measurement expectations, providing data that not only meets the high demand for radiometer measurements, but also lends itself to the development of finer resolution products blended with the European Satellite Agency (ESA) Sentinel mission’s Data. By blending the Sentinel synthetic aperture radar (SAR) data with the SMAP Passive data, SMAP can develop higher spatial resolution products that were originally promised by the mission, but now at a longer latency (every 12 days rather than every 3 days). This blending also allows the mission to deliver combined passive/active products highly sought after by the user community.

‘Early engagement with science data users result in much more rapid and meaningful use of new satellite data products’ – Brown

‘Combining the SMAP Passive signal with Sentinel allows the mission to provide higher resolution soil moisture products every 12 days,’ says Escobar.

The ICESat-2 Satellite

The effects of climate change are closely reflected by the sizes of the planet’s ice sheets. The first Ice, Cloud and Land Elevation Satellite (ICESat) was created in the 1990s to measure the growth and retreat of ice sheets across the globe. Operating until 2009, it was than succeeded by a newer model named ‘ICESat-2’, which sprang into action in 2016.

The ICESat-2 satellite houses an instrument called the Advanced Topographic Laser Altimeter System (ATLAS), whose aim is to collect much higher resolution readings of ice sheet and sea ice thickness than ICESat was capable of. Accurately measuring the height of ice sheets has long been a challenge for scientists, but this is now possible with ICESat-2, which can measure the changing thickness of ice sheets across polar regions.

When used beyond the polar world, ICESat-2 can also measure elevations in ocean and land. Such versatility allows it to estimate vegetation height, cloud elevation and sea level. The team has even combined this tool with specific projects to identify ice bergs in shipping lanes, and to help safely guide hunters in Alaska. This is achieved with the help another airborne instrument called the Multiple Altimeter Beam Experimental Lidar (MABEL), which offers an enhanced ability to analyse surface features such as ice, inland water, coastal ocean and regions of forest. As part of the ASP mission, Escobar and Brown are working towards bringing models and programs to organisations that can benefit from having access to ICESat-2 data.

NASA’s Carbon Science Research

In yet another important initiative, the NASA’s Carbon Science Research project seeks to enhance community expertise in carbon monitoring, by showing them how remote sensing technologies can help reveal the Earth’s carbon cycle. Its pilot projects focus on monitoring reporting and verifying the Earth’s carbon sources, sinks and fluxes, by measuring the carbon content in vegetation, land, atmosphere, oceans and the coast – the movement of carbon dioxide (the primary driver behind climate change) between the biosphere and the atmosphere.

Strategies are aimed towards institutions that monitor the ocean, land and atmosphere – realms that hide clues of where carbon is stored, and released. Carbon sinks are places such as forests, soils and oceans that absorb more carbon dioxide than they release, and are vital for helping us to curb climate change. Conversely, carbon sources contribute more carbon dioxide to the atmosphere than they absorb, such as forest fires and burning fossil fuels. The interplay between sinks and sources is what NASA’s Carbon Science researchers set out to observe, while also sharing their insights with institutions that may benefit from the information – whether it be organisations dedicated to climate change mitigation, food security or forest management.

To achieve this, the team organises, facilitates and translates the communication between carbon monitoring scientists and decision-making organisations, such as government regulators. By identifying gaps in knowledge, challenges in access and awareness and by aligning the appropriate data needs with science capabilities, Escobar and Brown work to find ways of helping larger communities understand potential uses and impacts of carbon science data to inform major decision processes. This is of particular relevance to environmental regulators, and targets that seek to reduce the impacts of climate change, such as the *United Nations Sustainable Development Goals.*

Our Place on the Planet

Escobar and Brown emphasise that although obtaining accurate Earth science data is vital in our quest to combat climate change, it is just as important to translate the relevance of this data collection to groups that can benefit from it. Through the NASA Earth Science Division and especially the Applications Sciences Program, the team is helping organisations to use NASA’s remote sensing projects for the benefit of the user (tax payers), in the most relevant way for their particular goals.

Using remote sensing science in business, marketing, risk management and environmental protection can increase awareness, reduce risk and help inform decisions that need to be made day to day by tax payers. From allocating resources to roads for snow preparedness, to assessing potential property losses in flood predictions, to evaluating the risk of residential power outages prior to storms, remote sensing contributes to all of this and more. All of this links directly to the conservation of jobs, resources and lives. It’s simply a matter of translating the science into societal relevance.

By involving users from the mission inception, the team is also adding value to satellite surveillance missions, and Earth system science. In the future, Escobar and Brown will continue to increase community involvement with NASA’s missions and remote sensing programs. After all, such information must be shared with those who can use it to enforce positive change, for the benefit of humanity. If with information comes power and responsibility, the team is empowering decision makers across the globe to take action against the risk of climate change and make informed decisions to mitigate its effects. As Escobar puts it: ‘Information is only useful when its used and applied, and not using information that can avoid a hazard or danger can be priceless.’

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FUNDING

NASA

SUSTAINING INDUSTRY INTO THE FUTURE

It is becoming increasingly critical to accurately assess our methods for producing energy, so that we can prosper without continuing to damage our planet's delicate environment. **Professor Vladimir Strezov** and his team at Macquarie University are uncovering the realities of industrial processes so that their economic worth and environmental impact can be kept in sustainable balance.

Avoiding a Finite Future

In a developed society, energy use is the means through which we engage with technology in any process or activity, and is proportionate to gross domestic product itself. The fundamental issue with this is that the forms of energy generation that we currently use cannot sustain us into the future of development that rates of growth indicate. 41% of electricity generation is powered by fossil fuels – resources of a finite quantity on Earth that cannot be renewed.

Professor Vladimir Strezov of Macquarie University, Australia, has been investigating multiple approaches to industrial processes that can be sustained into the future. He and his frequent collaborators, Annette Evans and Tim J Evans, focus on producing data that can be used to align the needs of industry with the limits on our resources. 'Our research aims to develop strategies and technologies for reduction of environmental impacts through improved energy efficiency of the industrial processes, reduction in emissions and integration of renewable energy sources,' Professor Strezov explains.

Our increasing demand for electricity necessitates reduced impacts. The better standards of living that we are enjoying, coupled with continued population growth, comes with impacts on the required level of energy production. Without drastically rethinking our current methods, developing countries will need increasing amounts of fossils fuels, and this will increase greenhouse gas emissions considerably, leading to devastating impacts on our already-damaged climate. Our current dependence on fossil fuels cannot be sustained – a dramatic shift is needed to invest in systems that allow more energy generation from renewable sources.

Prioritising our Longevity

As Professor Strezov has highlighted in his research, humans have until recent history taken the planet's resources for granted as unlimited. The word 'sustainable' was first used in The Limits to Growth by Club of Rome in 1972, which stated that 'we are searching for a model that represents a world system that is: 1. sustainable without sudden and uncontrolled collapse; and 2. capable of satisfying the basic material requirements of all its people'. *The United Nations Conference on the Human Environment* in 1972 resulted in the *Stockholm Declaration and the UN Environment Programme*. Sustainability is about prioritising the future as highly as the present, and has economic, social and environmental dimensions.

In the last few decades, it has been established empirically that there is a need to be economical about our growing consumption. Professor Strezov highlights that our current rates of consumption indicate limited time left for fossil fuels – coal will run out in about 109 years, oil in 53 and gas in 54. The Earth's resources of coal, oil, natural gas, uranium and minerals need to be preserved as part of the resource component of sustainability.

Over time, the principles and metrics by which sustainability is measured have become more sophisticated. The *1980 World Conservation Strategy: Living Resource*

‘Our research aims to develop strategies and technologies for reduction of environmental impacts through improved energy efficiency of the industrial processes, reduction in emissions and integration of renewable energy sources.’

Conservation for Sustainable Development stated that ‘human beings, in their quest for economic development and enjoyment of the riches of nature, must come to terms with the reality of resource limitation and the carrying capacities of ecosystems, and must take account of the needs of future generations.’ Of the principles of the *Stockholm Convention*, some included ‘non-renewable resources must be shared and not exhausted’ and ‘pollution must not exceed the environment’s capacity to clean itself’. Current environmental criteria for industrial sustainability include consumption, greenhouse gas emissions, emissions to air, emissions to water and waste.

Quantifying Sustainable Development

The need for change is becoming more widely accepted. There is high demand for change in the ways that we power our societies – for example, 70% of Australians wish for coal use to cease in favour of other energy sources.

There is, however, a lack of consensus on the best methods to increase sustainability of industrial processes. A wide range of different sustainability indices have emerged, including the Change in Wealth Index, Ecological Footprint, Environmental Performance Index, Environmental Sustainability Index, Genuine Savings Index, Global Well-Being Index, Happy Planet Index, Human Development Index and Sustainable Society Index.

There is no index with a consensus that is both political and scientific. Professor Strezov has noted that one limitation is that no single indicator can give an exhaustive view of sustainable development. There has been a call from scientists and policymakers to better integrate to develop sustainable development indicators so that their different purposes are being adequately addressed. Sustainability assessments based on industrial activity are possible through the use of pollutant inventories, but these inventories are still in need of being consolidated and standardised.

Forms of Energy and their Worth

Professor Strezov and his colleagues have investigated the feasibility of sustaining multiple energy sources. Forms of energy generation that are alternatives to fossil fuels include hydropower, wind energy, geothermal energy, natural gas, biomass combustion and gasification, solar power and tidal power.

In an analysis by Professor Strezov and his team, biomass technologies indicated high levels of efficiency that compare with the best coal and wind technology. They point out that biomass energy crops, however, have the most limitations in that they require agricultural land, making them the form of energy that requires the most land. Use of biomass residues (typically by-products of forestry or agriculture) are generally more sustainable than biomass-dedicated energy crops. Additionally, biomass demands resources that might otherwise be used for heating and cooking, which can impact economically disadvantaged areas.

Professor Strezov and his colleagues have also assessed the sustainability of other energy sources. Coal, gas and geothermal electricity, in that order, produce the highest greenhouse gas emissions. Wind powered and hydroelectric energy are the most sustainable energy sources.

While more expensive than coal, nuclear, gas and hydro, Professor Strezov's investigations highlight that biomass dedicated energy crops are still cheaper than wind and geothermal energy. Photovoltaic technology is by far the most expensive energy source, and has the lowest electrical efficiency. However, it has the advantage of solar energy being highly abundant as a power source.

The Value and Cost of Minerals

Professor Strezov, along with Dr Tim Evans, has also investigated the degree to which various mineral processing industries could be integrated into a sustainable society. They used the Australian iron, steel, aluminium, lead, zinc, copper and gold industries as case studies. During their assessment, the duo employed environmental parameters including consumption, greenhouse gas emissions, harmful atmospheric emissions, metals, organic air toxins and non-recyclable waste produced during metal production. The minerals were assessed according to the risk they pose to the environment along with their ultimate economic contributions.

The team found that lead and nickel were the most problematic materials for the purposes of sustainable development. Lead involves the emission of harmful volatiles, toxicity and high ore depletion rates, while nickel causes a high level of toxic waste while contributing relatively little to the economy. The aluminium industry was found to be the worst in terms of greenhouse gas emissions and water consumption. While the iron and steel industries were assessed as being the most sustainable, they create the most organic air toxins, which pose great environmental risk.

Steelmaking: Maintaining a Crucial Industry

Professor Strezov and his colleagues have worked to establish the sustainability of three forms of steel production – blast furnace, electric arc furnace and direct reduced iron. The research team employed parameters of economics, greenhouse gas emissions, freshwater consumption, land use requirements and air pollution. They found that blast furnace based processes were 3 to 3.5 times less sustainable than electric arc furnace and direct reduced iron technologies. Electric arc furnace steelmaking was found to be slightly more sustainable than the direct reduced iron method – largely due to electric arc furnace technology making use of scrap steel (although scrap steel not being abundant is a constraint).

Professor Strezov and his colleagues also established that the main advantage of direct reduced iron steelmaking was its use of natural gas and the highly controllable emissions of the method. Overall, they also found that iron and steelmaking technology is less sustainable than food production from wheat, but more sustainable than producing electricity from coal.

A Renewed Path

Professor Strezov and his colleagues have found that renewable energy sources have a number of other distinct advantages over fossil fuels. Their more abundant nature makes them less sensitive to price fluctuations, making them a more consistently logical investment. Additionally, they don't have the transportation issues of legality and safety that are associated with uranium, gas and coal. The research team highlights that another advantage of renewable resources is that regions with less mineral resources are offered improved energy security.

Part of the reason that coal and gas have remained in general use is that they are reliable and inexpensive. This places them in the position of being intimately integrated with economic processes. For this reason, an abrupt abandonment of these energy sources without a transition to renewables being facilitated is not practical. Professor Strezov and his colleagues note that renewable energy resources must first be incentivised and encouraged.

Consolidating Sustainability

The next steps of research for Professor Strezov's team will involve understanding the mechanisms behind how dioxins form – some of the most toxic chemicals ever produced by humans – during iron ore processing and their reduction and better control. The team will also monitor the chemistry and concentration of atmospheric particles in Chinese urban centres near iron and steelmaking plants. The production of biofuels from underutilised organic wastes will be a further focus of their research, specifically through the use of thermal processing methods such as pyrolysis.

Through providing better understandings of the costs of energy-related processes, Professor Strezov and his team aim to help ensure the sustained progress of our human civilisation.

Meet the researcher

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Professor Vladimir Strezov's research is in the area of industrial ecology, focusing on the role of industrial processes in sustainable development. He earned his PhD in Chemical Engineering from the University of Newcastle, Australia in 2000. Since 2015, he has been a professor in the Department of Environmental Sciences at Macquarie University in Sydney, Australia. Professor Strezov is advisory board member for the Australian Renewable Energy Agency (ARENA) and Fellow of the Institution of Engineers Australia. He has written over 200 publications and two books: *Biomass Processing Technologies* with TJ Evans (2014) and *Antibiotics and Antibiotics Resistance Genes in Soils* with MZ Hashmi and A Varma (2017).

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FUNDING

Australian Research Council.

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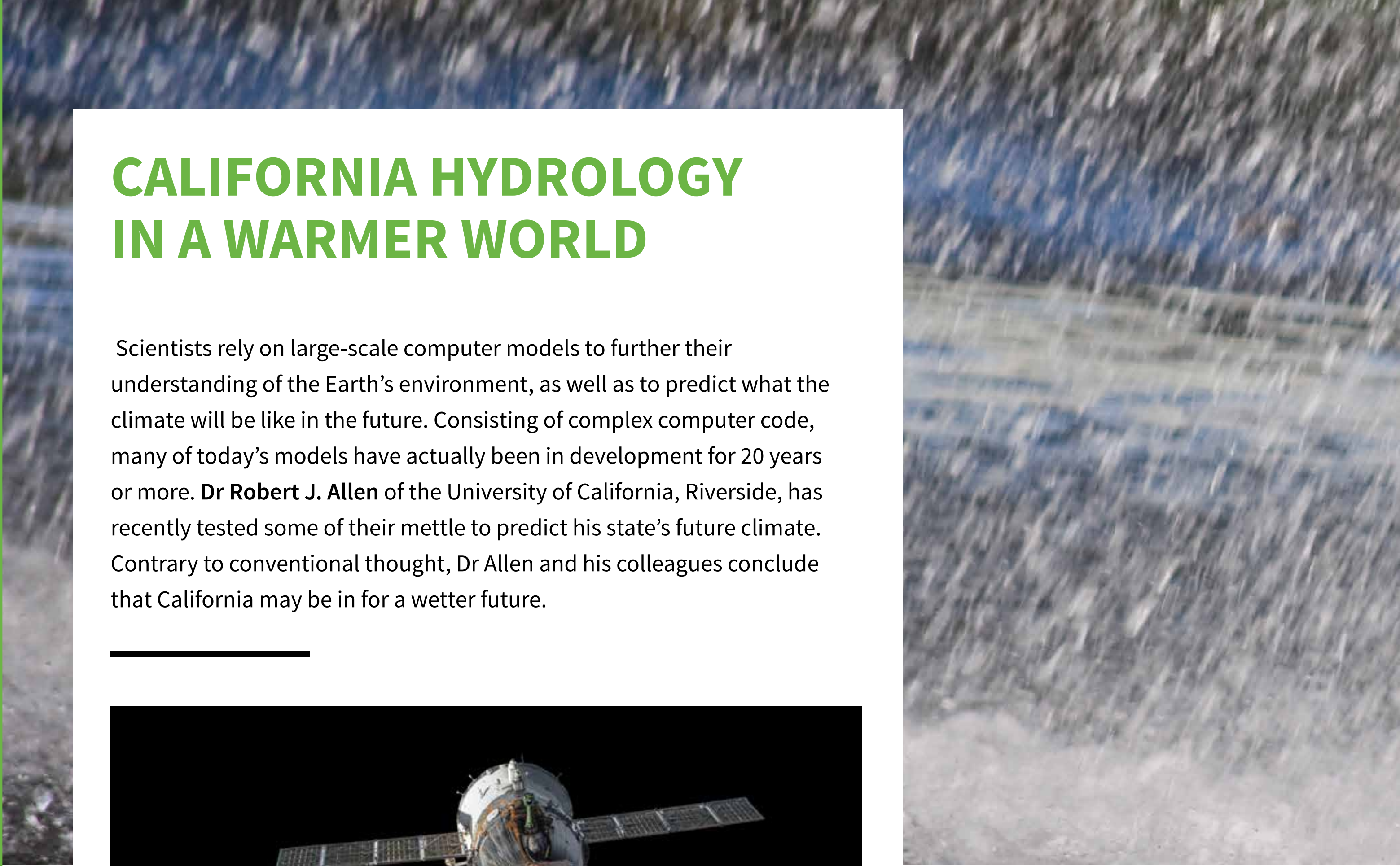

CALIFORNIA HYDROLOGY IN A WARMER WORLD

Scientists rely on large-scale computer models to further their understanding of the Earth's environment, as well as to predict what the climate will be like in the future. Consisting of complex computer code, many of today's models have actually been in development for 20 years or more. **Dr Robert J. Allen** of the University of California, Riverside, has recently tested some of their mettle to predict his state's future climate. Contrary to conventional thought, Dr Allen and his colleagues conclude that California may be in for a wetter future.

Global Models

Dr Robert J. Allen has been keenly interested in how climate change is going to affect atmospheric circulation for nearly 20 years. His research team uses both ground and satellite observations along with what they call a 'suite of global climate models'.

One such suite is the Coupled Model Intercomparison Project (CMIP), a brainchild of the World Climate Research Programme. The Programme, jointly created in 1980 by the International Council for Science and the World Meteorological Organization, aims to understand and better predict climate variability and change, along with the impact of human activity on it. CMIP, which is a collection of models, has been the Programme's biggest and latest effort to date. It started two decades ago when scientists began loosely working together on climate change. At the time, only a few models were available for comparison.

Since then, the threat of climate change has become substantially greater, and scientists are more loudly sounding the alarm on a number of worrying trends. The foremost trend in the last century has been documented record levels of carbon dioxide in the atmosphere, which has been primarily brought about by burning fossil fuels. This rise in carbon dioxide and other greenhouse gases has subsequently led to significant increases in both air and sea surface temperatures across the globe. Arctic and Antarctic sea ice is melting, as is Greenland, causing sea levels to rise measurably. At all levels, society will be affected by these effects, including changes in precipitation and fresh water resources, and intensification of storms and droughts.

Not surprisingly, research interest in climate change has also intensified and around 30 modelling centres have sprouted up around the world. CMIP's role has been to bring all their various protocols, mechanisms and experiments under one standardised umbrella. Even more modelling centres will be involved when the sixth phase of the project, known as CMIP6, is released soon. For now, the fifth phase of CMIP (or CMIP5) has been the most widely used suite of models. When CMIP5 was released in 2011, its scale of size and capability of producing long term simulations was unprecedented. For the first time, it joined conventional global climate models with Earth system models, allowing researchers to run more realistic simulations in both the 20th and 21st centuries.

To appreciate how models have helped our understanding of the Earth's past, current and future conditions, one only has to look at the successes of previous endeavours. For example, efforts of the World Climate Research Programme have resulted in some significant accomplishments, including the Tropical Ocean and Global Atmosphere (TOGA) project. TOGA was a breakthrough for understanding and forecasting El Niño, a coupled ocean-atmosphere phenomena also referred to as ENSO. The EN refers to El Niño, which is the ocean component, in this case the warming of the central/eastern Pacific sea surface temperatures. The SO refers to the Southern Oscillation, or the atmospheric component.

Dr Allen explains that global climate models, along with hard data help his team to 'identify observed changes in our climate system,

‘My research seeks to improve our understanding of how climate change has affected, and will affect, atmospheric circulation. This includes global to regional scale change, as well as the resulting impacts of societal relevance, including precipitation shifts and changes in fresh water resources, as well as perturbations to extreme events.’

understand the drivers of the observed change, and improve our understanding of future climate change.’

CMIP, CESM and California

Dr Allen focused his research on California because there are large uncertainties in its future climate change projection. California, which stretches along some 1,350 kilometres of coastline in the western US, garners interest because of its size, population and economic importance. Its economy, repeatedly rated in the world’s top 10, has a Gross Domestic Production of $2.448 trillion, comparable to that of the UK and France. Climate change in California could impact not only the state’s important agricultural economy but also increase risk of wildfires and severe weather events. ‘Significant uncertainty exists as to how climate change will impact California, the most populous state in the US,’ says Dr Allen. ‘Of particular importance are changes in hydrology, including precipitation.’

Predicting future climate in California has turned out to be a tricky proposition, however. Most climate models tend to agree that the subtropics will experience a decline in precipitation and become drier. Middle to higher latitudes, on the other hand, should experience higher rainfall and become wetter in response to increasing greenhouse gases. California is located in the middle, or transition, of these zones – so which model outcome should be applied here? Not only that, California experiences relatively large year-to-year variations in rainfall, simply due to interactions between the ocean and atmosphere.

Adding to the uncertainty is that even the best models have shortcomings. For example, CMIP3, an earlier phase of CMIP, predicts significantly less precipitation for central and southern California than the later CMIP5 phase. The reasons for the different prediction are not entirely understood but most likely related to model differences.

These uncertainties led Dr Allen and his team to look at projections again, this time using CMIP5 along with other global climate models such as the Community Earth System Model Large Ensemble (CESM LENS) project. In general, their findings have highlighted the importance of rising sea surface temperatures in the tropical Pacific Ocean, similar to those measured in El Niño events. In contrast to previous projections, they conclude that increases in greenhouse gases and warming sea surface temperatures may actually result in increased precipitation for California in the 21st century.
Dr Allen and his team describe various El Niño-like changes in the model simulations. One is a weakening of the ‘Walker circulation’, which is a well-known atmospheric system in the Pacific Ocean. In a normal Walker circulation, trade winds blow from east to west and bring moist air to the west Pacific Ocean. There, the moist air rises and forms clouds that dump all their moisture as rain. The drier air then gets blown back by winds aloft across the Pacific to the east. In Dr Allen’s analyses, however, the pattern is dampened.

Another change demonstrated in the models is an increase in upper level divergence in the central/eastern tropical Pacific. This in turn causes a poleward propagating ‘Rossby wave’ – a naturally occurring meander of high atmospheric wind. Another response to warming waters is that the Pacific jet stream shifts south-eastward, which leads to an increase in storms in the east Pacific. Global warming also increases California’s moisture convergence, which leads to precipitation.

Dr Allen describes his projection as a ‘possible shift of the tropical Pacific to a more El Niño-like background state’. He is careful, however, to explain that El Niño is not necessarily a required response for the increase in California precipitation. ‘The important conclusion is that tropical Pacific warming drives the atmospheric response and the California wettening,’ he says.
In Dr Allen’s view, wetter futures for California were only predicted in models

that simulate the link (or 'teleconnection') between El Niño and the Californian climate. 'Not all models are able to simulate the observed teleconnection between Niño 3.4 sea surface temperatures and California precipitation,' Dr Allen explains. 'We show that those models that can simulate this teleconnection yield larger and more consistent increases in California precipitation.'

'Moreover,' he adds, 'using idealised simulations with two different models, we show that this response is directly related to tropical Pacific sea surface temperature warming. Our results help to explain the large uncertainty in future California precipitation projections, and imply California may become wetter – not drier – in a warmer world.' Dr Allen and Rainer Luptowitz, a former graduate student, published these results in *Nature Communications* in July 2017.

Reassessing California's Drought Risk

As a follow-up, Dr Allen and his team have continued to analyse the output of the modelling centres to project the risk of future droughts in California. Up until now, scientists have believed that climate change is going to bring about a more arid climate, thus increasing the frequency and intensity of drought.

'Severe and widespread droughts during this century are of particular concern for south-western North America, including California,' says Dr Allen. 'Some studies have suggested that future drought risk in south-western North America may even exceed that during the driest centuries of the Medieval Climate Anomaly.' The Medieval Climate Anomaly, which lasted from around 950 to 1250 AD, is of great interest to climate scientists, because during that time temperatures in the Northern Hemisphere were mild, at least 0.5° warmer on average. It is the only time in the last 1500 years that temperatures were as warm as those being recorded today. However, Earth's global average temperatures today are already higher at 0.85°C and are trending upwards at a much faster rate.

As with his previous work, Dr Allen has concluded that models that better simulate the El Niño-California teleconnection show precipitation in California increasing along with surface water availability and runoff, leaving the deep soil moisture levels available for plants and crops. As such, these models demonstrate a negligible change in annual drought risk at the end of this century relative to the end of the 20th century. In contrast, other models that poorly simulate the ENSO teleconnection yield a significant increase in drought risk for California.

Next Steps

Dr Allen and his team plan to expand on this work in future research. They want to formally investigate changes in California drought and flooding cycles to include statistics on precipitation, surface water availability and soil moisture.

Adding to that, Dr Allen says, 'the dynamical mechanism will be further explored, including how the zonal heterogeneity of the climatological state of the tropical Pacific may lead to greater destabilisation of the atmosphere in the eastern tropical Pacific in response to warming, which in turn drives the enhanced convection, Rossby wave response, and extra tropical teleconnection with California.'

Although Dr Allen's research suggests that California may not experience significant increases in annual drought, continued concern is still warranted during the dry season. Moreover, the state should prepare for other possible negative consequences, such as increased storm severity and flooding.

Meet the researcher

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Dr Robert J. Allen received his PhD in Atmosphere, Ocean and Climate Dynamics from Yale University in 2009, after obtaining his MSc in Applied Climatology in 2003 at Cornell University in Ithaca, New York. He has been a Professor in the Department of Earth Sciences at the University of California, Riverside since July 2011. There, he teaches both undergraduate and graduate courses in Atmospheric Science and Global Climate Change. His main research interests are climate variability, land-atmosphere interaction, atmospheric aerosols/short-lived pollutants and large-scale climate dynamics. Dr Allen has authored or co-authored several articles and has been invited to public talks related to his work with climate change and modelling. He also serves on UC Riverside's Graduate Admissions Committee, as well as the Geology Social Committee.

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SOLVING LONG-TERM WICKED PROBLEMS

Climate change is one of the most pressing long-term challenges facing humanity and planet Earth. However, scientific uncertainty still leaves the scope of the threat unclear, and the path forward even more so. Now **Dr Robert Lempert** and his colleagues at RAND Corporation have developed a new approach – Robust Decision Making (RDM). Instead of focusing on trying to improve prediction, they use analytics to try to improve decisions when the future is uncertain.

Good Decisions Without Good Predictions

Quantitative, evidence-based analysis is indispensable for making good policy choices. Therefore, society often looks to scientists to make predictions about the future. This seems natural, because prediction is the bedrock of science, enabling researchers to test their hypotheses. But many of society's biggest challenges present conditions of deep uncertainty, involving many interdependent systems undergoing fast-paced, transformative change. Despite our best efforts at prediction, we are certain to be surprised, says Dr Robert Lempert, Director of RAND Corp's Pardee Center for Longer Range Global Policy and the Future Human Condition. Deep uncertainty also fuels political gridlock, because in a diverse society, people embrace those predictions that best justify their preferred solutions.

Climate change presents an archetypal example of the challenge of making good decisions under conditions of deep uncertainty. Burning fossil fuels – oil, coal, and gas – has helped grow the global economy 10-fold over the last seventy years, but has also thickened the blanket of greenhouse gases warming the Earth by 40%. Continuing this path poses huge risks to humanity, but those risks are hard to assess. The climate is a complex system being pushed past familiar bounds. We don't know how fast the seas will rise or how frequently extreme storms will strike. Halting climate change would require a technological and behavioural revolution that weans the global economy from fossil fuels at an unprecedented rate. Any action – or inaction – presents profound moral implications: It will affect equity among people living today, fair treatment of future generations, and humans' relationship with nature.

To help manage such deeply uncertain challenges, Dr Lempert and his colleagues have re-imagined how quantitative models and data can best inform evidence-based decisions. Analytics become a vehicle to help people both to open and discipline their imagination – systematically expanding the range of futures considered; testing the consequences of myriad assumptions; crafting promising new responses to dangers and opportunities; confronting ethical trade-offs; and sifting through a multiplicity of scenarios, options, and objectives to agree on robust and flexible approaches for managing risk. Our world is filled with ever expanding computing power. Many scientists focus on using computers to make better predictions. Dr Lempert uses them to inform better decisions.

A combination of new information technology and new insights from the decision sciences enables this new approach. Dr Lempert has helped to pioneer an approach called robust decision making (RDM), which rests on a simple concept. RDM stress-tests proposed decisions against thousands or millions of plausible paths into the future. Analysts then use visualisation and statistical analysis of the resulting large database of model runs to help decision makers identify the key features that distinguish those futures in which their plans meet and miss their goals. This information illuminating a proposed strategy's vulnerabilities helps decision makers to

‘In college, I double majored in physics and political science, and was struck by how the beautiful, elegant, precise models of the former seemed so alien to the latter.’

identify, evaluate, and choose more robust strategies – in other words, the strategies that perform best across the largest range of futures. RDM combines the best features of scenario analysis, red-teaming, and quantitative risk analysis.

RDM is now being used to manage the deeply uncertain risks of climate change. In 2012, for instance, Dr Lempert's RAND colleagues, Dr Dave Groves and Dr Jordan Fischbach helped the US Bureau of Reclamation study the 50-year future of the Colorado River Basin. The Colorado River system serves 30 million people in seven states and irrigates 15 percent of US agriculture. Growing demand, increasing temperatures, and declining precipitation threaten the future management of the river. Using RDM, the stakeholders – the Bureau of Reclamation and other interested parties – tested the performance of current river management against 23,000 alternative futures. The alternative scenarios reflected different (but possible) projections of the future climate, drawn from global circulation models and paleoclimate reconstructions of past mega-droughts in the region, assumptions about future demand, and political assumptions regarding how the parties might respond to future crises. This analysis helped a diverse and often contentious group of stakeholders agree on the vulnerabilities facing the river system and explore hundreds of options for reducing the imbalance between water supply and demand. Planners across the Basin now use the results of this study, which won the prestigious Department of Interior ‘Partners in Conservation’ award, to support deliberations regarding specific investments towards a robust, adaptive strategy for the Colorado River. The Bureau of Reclamation is also using and training its staff in these methods.

Robert Lempert, Problem Solver

Dr Lempert's passion for applying new tools to solve wicked problems stems partly from his up-bringing. ‘As a child, I grew up being good at science and fascinated by it, in a family devoted to public service,’ he tells us. ‘My mother spent 30 years as a local elected official. My brother represented Silicon Valley for 10 years in the California legislature. My sister is mayor of Princeton New Jersey. I have always been interested in the intersection of science, policy, and politics. I am also an environmentalist.’ Educated in physics and politics, he found the models adopted by the two sciences to be remarkably different: ‘In college, I double majored in physics and political science, and was struck by how the beautiful, elegant, precise models of the former seemed so alien to the latter. In graduate school, I studied condensed matter physics and science policy.’

Dr Lempert's interest in connecting models to complex and contentious policy challenges was fuelled by arguments raging when he first arrived at RAND in the mid-1980s. ‘There was a big debate between those who built big military simulation models and those who questioned their utility,’ he recalls. ‘One telling moment was the Falklands war. When the British fleet set sail for the South Atlantic, the model sceptics confronted the model builders. You know in detail all the British and Argentine forces, the sceptics said, and have a month to run your models. Tell us how the battle will unfold. The model builders demurred, explaining that their models were only for “insight”. It wasn't entirely clear what that meant.’

RAND's Steve Bankes cut this Gordian knot with his concept of 'exploratory modelling', in which simulations and data are used not to predict the future but to map large sets of assumptions onto their consequences, without necessarily privileging any one set of assumptions over another. The analytic frameworks for predictive decision and risk analysis evolved in the 1950s and 1960s when relative computation poverty made a virtue of analytics recommending a single best answer based on a single best estimate prediction. But Dr Bankes, envisioning a future of ubiquitous and inexpensive computation, explored models better suited to complex problems that defy a single, ideal solution.

Dr Lempert seized upon the exploratory modelling concept as a means to study climate change and mitigate its effects. Climate change, he explains, is a 'wicked' problem – one with irreducible scientific uncertainties, non-linear dynamics, and complex ethical dilemmas. Wicked problems aren't really understood until a solution has been reached. 'Halting or managing climate change will require evidence-based decision making over a very long-time horizon,' Dr Lempert says. 'But the quantitative tools we had were inadequate to the task because they required us to assume more than we could possibly know. An important moment for me came when I realised we didn't need to rely on best-estimates in order to make progress. We could use computers to stress-test a million different assumptions.' These ideas took form during discussions at a 1991 a meeting at the Santa Fe Institute. 'It was an amazing mix of people, including Steve Bankes and CalTech's Bruce Murray. Discussions there crystallised for me new ideas on how to use models and ubiquitous computation to improve reasoning about how best to shape the future. It seemed like an ideal way to address climate change, and we've been working on it ever since,' he explains.

Analytics for Democratic Deliberation

Dr Lempert's Pardee Center serves as an incubator within RAND, a public policy research institute, for developing and disseminating new tools for managing the future. For instance, to demonstrate the potential of multi-scenario analytics and high-performance computing to wicked problems, RAND and Lawrence Livermore National Laboratories recently revisited the Colorado Basin negotiations, They ported the Reclamation planning models to LLNL's supercomputers, shortening the time it took to analyse 23,000 scenarios from days to minutes. Stakeholders gathered to use this system for real-time, data-supported deliberations over the best means to manage climate change and other factors stressing the river system.

But supercomputers aren't necessary for RDM. Users have begun to move their climate adaptation models to the cloud, where they can run thousands or millions of scenarios to anticipate their vulnerabilities to multiple possible future developments and explore options for managing the full range of risks. In recent years, cities and water agencies in South Florida Allegheny County, and the Netherlands have begun to use these techniques. The World Bank has begun incorporating these methods into their guidelines for water and other systems.

RDM approaches are also being used by the research network on Sustainable Climate Risk Management (SCRIM), which asks the question: 'What are sustainable, scientifically sound, technologically feasible, economically efficient, and ethically defensible climate risk management strategies?' For New Orleans, for example, Dr Klaus Keller, Dr Lempert and other SCRIM researchers have been building new representations of the deeply uncertain risks of rapid sea-level rise to the Louisiana coast. They are also studying strategies for decarbonisation, that is, reducing emissions of climate-altering greenhouse gases.

'Those pursuing decarbonisation often shy away from uncertainty, concerned that acknowledging it will delay action or show a lack of leadership,' says Dr Lempert. But uncertainty is at the heart of the issue. Achieving deep and rapid decarbonisation will require technical, political, and social breakthroughs that result in even more unpredictability – forcing decisionmakers to assess risky and seemingly implausible trade-offs. Dr Lempert is thus working with a network called the Decarbonization Dialogues to help the diverse, independent actors pursuing deep decarbonisation better recognise and manage the deep uncertainty involved. In other recent work, Dr Lempert and his RAND colleague Steven Popper used RDM and agent-based modelling to explore the long-term political persistence of alternative forms of greenhouse gas regulation. RDM is also being applied to other policy issues as diverse as national security, health, and tax and fiscal policies.

Researchers from RAND, Deltares, TU Delft, Penn State, the World Bank and others recently founded the Society for Decision Making Under Deep Uncertainty to bring together the growing international community of researchers and practitioners who are adopting this vision of managing the future. At the root of this, Dr Lempert seeks a new form of collaboration between humans and machines. People are good at intuiting creative solutions, but also excel at convincing themselves of things that aren't true. Computers can systematically test the consequences of assumptions and exhaustively search for counter examples. The RDM method can meld the two with multi-scenario, multi-objective analytics informed by the best scientific evidence. By illuminating trade-offs, the decision-making process can be made more open, accessible, and equitable.

To successfully manage climate risk, society will need to be both bold and careful. Analytics designed to inform better decisions, rather than make better decisions, can help.

Meet the researcher

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Dr Robert Lempert is a principal researcher at RAND Corporation and director of RAND's Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition. His research focuses on risk management and decision-making under conditions of deep uncertainty, with an emphasis on climate change, energy, and the environment. Dr Lempert is a Fellow of the American Physical Society, a member of the Council on Foreign Relations, a lead author for the US National Climate Assessment, Working Group II of the United Nation's Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, and has been a member of numerous study panels for the US National Academies, including the Transportation Research Board's *Climate Change and US Transportation*, and the National Research Council studies *America's Climate Choices and Informing Decisions in a Changing Climate*. Dr Lempert was the Inaugural EADS Distinguished Visitor in Energy and Environment at the American Academy in Berlin. Lempert is also the inaugural president of the Society for Decision Making Under Deep Uncertainty. A Professor of Policy Analysis in the Pardee RAND Graduate School, Dr Lempert is an author of the book *Shaping the Next One Hundred Years: New Methods for Quantitative, Longer-Term Policy Analysis.*

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FUNDING

National Science Foundation
John D. and Catherine T. MacArthur Foundation
US Environmental Protection Agency
World Bank
Frederick S. Pardee

CLIMATE MATTERS: A NOVEL APPROACH TO EDUCATING AMERICANS ABOUT HUMANITY'S GREATEST CHALLENGE

Over the past few decades, global climate change has emerged as the preeminent issue facing modern society. In many countries around the world, climate change is shifting weather patterns for the worse, with impacts predicted to grow increasingly more erratic and severe. Despite this, the public's understanding of climate change is often limited and rife with misinformation. **Dr Edward Maibach's** innovative program, Climate Matters, empowers local weathercasters to become beacons of public education for climate change.

Climate Matters founder Joe Witte (NASA) and program directors Bernadette Placky and Sean Sublette (Climate Central) join George Mason University professor Dr John Cook and a slew of TV weather casters at a March 2017 climate change communication training hosted by Climate Matters at NASA Goddard Flight Center

Gaps in Public Perception

To tackle global climate change, one of the primary hurdles to overcome is changing the public's misperceptions of the risks and immediacy of the problem. Research indicates that the majority of Americans believe that climate change is happening and see it as a concern. However, when Dr Edward Maibach of the George Mason University Center for Climate Change Communication and his colleagues at Yale and Mason completed a survey in 2008, the US public ranked climate change as the tenth most important issue out of eleven. While most Americans agreed that climate change is an important issue, they typically viewed it as something that does not affect them

directly, perceiving the effects of climate change as occurring far in the future or far from their homes. Unfortunately, this is not the case – climate change is currently impacting every region of the United States, mostly altering weather patterns for the worse. Without decisive intervention, the progression of climate change is poised to disrupt global agriculture, increase disease transmission, and decrease water availability in many areas, among other harms.

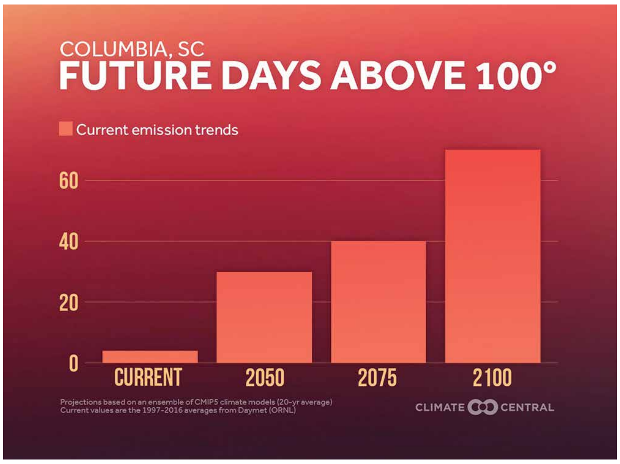
Dr Maibach's 2008 survey revealed misperceptions about climate change in the American public. Beyond the belief that climate change will not affect them personally, many people were unaware of the human cause behind climate change and some of the devastating effects associated with it. Many people also, however, indicated a desire to learn more about the causes, impacts, and possible solutions for climate change.

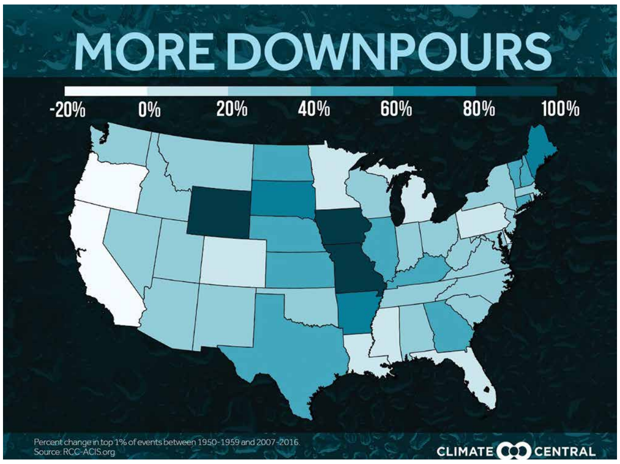
Fortunately for everyone involved, the results of Dr Maibach's survey came across the desk of senior TV meteorologist Joe Witte. A graph describing public trust in different information sources caught Joe's eye – he noticed that television weathercasters were among the top trusted sources of climate change news. As Dr Maibach describes: 'He contacted me with great enthusiasm, suggesting that if he and his colleagues were trusted as a source of information about global warming, perhaps we should develop resources to help them report on climate change – because they have great access to the public, and strong science communication skills.'

An Under-Utilised Resource

In 2009, Dr Maibach and his colleagues from Mason and Climate Central, a non-profit

‘We currently have over 430 weathercasters participating in the project, who broadcast from 262 stations in 136 of America’s 210 media markets… Moreover, on air reporting about climate change by weathercasters increased over 1,200% in the four-year span from 2013 to 2016.’





science communication organisation, received funding from the National Science Foundation (NSF) to investigate how to make use of a potential ally in public climate education: your local TV weathercaster. The TV weathercast is uniquely poised to provide effective climate change educational segments for a number of reasons. It is among the most reliably watched segments of most local news programs, with many people reporting that they watch the local news primarily for the weather report. This advantage holds even as increasing numbers of people obtain their information from digital media, as local weathercasters increasingly provide weather information to viewers across a range of digital platforms. Further, the large audiences reached by local weather forecasts are diverse in age, income, education, and racial demographics. Across their broad audiences, meteorologists and weathercasters are viewed as trusted sources of non-political climate change information.

While climate scientists are typically ranked as the most trusted source of climate change information in the US, scientists have limited access to the public and in certain demographics, particularly conservatives, trust in scientists has declined. Weathercasters on the other hand are not only trusted, they have strong access to the public, strong communication skills, and the information they convey is not viewed as political, since the weather itself is not political. The weather forecast is the most common voluntarily sought form of science education, and previous research suggests that it is an effective venue for related topics, such as geography, public health, and hurricane risk.

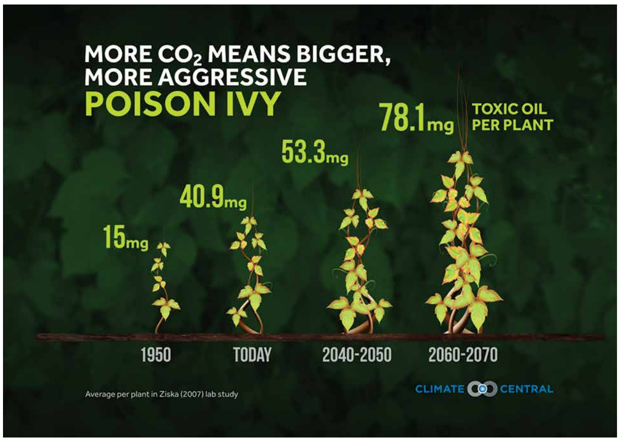
In 2010, Dr Maibach and colleagues completed a survey of over 500 weathercasters to better understand their potential interest in offering science and climate change information as part of their regular weather forecast. He found that 94% of responding weathercasters said that weathercasters were the only person in their newsroom trained in science or the environment. Many meteorologists and weathercasters have scientific backgrounds, and all have extensive experience as science communicators. For example, following earthquakes in Haiti and Chile that gained international headlines, many local weather people became the station expert in plate tectonics, offering complex scientific concepts about why earthquakes occur in accessible terms and examples.

They are also overwhelmingly interested in offering educational segments on climate change – 79% of respondents indicated that they would be interested in becoming the station science expert, and nearly two thirds responded that they would like to report more on climate change, in particular stories that impact their local areas. So, not only are many weathercasters already uniquely qualified to offer educational segments on science topics, many are also eager to provide specific information on climate change.

Perhaps the greatest benefit of offering climate change education in conjunction with the local weather forecast is the potential to help viewers link climate issues with their personal lives. People learn complex information most quickly when it is offered in the form of concrete examples and narratives that are easily applied to their experience. The more times they encounter information presented this way, the stronger the lesson will be. When weathercasters are able to present information about climate change in conjunction with related local weather events, it helps people understand that they are personally experiencing the effects of climate change. Therefore, they are more likely to view it as a serious issue that requires their attention. Severe weather events offer particularly strong climate change learning opportunities, as many of these events are becoming more common and more severe as a result of global warming.

Overcoming Barriers to Climate Change Education

While many of the weathercasters who participated in Dr Maibach’s 2010 survey indicated their interest in reporting on climate change, 90% said that they would need additional resources to do so. At the local level, most weathercasters lack access to climate scientists for interviews or commentary, and do not have the time to sift through the latest peer-reviewed articles. They would also need additional high



quality graphics and visual materials, and most simply do not have the time or resources to produce additional segments about climate change in a strategic manner.

As part of their NSF-funded initiative inspired by Joe Witte, Dr Maibach, Climate Central's climate scientist Heidi Cullen, and their colleagues partnered with a local TV station in South Carolina in 2010 to find ways to overcome these barriers and produce effective educational segments about climate change at the local level.

Working with a team of broadcast meteorologists, climate scientists, communication scientists, writers and graphic designers from a number of collaborating institutions, Drs Maibach and Cullen developed scripts and graphical materials for twelve short segments on climate change. The result was Climate Matters – a monthly educational series presented just prior to the evening weather forecast. Topics were selected to be relatable to local weather events, and included high temperatures, extreme heat, hurricanes, intense storms, sea level rise, human causes of climate change, air quality and drought.

Each minute-and-a-half segment was designed to be a self-contained short lesson on climate change, focusing on one or two major points selected to be as connected as possible to the experiences of the viewer. For example, a segment on poison ivy explained how certain plant pests thrive under increasing carbon dioxide levels and are likely to become more prevalent without intervention. The team's goal was to show viewers that climate change is an issue that already impacts their everyday lives, thus helping to change their misperception of climate change as a distant problem.

To assess the effectiveness of the program, Dr Maibach and his colleagues needed to measure climate change beliefs in local viewers both before and after the segments aired. To do so, they randomly dialled numbers to conduct phone surveys in the station's local area, collecting the initial climate beliefs of over 1,000 viewers. A year later, after the Climate Matters segments had aired, they were able to repeat the survey with 500 of the original participants, and survey over 900 new participants.

The results showed that Climate Matters was a success. After airing the segments, station viewers were more likely to report that they were certain that climate change was happening, and that they felt it was a harmful force, regardless of whether or not they specifically remembered seeing the segments. Those who were able to recall specific Climate Matters segments were also more likely to attribute climate change to human causes. The program had reached its target audience and influenced their perceptions about climate change.

Changing the Face of Climate Change Education

Six years after the initial Climate Matters pilot, the program has blossomed into a resource for informal climate education nationwide. Every week, a team of meteorologists, research scientists, data analysts, journalists, and creative designers at Climate Central put together a comprehensive package of content about various current climate change topics. Each package includes TV-ready visuals, detailed descriptions of the latest science behind the week's topic, current climate change information from NASA and the National Oceanic and Atmospheric Association (NOAA), and a round-up of new climate research findings. The packages are designed to be current and relevant, and to dramatically reduce the production burden for weathercasters interested in including climate change education as part of their segments.

Climate Matters has also expanded beyond the short TV weather segment to support weathercasters in climate change education across a variety of mediums. To engage with growing digital content consumption, Climate Matters offers interactive media and tweetable facts that can be easily embedded in station websites or social media. They provide a range of resources that are suitable for the local community outreach presentations that many weathercasters give. Climate Matters also provides video and production support to meteorologists who are interested in developing and producing their own original climate change stories and specials.

From a one-year pilot-test with one weathercaster in South Carolina, the program has grown into an incredible force for education. 'We currently have over 430 weathercasters participating in the project (including 31 who broadcast in Spanish), who broadcast from 262 stations in 136 of America's 210 media markets, including 24 of the top 25 media markets,' says Dr Maibach. 'Moreover, on air reporting about climate change by weathercasters increased over 1,200% in the four-year span from 2013 to 2016.'

On September 1st 2017, Climate Matters will begin to offer resources to non-weather journalists in hopes of extending the reach of local climate reporting and education. As humanity continues to face the ever-increasing threat of global climate change, a challenge that requires participation from people in all walks of life, programs such as Climate Matters offer an innovative approach to science education and involvement.

Meet the researcher

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Dr Edward Maibach began his educational career at the University of California, San Diego with a Bachelor's degree in Social Psychology in 1980, and continued on to receive a Master's in Public Health from San Deigo State University in 1983. He was then awarded his PhD in Communication Science from Stanford University in 1990, completing research on social marketing and campaigns to encourage healthy behavioural changes. During his career, he has served as an Assistant Professor at Emory University (1990–1995), Adjunct Associate Professor at Georgetown University (2002–2003), and Professor at George Washington University (2005–2007), teaching graduate level courses in health communication and social marketing. He has also served as Worldwide Director of Social Marketing for Porter Novelli International, Associate Director of the National Cancer Institute, and Board Co-Chair for Kidsave International, developing innovative marketing and communication strategies. He joined George Mason University in 2007 as Professor and Founding Director of the Center for Climate Change Communication, the nation's first research centre devoted to the challenges of communication and behavioural change associated with climate change.

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FUNDING

US National Science Foundation

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CENTER for CLIMATE CHANGE COMMUNICATION

PLANETARY SCIENCE

BREAKING NEW GROUND IN PLANETARY SCIENCE

In this section of the edition, we showcase the latest ground-breaking findings in the diverse fields of geophysics and planetary science. Here we explore everything from the threat of anomalous solar activity, to asteroid mining, and even planning the first manned mission to Mars.

Our last section dealt with our changing and unpredictable climate – so to kick start this section we move slightly beyond our atmosphere, where another danger lurks. While climate change is increasing the frequency of destructive terrestrial weather, the conditions surrounding our planet – so-called 'space weather' – can also become perturbed, leading to tangible problems here on Earth.

Space weather is caused by the continuous stream of charged particles emitted by the Sun – the 'solar wind' – which is made up of highly energetic electrons, protons and other particles. Fortunately for us, Earth's outer core of molten iron gives rise to a protective magnetic field, which 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 particles and radiation in great bursts, which upon reaching our magnetosphere can trigger dramatic phenomena such as geomagnetic storms and auroral displays. During a geomagnetic storm, the increased electric current in the Earth's magnetosphere and upper atmosphere can affect our electricity supplies, disrupting power lines, and even causing widespread blackouts.

These large 'bursts' of charged particles and their effects on the magnetosphere can also cause damage and disruption to the satellites we rely on for our communication systems, air-traffic control, weather forecasting, GPS and the internet. Therefore, if they fail, our societies could begin to unravel, with food supply chains quickly breaking down. For these reasons, and of course a desire to better understand the mysterious interactions between our planet's magnetic field and the solar wind, space weather is currently a highly active area of research.

In the first two articles of this section, we introduce two leading research teams in the field of space weather – Dr Toshi Nishimura and Dr Ying Zou at Boston University, and Dr Jeffrey Forbes and his colleagues at the University of Colorado. While the Boston University team try to pin down the exact mechanisms by which auroral displays are triggered, Dr Forbes and his team investigate how our terrestrial weather affects space weather.

Back down here on solid ground, a team of geologists at The University of Texas at Austin are investigating how fractures grow under the Earth's surface, so that they can create reliable models that predict how fracture patterns develop over millions of years. In the next article of our planetary science section, we introduce their work towards understanding the paths that fluids travel deep underground, which is valuable to industries that extract resources contained within rocks.

However, Earth's resources are becoming swiftly depleted, so many scientists are now looking to space to obtain valuable supplies, such as precious metals. Next, we introduce the work of Dr Daniel Durda and his team at the Southwest Research Institute in Boulder, Colorado, who are searching for practical ways to exploit nearby asteroids, through investigating how materials on their surfaces act in microgravity. Because asteroids are considered to be well-preserved building blocks of the terrestrial planets, containing material that was around at the very beginning of our solar system's formation, Dr Durda's work is also offering insight into how Earth and the other terrestrial planets evolved.

Also probing the early stages of solar system formation is Dr Melissa Morris and her team at the State University of New York at

Cortland. In this section, we showcase their research into chondrules – tiny spheres of rock that are found in meteorites known as chondrites. By gaining a deeper understanding of the conditions under which chondrules form, Dr Morris aims to clear up some of the uncertainties surrounding what happened during the early protoplanetary disk stage of our solar system.

Another way to understand how the solar system formed is to investigate the isotopes present in meteorite samples, which as mentioned above, act as well-preserved fossil records of the early solar system. This is the approach taken by Dr François Robert and his colleagues at the National Museum of Natural History in France. Here, we discuss their exciting discoveries regarding the isotopic fingerprints of meteorites and lunar soils, which the team use to resolve many unexplained phenomena, such as the origins of water on Earth.

This leads us on to an upcoming CubeSat mission to the Moon, which aims to uncover how much water ice is hidden in the Moon's permanent shadows, and where this water came from. Here, we meet Dr Craig Hardgrove and his colleagues at Arizona State University, who are leading the Lunar Polar Hydrogen Mapper (LunaH-Map) mission, due to launch in 2019. If the team find that water exists in sufficient concentrations, the Moon could be used as a refuelling station where hydrogen fuel could be produced, for astronauts on their way to Mars.

Another major challenge for astronauts on their way to Mars will be the communication latency with mission control, which will grow to be as much as 20 minutes during the journey. To tackle this challenge, Drs Karen Feigh and Matthew Miller at the Georgia Institute of Technology are examining what support will be required when astronauts need to make spacecraft repairs outside, when there is such a communication lag with Earth. To help the researchers develop prototypes, software engineer, Cameron Pittman, also joined the team. In the final article of this fascinating section, we reveal the team's findings, and present their latest technologies that astronauts can use when embarking upon deep space missions in the near future.

STUDYING THE AURORAS AND WHAT MAKES THEM SHINE

Space physicists **Dr Yukitoshi (Toshi) Nishimura** and **Dr Ying Zou,** along with their colleagues at Boston University and at UCLA, study the interactions between Earth's atmosphere and energy that flows from the solar wind to determine how the Northern Lights – and the Southern Lights – get their beauty.

Beauty is in the Eye of the Beholder . . . Especially at Night

From earliest childhood, most of us have been struck by the wonders of Nature that surround us. The blue seas, the verdant forests, the colourful birds and fascinating animals – all of these have at one time or another awed us with their beauty and fascination. But one special sight that has drawn human attention from the dawn of history is the twinkling, always moving but somehow unchanging, night sky. The stars, the planets, the romance of the Universe – it appears to be moving around us just outside our reach. It was this very sight that inspired Dr Toshi Nishimura to make space physics his life's work. 'I was a kid who liked to watch stars and think about undiscovered worlds in the universe,' he tells Scientia. 'One day my parents bought me a small telescope and I was excited by watching Saturn's rings, the Jovian satellites, lunar craters and comets.' This became his passion. So when Dr Nishimura went to the college, he took lectures of space science and electromagnetism, and soaked up his professors' enthusiasm about space. That energy simply whet his curiosity even more, so he decided to study the science of space.

But there is one particular phenomenon of the night sky, one that people in many parts of the world never see, that is perhaps the most stunning of all the night's visions – the auroras, those hypnotic shows of dancing lights that fill the skies, especially near or after dark in the higher latitudes. In the northern hemisphere, it is called the aurora borealis or Northern Lights, while south of the equator, it is the aurora australis or Southern Lights. Often highlighted in movies and television programmes set in extreme northern locations, auroras are usually depicted as pale green or pink. However, auroras have been seen in shades of red, yellow, green, blue, and violet.

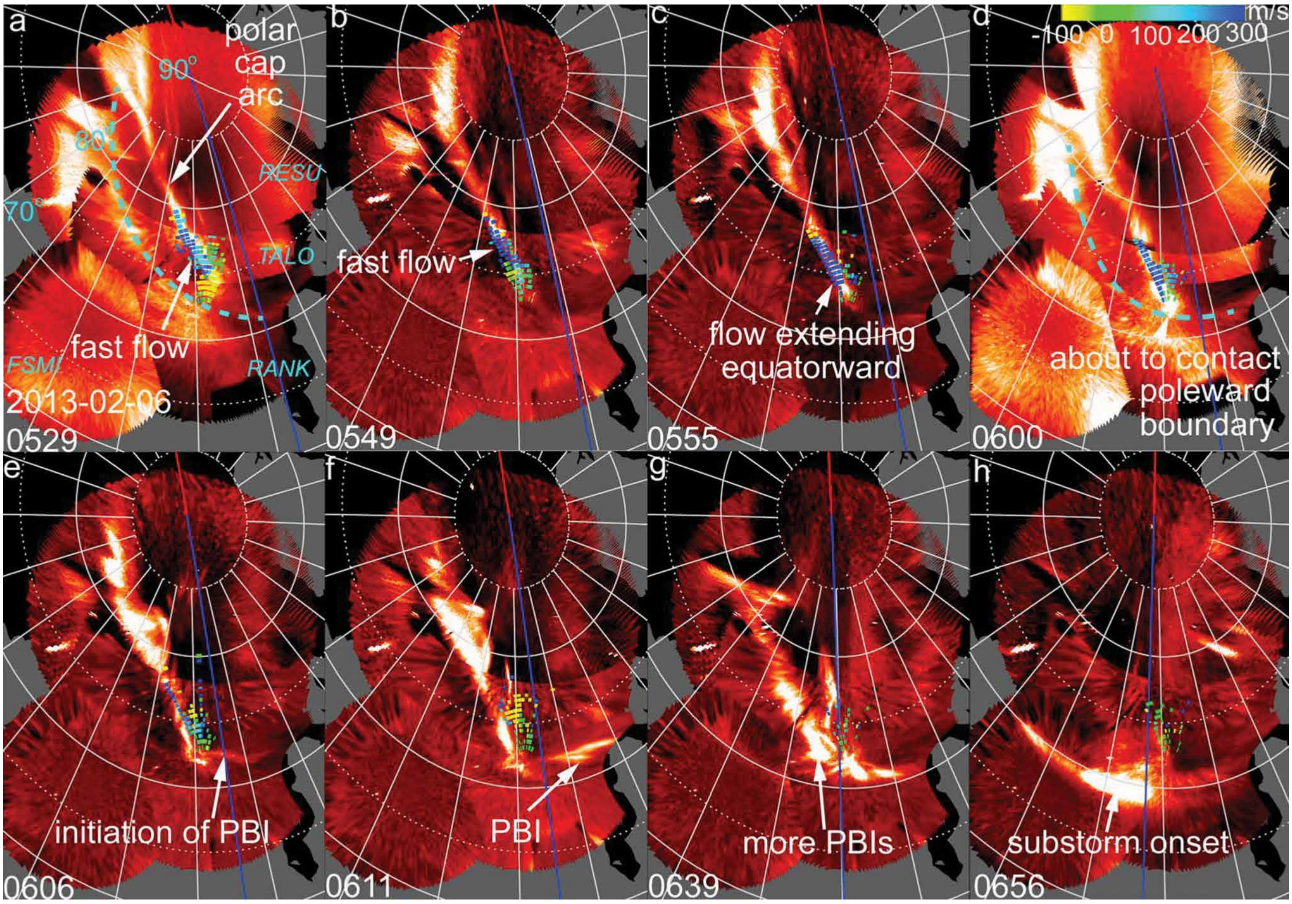
Auroral displays can appear as patches or clouds of light, or they can be seen as arcs, rippling curtains or shooting rays, eerily lighting up the sky. These wondrous light shows are glorious to watch and are high on many people's 'bucket list.' In fact, Dr Ying Zou thinks that auroras don't only serve as Nature's works of art. According to her: 'Auroras not only entertain us, but they also communicate with us, telling us what is happening in near Earth space – we just have to learn how to interpret their language. Studying auroras is truly the most romantic profession I can think of.' And that is exactly the research she and Dr Nishimura have been working on, finding out what is happening in space that makes it possible for us on Earth to see the beauty of the auroras. This approach has the great advantage of grasping the state of space through imaging and radar remote sensing techniques.

Everyone Talks About the Weather – But Space Weather?

The dynamic flowing and ebbing of energies in the space around the Earth – space weather – has significant effects on our life here on Earth. 'Space weather phenomena have large impacts on human life through disturbances of radio communication and spacecraft operation,' explains Dr Nishimura. High-energy plasma particles shot to Earth by the Sun can bombard delicate electronic instruments and even cause energy fluctuations in the electrical grid, causing massive power outages.

For example, in 1989 a massive solar storm struck the Earth, knocking out power in Québec, Canada, for hours, interrupting transmission from NASA and other satellites, and even interfering with communications vital to an on-going UN-Australian military peace keeping operation on the African continent. The Northern Lights caused by this storm were seen as far south as Texas and Florida in the United States. This space weather and these types of potentially disastrous effects are caused by the effects of those high-energy particles that make up the plasma stream from the Sun called solar wind and their interaction with the Earth's magnetic field, the magnetosphere. The plasma particles are charged and therefore can be affected by the Earth's magnetic field, causing massive energy flows and shifts that essentially produce near-Earth space weather conditions.

‘Auroras not only entertain you, but they also communicate with you, telling you what is happening in near Earth space – you just have to learn how to interpret their language’ – Dr Zou



Snapshots (630.0 nm) showing the association of a polar cap arc to poleward boundary intensification activity within a thick auroral oval on 6 February 2013. Y Zou, Y Nishimura, LR Lyons, EF Donovan, K Shiokawa, JM Ruohoniemi, KA McWilliams, and N Nishitani, J. Geophys. Res. Space Physics, 2015, 120, 10698–10711.

The scientific community has made tremendous progress on understanding and forecasting this space weather in recent years. However, Dr Nishimura says one big challenge right now is the capability to predict sudden energy releases and particle acceleration processes. These often start in a localised area in space, but it has been very difficult to pin down their energetics. More specifically, it is hard to figure out how the solar wind coming to Earth on the dayside – the side where energy from the Sun first reaches – transfers its energy to the night-side of the Earth – away from the Sun – and then releases a large amount of energy to the Earth’s atmosphere. Some of this energy can be seen – as the auroras. Dr Zou adds: ‘Although the location and activity of the global-scale auroral activity has been correlated well with solar wind driving, when and where individual auroral arcs, for example, intensifications along the poleward boundary of night-side aurora oval, brighten is not well explained.’ In other words, why do the auroras pop out in particular areas and not in others?

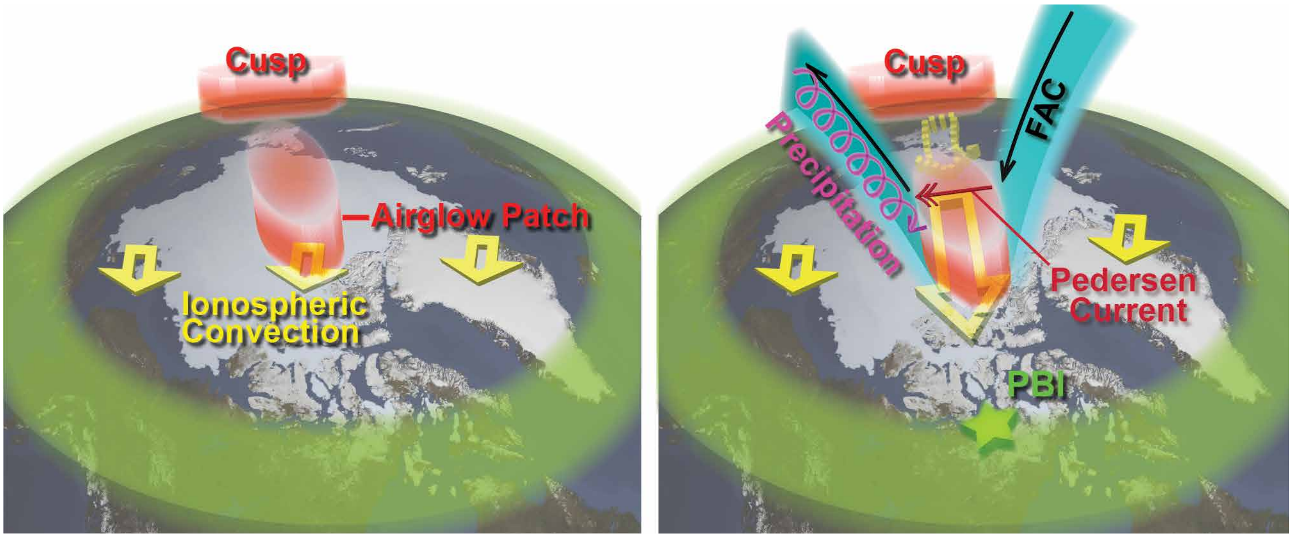
Dr Nishimura, Dr Zou and their colleagues are hot on the trail of the mechanism by which these energy flows somehow trigger auroras. They have some promising data showing how the energy flows across the regions around the Earth’s poles called polar caps, giving them an idea of how the system works.

Predicting Night-side Auroras

To actually understand how the energy flows through the magnetosphere and causes the auroras, these displays must be observed from different locations across the globe to determine how the energy gets from here to there. Drs Zou and Nishimura’s group is using a network of imagers and radars to follow the energy and map out how it flows from the solar wind, from dayside to night-side, where the auroras shimmer and shine.

In a paper published in the journal Geophysical Research Letters, Dr Nishimura, Dr Zou and their colleagues reported on data derived from their observations of the dayside, polar cap, and night-side auroras using three all-sky imagers (from the Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, Optical Mesosphere Thermosphere Imagers (OMTI), and University of Oslo), two Super Dual Auroral Radar Network (SuperDARN) radars, and Defence Meteorological Satellite Program (DMSP) satellite. They found that a dayside aurora moving toward the pole evolved into a diffuse glow called polar cap patch that then propagated across the polar cap and then activated a large, bright, night-side aurora along the poleward boundary of the night-side auroral oval. The SuperDARN observations showed fast flows away from the Sun associated with the dayside bright aurora, and the DMSP satellite measured

‘We discovered a new mode of energy transport from dayside to night-side, and its importance to triggering night-side energy release processes that create auroras’ – Dr Nishimura



increased precipitation of energetic particles and enhanced plasma density with a strong flow burst moving away from the Sun.

The polar cap patch coincided with a narrow flow channel away from the Sun as well. The propagation across the polar cap and the subsequent night-side auroral flares told the group that the channel of energy flow originated from dayside and then reached the night-side, triggering a localised energy release in the night-side magnetosphere. Dr Nishimura explains this: ‘We discovered a new mode of energy transport from dayside to night-side, and its importance to triggering night-side energy release processes that create auroras. This finding opens up a possibility of predicting night-side aurora brightening by tracing localised transient energy flow from dayside to night-side.’

A Tedious but Rewarding Process On-going Still

Besides these first observations of energy transport from dayside to night-side and aurora triggering, which were done by simultaneous imaging operations in Europe and North America, the group has also made several other significant discoveries. They have carried out a statistical study of energy transport from dayside to night-side and its relation to the interplanetary magnetic field. Their findings, which were published in the Journal of Geophysical Research: Space Physics, indicate that the polar cap patches moved across the pole from dayside to night-side pretty much in unison with localised plasma flows across the pole. Essentially, if you watch how patches move, you can tag areas of the sky that carry a large amount of energy from the solar wind.

In the same journal, the team reported specific imaging of night-side auroral triggering, determining that the auroras were probably triggered by plasma flows over the pole, rather than simply coincidentally being in the same area. Further, they determined where the energy required to power auroras is stored. In a pair of papers looking at numerical simulations of day-night energy transport and night-side auroral triggering, they offer a better understanding of the processes involved in the flow of the energy that creates beautiful auroras.

Where Do They Go Next?

Now, according to Dr Zou: ‘We will examine the dayside source process of the intense night-side aurora triggering. This is where the solar wind interacts with the Earth’s magnetosphere transferring mass, momentum, and energy into the magnetosphere.’ She says this interaction often generates rapid anti-sunward directed flow bursts in the conjugate dayside ionosphere, some of which can propagate thousands of kilometres away over an hour-long period to the night-side auroral oval, triggering night-side auroras. They are interested in what solar wind conditions drive the formation of these flow bursts, what controls the flow shapes and sizes, and what determines how far the flows propagate towards night-side. This kind of information will be an essential component of their proposed day-to-night coupling system. They want to nail down every step involved in how the energy gets from the Sun to generating the aurora, and investigate why are they triggered the way they are.

‘We started this aurora research by looking at the night-side polar region, where the aurora is most commonly seen,’ Dr Nishimura tells Scientia. ‘But the ultimate energy source of the auroras is in the solar wind, on the dayside of the Earth, so our exploration has been to search and walk against the flow of energy.’ In other words, they are tracking the energy backward, against the flow, from the aurora to the solar wind (and therefore the Sun). So far, they have just reached the source of the flow on the dayside and found the path, so their research will further look at the behaviour of the energy flow from the solar wind to the dayside of the Earth. But auroras aren’t the only phenomena of interest. They aren’t the scientific end game.

Another important direction their research is heading – in fact, perhaps the most important direction – is using their newly acquired knowledge to better qualify and quantify Space Weather. There is still a long way to go before they can predict radio communication disruptions, satellite operation disruptions, or power grid failures, but that is the ultimate goal. Dr Nishimura, Dr Zou and their colleagues feel that we as a community should keep moving forward in our description and understanding of Space Weather phenomena, both to better understand the beauties of Nature, and also for our own self-defence.

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Dr Toshi Nishimura received his training in Geophysics from Tohoku University in Japan. Here, he achieved his PhD in 2009, for a thesis entitled 'Evolution of convection electric fields in the magnetosphere during geomagnetic storms and substorms.' Dr Nishimura went on to a JSPS Research Fellowship at Nagoya University and then moved to UCLA in California as a visiting scholar and then as a research scientist. He received a James B. Macelwane Medal from American Geophysical Union in 2016. He joined the faculty of Boston University in 2016, where he is currently Research Associate Professor in the Department of Electrical and Computer Engineering and a member of the Center for Space Physics, where he is actively engaged in studying a variety of topics in Space Science, particularly aurora and upper atmospheric phenomena.

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Dr Ying Zou received her baccalaureate in Space Physics from Peking University and then did her graduate work at UCLA, where she received her PhD in 2015. She received Jacob Bjerknes award from UCLA in 2015. From 2015 to 2017 she was a postdoctoral scholar at UCLA, and in 2017 she joined the staff at Boston University where she is currently a research scientist with the Center for Space Physics. She has been selected for a Jack Eddy postdoctoral fellow in 2017. Dr Zou's present research interest is the mechanism of the auroras, particularly those arising from currents flowing around the polar caps.

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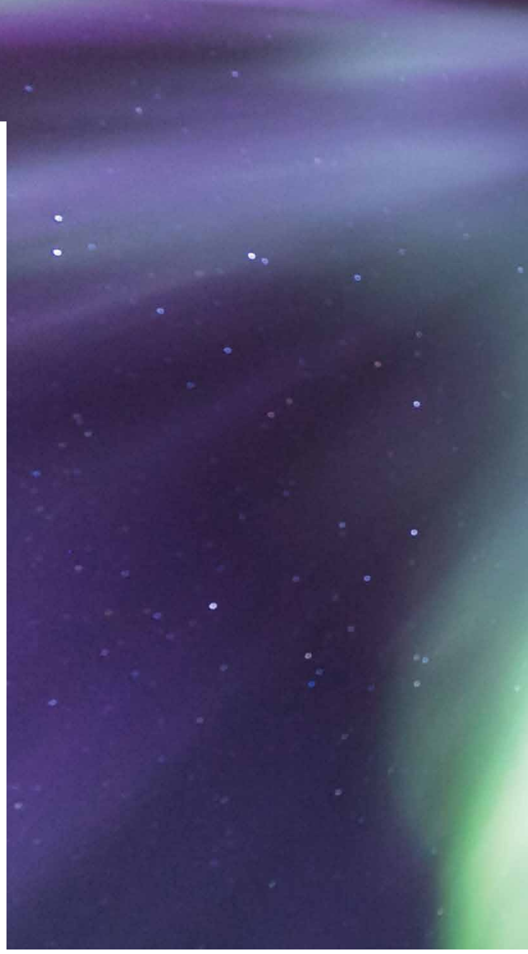
FUNDING

NSF
NASA
U.S. Air Force Office of Research
Canadian Space Agency
International Space Science Institute in Beijing



EXPLORING HOW THE LOWER ATMOSPHERE INFLUENCES SPACE WEATHER

Professor Jeffrey Forbes and his team at the University of Colorado use data from multiple satellites and global modelling to determine how terrestrial weather affects the near-Earth space environment.

When we think of the weather, we think of the wind and rain and the climate generally – down here close to the ground. Perhaps some weather happens up in 'the sky', where we see jet airplanes leaving contrails amongst the stratus clouds. But higher than that and we get into space, where satellites and meteors travel out of our sight. We think of weather down here as different and separate from space up there. But that would be a mistake. There's a lot going on in space, particularly close to the Earth's atmosphere, and our weather influences the conditions in near-Earth space to a great degree.

The Earth's atmosphere itself is a complex and dynamic system that can be thought of as existing in layers, each layer having different temperature characteristics. Closest to the ground and what we usually think of when we talk about the weather is the troposphere, comprising about three quarters of the atmosphere and reaching between 10 and 15 kilometres from the surface. Next is the stratosphere, which contains the ozone layer, buffering us against most of the ultraviolet rays from the Sun. Above the stratosphere lies the mesosphere – beginning at about 50 kilometres above the surface and the coldest layer of the atmosphere. Then there's the thermosphere, the layer that encompasses the ionosphere, where molecules are ionised by solar radiation, above about 90 kilometres from the surface. And finally, there's the exosphere, the extended layer at the very top of the atmosphere where particle collisions are infrequent. In an aerospace context, the 'line' between the atmosphere and space is roughly about 100 kilometres above the surface, and is known as the Kármán line. Scientifically, this is where things get interesting, because Earth's magnetic field begins to exert its influence.

Well above the ionosphere, charged particles emitted from the sun – the solar wind – interact with the Earth's magnetic field – the magnetosphere – to initiate a chain of events that ultimately deposit energy into the high-latitude regions of the ionosphere and thermosphere and form a complex system of 'space weather'. In this region, fluctuations in space weather conditions can cause an array of problems here on Earth, such as power outages and the disruption of communication systems. It is in this region that Professor Forbes and his colleagues focus their attention. 'Our research entails studying how traditional weather and other lower-atmosphere processes influence this region through the vertical propagation of waves,' he explains. 'We also investigate how disturbances on the Sun influence this region through extreme ultraviolet radiation and through massive ejections of charged particles from the Sun that interact with Earth's magnetic field to deposit energy.'

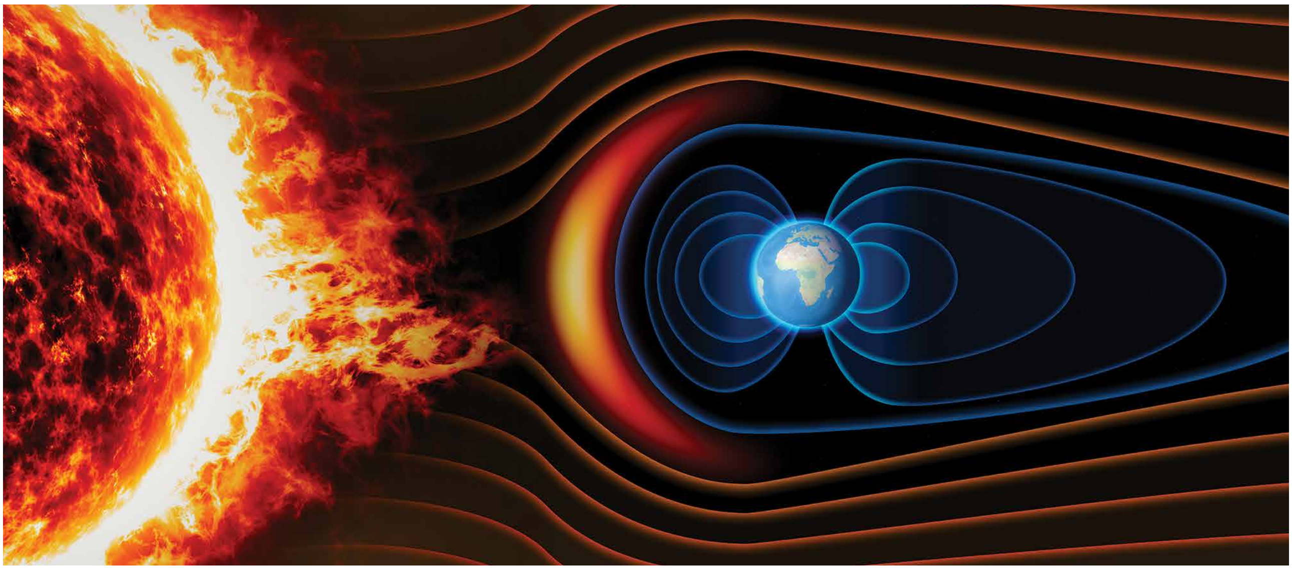
Getting Started by Fantasising About . . . Rockets?

Together, the interaction between the various atmospheric regions and the ionosphere is what Professor Forbes regards as one big 'Atmosphere-Ionosphere system', or 'A-I system'. He calls the region of the A-I system that stretches from between about 80 and 150 kilometres from the surface the 'atmosphere-space interaction region'. This is where much of the energy from the Sun and near-Earth space environment – often called 'geospace' – is transferred to the atmosphere, and where vertically-propagating waves interact with the Earth's magnetic field to generate electric fields that oscillate about in the higher altitudes and transport charged particles. Originally, though, Professor Forbes wasn't planning to study the atmosphere and space weather.

Professor Forbes tells Scientia that he was doing his undergraduate work in engineering at the University of Rhode Island when he

fortuitously spied a poster on a corridor wall showing Professor Bowhill at the University of Illinois peering into an instrumented rocket. The rocket was designed to be launched into, and collect data from, the upper atmosphere. 'Less than a year later, I found myself at the University of Illinois and thoroughly enjoying

'This field of study is interdisciplinary, requiring the study of atmospheric dynamics, electric and magnetic fields, chemistry, and collisions between neutral and charged particles'



my study of the upper atmosphere,' says Professor Forbes. Bowhill made a big impression on Professor Forbes, who says that 'after I viewed what Professor Bowhill's life as an academician looked like, I knew that this was what I wanted to do for my career.'

From engineering in Rhode Island and Illinois to meteorology at MIT to the physics of atmospheric solar tides at Harvard, Professor Forbes didn't scrimp on training broadly for this career. One thing he says he loves about this area of science is that 'this field is interdisciplinary, requiring the study of atmospheric dynamics, electric and magnetic fields, chemistry, and collisions between neutral and charged particles.' Together with applying multiple disciplines of science to his work, his purview encompasses the entire planet. To get a proper picture of the atmosphere and its interaction with space weather Professor Forbes analyses satellite-based data, and crunches global numerical computer models. He wants what he calls a 'global perspective'.

The global perspective that Professor Forbes and his team gain from this satellite data is important for reasons that are quite practical. The ebbs and flows of plasma in near-Earth geospace can have significant deleterious effects on the function of many of our communications, surveillance, and geolocation systems, such as our world-wide Global Navigation Satellite System signals. We need satellite astronomical and aeronautical location data to allow us to locate and predict the paths of orbital debris, to allow us to avoid collisions with space junk, and to calculate re-entry paths. Professor Forbes feels that the 'practical relevance of this aspect of space weather to our 21st-century society motivates and intensifies' his desire to understand and predict the weather processes of the A-I system.

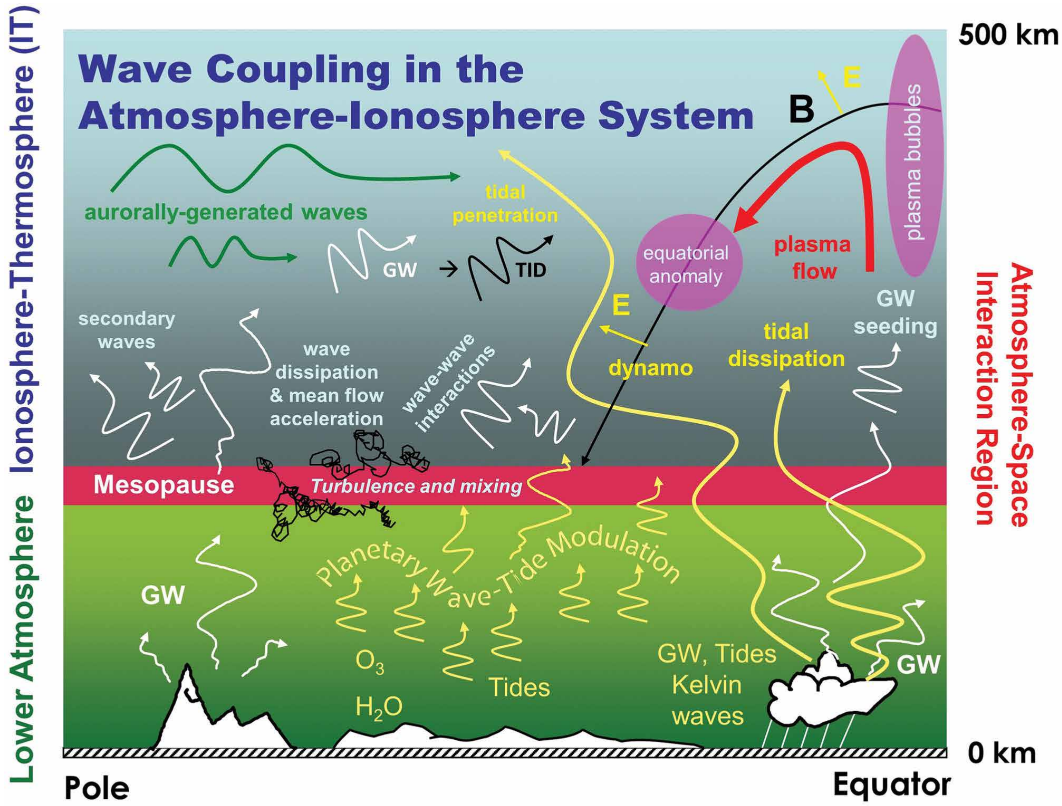
Riding Waves Vertically into Space

We are all familiar with the television weather forecaster's description of such things as high pressure waves, low pressure waves and jet streams, causing this or that weather. These atmospheric waves are important for us here in the troposphere, the lowest part of our atmosphere where weather occurs, but the effects don't stop there. Just as a boat rises and falls as the water waves propagate beneath it, the upper atmospheric levels become disturbed when waves propagate upward from disturbances in the troposphere. Professor Forbes and his colleagues are interested in how lower atmospheric waves interact with and transfer energy to the upper levels of the atmosphere, such as the ionosphere and its ocean of highly charged particles. This is where the rockets come in.

Professor Forbes' work consists in large part on using measurements from the TIMED, CHAMP, GRACE and GOCE satellites – launched by rockets, of course – to get his global perspective of the A-I system and on how the upper atmospheric layers respond to both meteorological influences in the lower atmosphere, and to energy originating from the Sun. His team has been focused more recently on waves that originate at lower altitudes, and how they affect the atmosphere-space interaction region.

The satellites his team use for their data collection have been busy. The TIMED satellite – short for Thermosphere Ionosphere Mesosphere Energetics and Dynamics – is a satellite designed by scientists at Johns Hopkins University and launched by NASA in 2001 to take measurements of the mesosphere and lower thermosphere. TIMED's mission has been extended several times and it still provides vital data. The CHAMP satellite – short for Challenging Minisatellite Payload – was launched from Russia by a German group to measure various parameters in the ionosphere and monitor space weather, before completing its mission in 2010. The GRACE satellite – or Gravity Recovery and Climate Experiment – is a joint mission between NASA and the German Aerospace Centre to measure gravitational anomalies across the globe. Launched in 2002, GRACE data is important in the study of Earth's climate, geology and ocean tides. Finally, the GOCE satellite – the Gravity Field and Steady-State Ocean Circulation Explorer – launched by the European Space Agency, provided data from 2009 until 2013 on gravitational gradients related to ocean currents, the Earth's mantle and volcanic activity.

The analysis of data from all of these satellites has proven invaluable to Professor



Energy and momentum are transferred from one point to another within the atmosphere-ionosphere system through the generation and propagation of waves. In the ionosphere wind perturbations associated with the waves can redistribute ionospheric plasma, either through the electric fields generated via the dynamo mechanism, or directly by moving plasma along magnetic field lines. Adapted from Figure 8.10, Solar and Space Physics Decadal Survey, National Academy of Sciences, 2012.

Forbes and his colleagues in their quest to understand the relationships between Earth's weather and space weather. This work has allowed them to uncover how atmospheric waves propagate upward and cause variations and perturbations in the conditions of near-Earth geospace.

Recently, a PhD student of Professor Forbes, Federico Gasperini, analysed data from the TIMED, CHAMP and GOCE satellites to show that waves excited in the lower atmosphere by tropical heating travel very high in the atmosphere, effectively linking lower atmosphere activity with the atmospheric drag that satellites experience. From his calculations, Gasperini concluded that between from 60% and 80% of the total variability in the thermosphere (during a time when the Sun was relatively quiet) can be traced back to vertical waves from the lower atmosphere, while only 10–20% is due to solar and geomagnetic effects. The remaining 10–20% of the variability was due to other processes that were unclear.

In any event, Gasperini, along with Professor Forbes and his colleagues, has proven that there is a large coupling effect from the lower atmospheric conditions – our weather – and activity in the upper levels of the atmosphere that interact with near-Earth space weather. Not only do the conditions in space – primarily the result of the solar wind interacting with the Earth's magnetosphere – have an effect on Earth's upper atmosphere weather, but Earth's lower atmosphere weather can have a vertical effect on the conditions up there, in geospace. It's a complex and synergistic system that warrants further study. Of course, further study is already in the works.

Plans for Studying Near-Earth Space in the Near-Future

Plans for the immediate future are promising. Professor Forbes has recently been funded by NASA and the NSF to use the Thermosphere-Ionosphere-Mesosphere Electrodynamics General Circulation Model (TIME-GCM) developed at the National Center for Atmospheric Research to numerically isolate the components of the ionosphere/thermosphere system. The TIME-GCM program is a 3-D time-dependent model of atmospheric conditions that reaches from about 30 kilometres above the surface to altitudes of 500–600 kilometres. The model simulates the circulation, temperature, electrodynamics, and compositional structure of the mesosphere, the thermosphere, and the ionosphere. The results of this model will enable the team to construct more specific models that take into account the massive data available from the various satellites. Professor Forbes says they hope this material will help them 'understand wave-wave interactions and other sources of complexity in the A-I system.'

Professor Forbes also plans to spend time using the unique data expected from the upcoming ICON mission. ICON – NASA's Ionospheric Connection Explorer, expected to be launched in mid-2017 – is specifically designed to collect data from the atmospheric levels where Earth weather and space weather collide. This is right up Professor Forbes' alley, and he thinks this mission will greatly advance our understanding of how waves of the lower atmosphere drive conditions in the ionosphere. Beyond ICON, Professor Forbes tells Scientia that his future research 'depends on which of my pending proposals are funded, and what emerges in the field that strikes me as interesting and challenging.' When the sky's the limit, you have lots of options.

Meet the researcher

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Professor Jeffrey Forbes received his PhD in in Applied Physics in 1975 from Harvard University in Cambridge, Massachusetts, for a dissertation entitled 'Atmospheric Solar Tides and Their Electrodynamic Effects'. After a number of research scientist and faculty positions – including service in the US Air Force and Air Force Reserve where he reached the rank of Lieutenant Colonel – in 1993 Professor Forbes joined the faculty of the University of Colorado in Boulder, where he is now Professor of Aerospace Engineering Sciences and holds an endowed chair in the College of Engineering & Applied Science. His research interests include planetary upper atmosphere environments, atmospheric coupling to lower altitudes, geomagnetic storm effects on the variability of satellite drag, and vertical propagation of tides and planetary waves. Professor Forbes has authored or co-authored nearly 350 articles published in peer-reviewed journals and other professional publications, as well as presented numerous papers at scholarly meetings.

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FUNDING

NSF
NASA
US Department of Defence
US Air Force Office of Scientific Research

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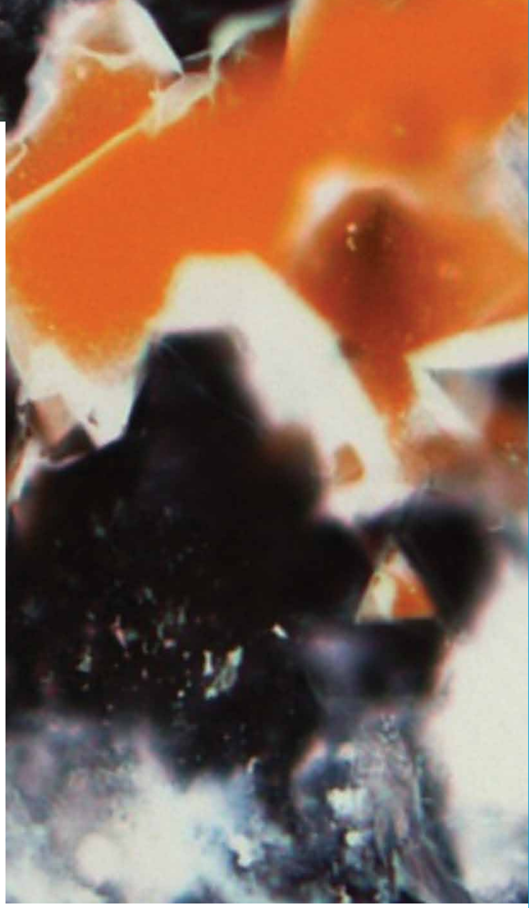
CRACKING THE PUZZLE OF ROCK FRACTURE WITH CRYSTAL CLUES



Drs Stephen Laubach, Jon Olson and **Rob Lander** and their team at The University of Texas at Austin are investigating the relationship between growth of fractures in rock, and chemical processes that occur within and around fracture openings. They are working to construct reliable models that predict how fracture patterns develop deep in the Earth. This builds an understanding of the paths that fluids travel deep underground, which is valuable to industries that extract resources contained within rocks, and to those that store waste materials underground.

The Problem with Cracks

Under the Earth's surface lies thousands of metres of rock layers. Many deeply buried rocks contain fluids that are mobile primarily through fractures. As petroleum resources become scarce and more waste must be stored underground, fractures have been drawing increasing attention from researchers. Scientists ask, 'how do fractures form?' and 'how can we better predict their spatial patterns?'

Structural geology is a broad field encompassing how rocks deform, including how they fracture. It's widely understood that fractures form in response to loads arising from burial and tectonic plate movements. Fracture is a mechanical process, and for decades increasingly sophisticated models based on fracture mechanics guided predictions of fracture patterns. However, Dr Stephen Laubach and his team at The University of Texas have demonstrated that chemical processes may be equally important. Combining mechanics and chemistry, the discipline of structural diagenesis brings these two viewpoints to bear on the problem.

The Subsurface – the Hidden Plumbing

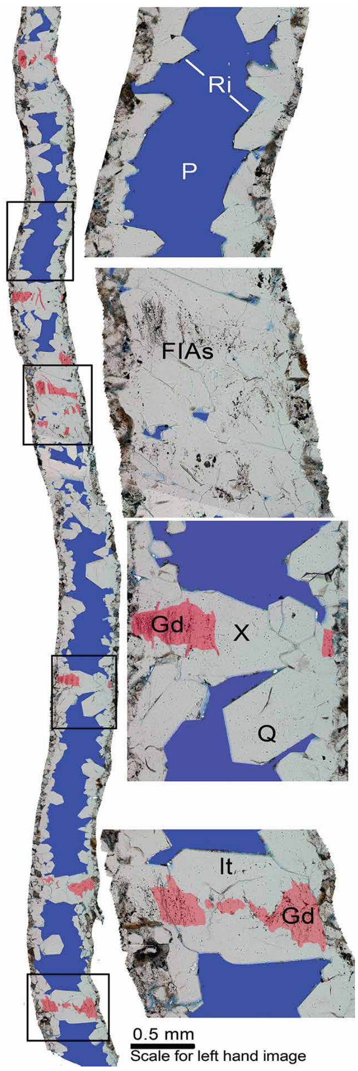
Of course, to study fractures, it helps to have actual examples. As it turns out, this is easier said than done. Geoscientists sample the subsurface with wellbores that can extract lengths of rock core that are about as wide as the fist of a large person's hand. Fractures are narrow, perhaps only a few millimetres wide, but may be hundreds of metres long and just as far apart. The wide distances between fractures, compared to the narrow dimension of rock that can be sampled, leads to a profound sampling challenge.

Engineers know that fracture plumbing is present because deep wells – many kilometres down – occasionally encounter the fracture 'pipes'. These interactions are often marked by the sudden appearance or disappearance of fluid. But just as it would be hard to understand the plumbing of your house by boring a single ten-centimetre diameter tube through the roof into the basement, the plumbing of deeply buried rocks is concealed by the inherent sampling problem. The sampling problem for fractures is so acute that in most cases observations are inadequate for practical purposes.

Why the Solution is to Make the Problem More Complicated

The challenges of thoroughly sampling fracture systems has limited scientists' observations and understanding. Any insights obtained from samples therefore need to be extended with predictive models. Ideally, such models would produce predictions that can be verified with the limited samples of fractures that are typically available to scientists.

Over millions of years, gradual shifts in the Earth produce fractures. Typical 'loads' that can cause fractures to form are well known. These include gradual strains accumulating from plate tectonics, local



Fracture pores (blue) and cement deposits. From Laubach et al. (2016).

‘Fractures are one of those problems that are so simple that they are really difficult’

Kira Diaz-Tushman and Tim Wawrzyniec measure fractures in outcrop. From Laubach & Diaz-Tushman (2009).

loads associated with folding and faulting, and ‘loads’ associated with elevated pore-fluid pressure, which can arise from the same temperature-driven process that convert organic-rich sediments into petroleum. Recently, however, researchers have become increasingly aware that the path to better models is obstructed by a fundamental conceptual problem. Fractures, individually, are too simple.

The problem of individual fractures being too simple is an example of the principle of equifinality, where a given end state – a fracture, for example – can be reached by many potential means, such as a wide range of loading paths. From a mechanics point of view, fractures grow by their walls moving apart and their tips extending into the rock. Based on their shape there is little difference between the fracture in rock caused by pressures associated with gas generation, and the crack in the windshield of your car, yet they form due to different loading paths and the pattern of the ensemble of fractures is likely quite different. Simple shapes record little information about why the fractures formed in the first place. Common types of fractures can form from multiple causes and exhibit no diagnostic relationship with the layers that contain them, or to the faults, folds, mountain building or hydrocarbon generation events that may have created them.

Whereas the shape of a single fracture gives few clues about its origin, different loads may create vastly different fracture patterns. For example, patterns caused by the pressures from natural gas generation could extend over wide regions while those caused by the strains associated with bending in a fold are likely to be localised in contorted parts of layers. These pattern differences would be useful to know.

Because the timing of processes like gas generation and folding can be independently determined using standard methods, choosing the appropriate model for predicting a fracture network would be considerably easier if fractures contained evidence showing when they formed. With timing information, a few samples might be sufficient to compare with the timing of gas generation or folding and to identify the right model.

Aside from being younger than the rocks in which they occur, none of the attributes of fractures that arise from purely mechanical processes record timing information. Thus, fractures would be easier to understand if they were more complicated! As Dr Laubach remarks: ‘Fractures are one of those problems that are so simple that they are really difficult… the more bizarre the crime, the easier it is to solve.’

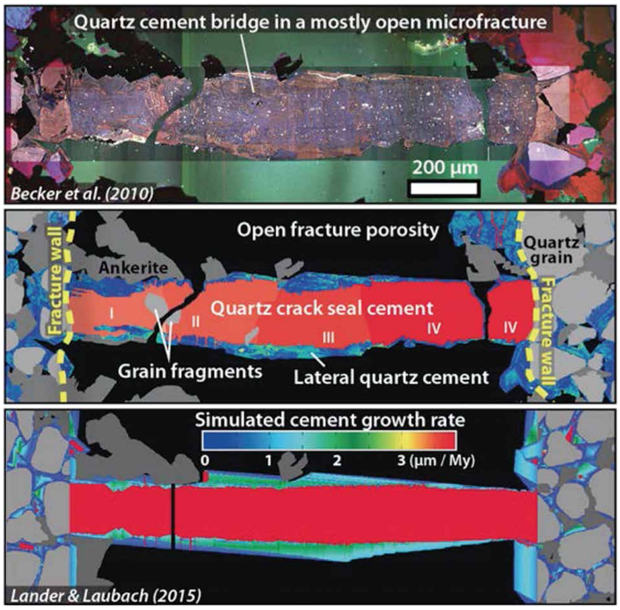
Revealing Subtle Complexity

Dr Laubach and his colleagues have been addressing these difficulties by investigating fracture development in relation to the minerals found in fractures. Hitherto little appreciated, mineral cements that line or fill fractures are widespread. Although such mineral deposits are unsurprising, given that newly formed fractures are reactive surfaces in contact with hot, mineral-laden waters, the internal structures and shapes of these deposits are quite strange and are uniquely informative. These deposits are a key for unlocking accurate predictions of fracture patterns – they are the solution to eqifinality.

The group discovered that cements can form both during and after fracture opening. They observed minute, pillar-like ‘bridge’ deposits that appeared to form while fractures were opening. Within these bridges, complex textures record repeated cracking and resealing of the accumulating cement deposits. Deposits trap miniscule quantities of fluid with each sealing increment, of which there may be hundreds. From these fluid inclusion assemblages, the team could measure temperature, salinity and other chemical attributes of the water, and the presence and type of hydrocarbons. Overlapping and crosscutting textures allowed them to identify the sequence. Thus, using these deposits, the team could elucidate the timing, temperature and chemical history of the fractures.

To understand how the deposits formed, Dr Laubach’s group devised a model of cement accumulation in fractures, compared its predictions to the actual history. They found that their model was able to make accurate predictions, giving them confidence that cement accumulation patterns can be used to unravel the timing and rate of fracture.

The bridges within the fractures are like a genetic sequence, allowing the team to differentiate each fracture from all others. Using evidence from the deposits, the team could show when the fractures started to open, how fast they opened, and when they ceased opening. This type of evidence was then compared with geologic records of loading history and with the output of mechanical models, enabling the team to identify the causes of fracture patterns and validate pattern predictions.



Measuring fracture sizes. From Laubach & Diaz-Tushman (2009).

Although mineral deposits may cause blockages, surprisingly, even over millions of years, some mineral deposits accumulate only minute veneers on fracture walls. The team's model, along with natural examples, shows that because cement deposits initially accumulate very rapidly on only some parts of fracture surfaces, whereas on other surfaces cement accumulates slowly, bridges are surrounded by open fracture pore space. In other words, even though the fractures locally contain rich records of their opening histories in deposits that are continuous from one wall of the fracture to the other, for the most part, the fractures are open and are viable conduits for fluid flow.

Persistent Open Fractures

Everyday experience and engineering experiments show that the fracture process may occur over the very short time periods of human experience, but the team's new research on the accumulation of cement deposits shows that many fracture patterns in the Earth grow in length and develop patterns over millions of years. These results have obvious implications for modelling and predicting fractures in the subsurface.

For example, the team found that in East Texas fractures began opening about 48 million years ago, and that some of these cavities continued to open slowly until recently and remain open to this day. This shows that fractures can, in fact, remain active and open for long periods of time.

Finding Fracture Patterns

While the size and abundance of fractures can tell us about the deformation rock has experienced, fractures can also interact with one another to initiate further activity and growth. They may grow in various directions, become inactive, or branch out and extend. The patterns of fracture size and clustering have marked effects on how rocks conduct fluid flow. Both mechanics and cement deposits affect these patterns.

Within their Basic Energy Science Project (from the US Department of Energy), the team is recreating how natural fracture patterns develop and comparing their results to patterns from models that account for both the mechanics and the mechanical effects of cement deposits. In addition to observing the size and spatial arrangement of fractures, across a variety of geologic formations and settings, they have had to develop new ways to quantify fracture spatial arrangement. Using these new methods, the team found that the growth of some sets of fractures is a self-organised process, in which small, initially isolated fractures grow and progressively interact, with preferential growth of a subset of fractures developing at the expense of growth of the rest.

A Holistic Perspective

Dr Laubach and his team have shown that if we want to find out about the attributes of fractures deep in the Earth, it is worth considering the chemical processes that occur within fractures. They are working towards a unified model of mechanics and chemical change (diagenesis), to better understand how fractures develop under the Earth's surface.

Analysing the mineral cements in fractures using sophisticated imaging techniques can illuminate fracture histories, leading to more accurate fracture pattern predictions. The research shows that cement deposits record fracture timing information that is otherwise unavailable, making the inherently limited samples of fractures more informative and valuable.

One benefit is that samples can be used to validate predictions of mechanical models that predict fracture patterns. Another surprising finding is that even under high-temperature subsurface conditions, fractures can remain open and act as conduits for fluid flow for millions of years. The incredibly slow growth rate of some fracture arrays is something that predictive models need to take into account. Furthermore, the increasing evidence that the cement deposits themselves can alter the type of pattern that develops points to the need for experimental and numerical modelling work to take this coupled process into account. The team's work in this regard will help industries that need to extract substances from the ground, while also deepening our understanding of geological history.

Meet the researcher

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Dr Stephen E. Laubach gained his MSc and PhD in Geology at the University of Illinois-Urbana, after obtaining a BSc from Tufts University in 1978. Dr Laubach is now a Senior Research Scientist in the Jackson School of Geosciences at The University of Texas at Austin. Here, he investigates methods for fracture and stress characterisation, and researches structural diagenesis. This involves supervising graduate student research, and leading the Fracture Research and Application Consortium and the Structural Diagenesis Initiative. He is an active member of various societies – including the American Association of Petroleum Geologists (AAPG), where he served as Elected Editor, Distinguished Lecturer, and on the Executive Committee.

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FUNDING

Research supported by grant DE-FG02-03ER15430 from Chemical Sciences, Geosciences and Biosciences Division, Office of Basic Energy Sciences, Office of Science, US Department of Energy.

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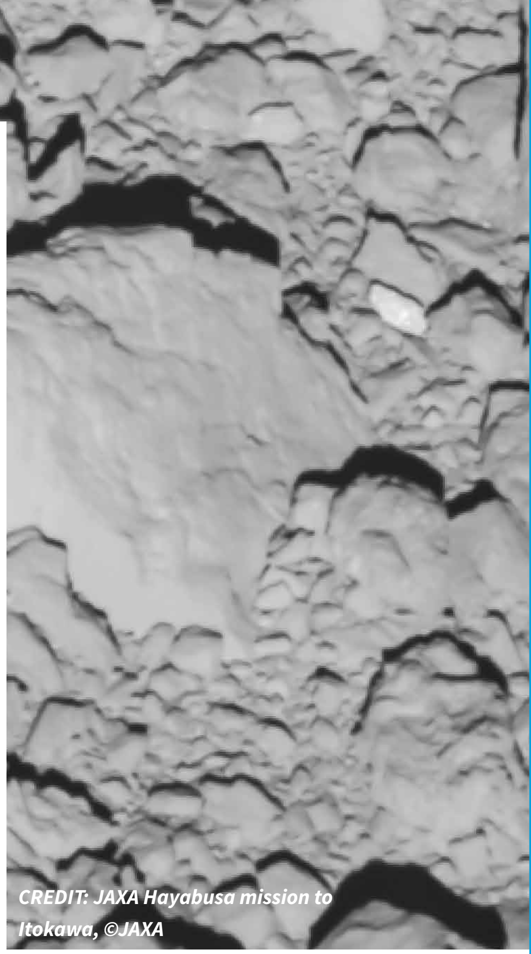
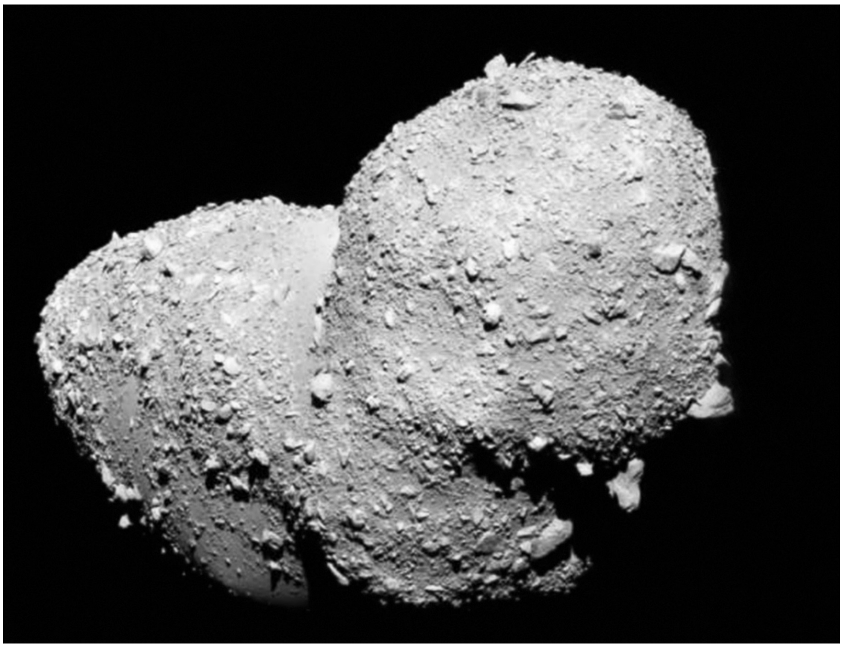
STUDYING THE SURFACE OF ASTEROIDS BY INVESTIGATING POWDER IN THE LAB

Space scientist **Dr Dan Durda** and his team at the Southwest Research Institute in Boulder, Colorado, are working to understand how the planets in our Solar System evolved. The team is searching for practical ways to exploit nearby asteroids, through investigating how materials on their surfaces act in microgravity.



CREDIT: JAXA Hayabusa mission to Itokawa, ©JAXA



Itokawa, CREDIT: ISAS, JAXA ©JAXA

We are not alone in our planetary neighbourhood. Scientists currently estimate that there are almost 17 thousand *near-Earth objects* – astronomical bodies whose orbits bring them to less than 1.3 astronomical units from the Sun. One astronomical unit, or 1 AU, is the distance between the Earth and the Sun (about 150 million kilometres), meaning that objects within 1.3 AU from the Sun are pretty close to Earth's orbit. Of these thousands of near-Earth objects, about 16,600 of them are asteroids – the rest being comets, meteoroids or miscellaneous spacecraft.

Asteroids are practically a fossil record of the solar system, containing material that was around at the very beginning of our Solar System's formation. Therefore, studying asteroids can give us invaluable insights into how our own planet evolved. According to Dr Dan Durda of the Southwest Research Institute in Boulder, Colorado, near-Earth asteroids are 'the most accessible and best-preserved fossil building blocks of the terrestrial planets.'

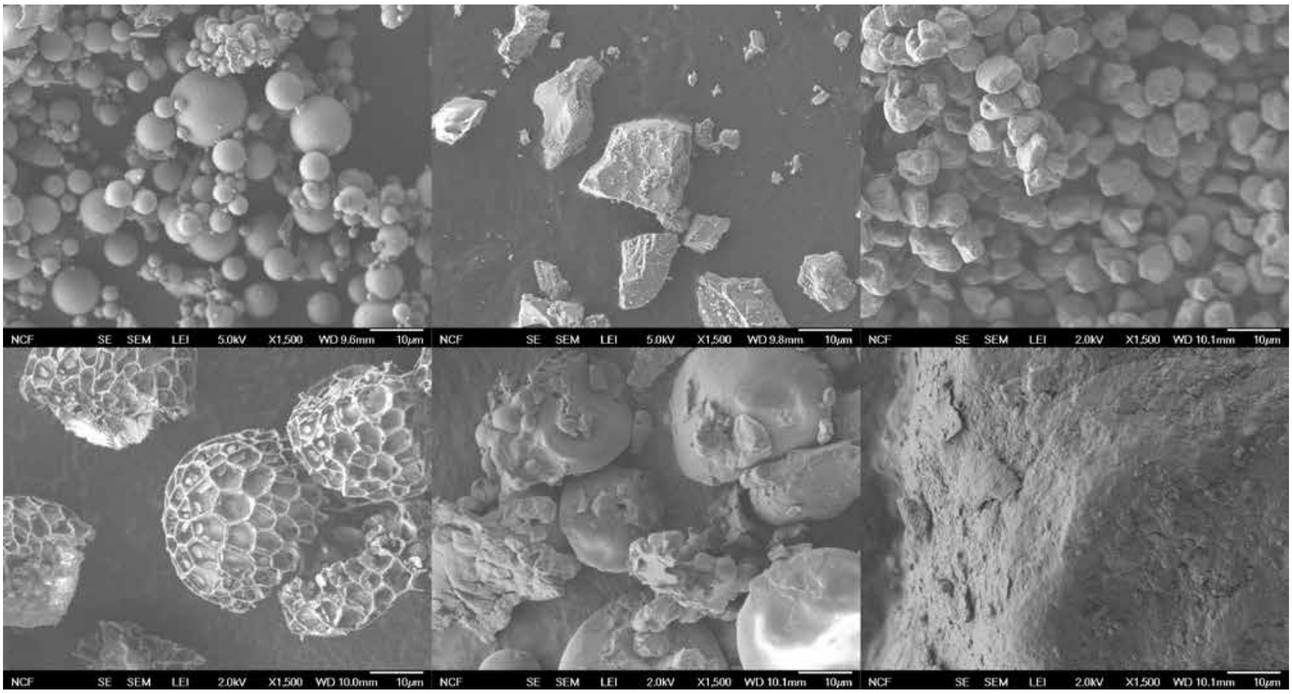
In addition, near-Earth asteroids are close enough that we could potentially mine them for valuable minerals. In Dan's words, they are 'literal gold mines in the sky'. Of course, due to their close proximity, these asteroids also pose the alarming threat of colliding with Earth. Therefore, having a better understanding of these objects might help us in designing strategies to mitigate potential impacts in the future.

But what about that cold, dark rock image that we often see in disaster movies – is this what asteroids really look like? Actually, no. Information provided by spacecraft launched in the last few decades has told us that asteroids are not simply naked masses of rock. For example, the spacecraft *Near Earth Asteroid Rendezvous-Shoemaker* (NEAR-Shoemaker) was launched in 1996 from Cape Canaveral, Florida, the first such mission intended to study an asteroid close up. After a flyby of the main-belt asteroid 253 Mathilde, in 2001, NEAR-Shoemaker orbited and actually landed on an asteroid called 433 Eros – the second largest near-Earth asteroid with a diameter of almost 17 km. Images of Eros show that it is not simply a mass of bare rock – it is covered at least partially with loose layers of gravel and dust, formed as a result of meteor impacts and other space weathering effects.

Similarly, in 2005, the Japanese spacecraft Hayabusa touched the surface of 25143 Itokawa, a small near-Earth asteroid less than 350 metres in diameter. Far from being a solid mass of rock, Itokawa was found to be mostly a loose aggregate of variable sized boulders – what scientists call a 'rubble pile' – that had accumulated over time through collisions of smaller pieces of space debris, perhaps from the break-up of larger asteroids. Hayabusa actually collected samples of dust from the surface of Itokawa and returned it to Earth in 2010. These samples showed that Itokawa was a non-metallic asteroid, having low levels of iron and nickel and being primarily made up of

CREDIT: JAXA Hayabusa mission to Itokawa, ©JAXA

'I've been fascinated with understanding the surface environments of small asteroids from the perspective of human and robotic exploration for many years.'



Scanning electron microscope views of the various powders used in laboratory experiments to explore the cohesive behaviour of granular regoliths on the surfaces of small asteroids.

material consistent with the most common type of rocky meteorites that fall to Earth – minerals present very early in the formation of the solar system.

Standing on Eros or Itokawa would feel somewhat like standing on a layer of sand or gravel – something scientists call 'regolith'. Regolith is a layer of heterogeneous, loose material that covers bedrock. Sand dunes and gravel beds are what we think of when we speak of regolith here on Earth, but now we know that regolith is present on extra-terrestrial bodies, including asteroids. However, regolith on Earth and other planets with atmospheres is quite different from that found on airless bodies such as asteroids, as the latter is almost entirely generated by impacts. Itokawa can be thought of as being entirely composed of regolith, since it apparently has no rocky core.

It is this characteristic of asteroids that Dan and his colleagues try to understand. They study how regolith on asteroid surfaces behaves, so that we might be able to land on and mine asteroids for materials we need to build space stations, or even habitable colonies on other planets.

What Goes Up Must Come Down – to Some Degree

'I've been fascinated with understanding the surface environments of small asteroids from the perspective of human and robotic exploration for many years,' says Dan. 'I think it's a good idea to gain a better understanding of what it's going to be like to work on and near their surfaces.' As mentioned earlier, Dan believes that asteroids are key to learning how the solar system formed and evolved, and they 'will be important in-situ resources for us when we're routinely exploring and navigating the inner solar system.' But there's a problem studying asteroids – compared to the Earth, or even the Moon – they're small.

Here on Earth, we are used to working in Earth's gravity. The acceleration due to gravity here on Earth – denoted as '1 g' – is around 9.8 m/s^2. This means that the speed of an object falling towards the Earth increases by about 9.8 metres per second every second – if we ignore the effects of air resistance. By contrast, gravity on the Moon is 1.6 m/s^2, or 0.16 g. So, a person on the Moon weighs only about 16% of what they weigh on Earth. Recall the images of the lunar astronauts bounding along the lunar surface, seemingly in slow motion, due to the low gravity.

The gravity on Earth dictates how regolith behaves here. Consider sand falling through an hourglass – it forms a roughly pyramidal mound due to the interaction between the pull of gravity and the cohesion of the sand's granules and friction as they rub together. The same can be expected of gravel falling from a conveyor – gravity dictates the shape of the pile because it is stronger than the forces between the particles themselves. But what happens to regolith on an asteroid that is only a fraction of the Earth's size? How do the forces of friction and the adhesion and cohesion of the regolith particles compare to the fairly minimal gravitational force, or 'microgravity', of an asteroid?

The flow and migration of regolith on an asteroid may not necessarily be the same as the flow of gravel or sand on Earth, since the gravity is minimal compared to the forces between the particles themselves. Take the asteroid Eros, for example. With a mass of roughly $7x10^{15}$ kg compared to Earth's $6x10^{24}$ kg, Eros' gravity is many orders of magnitude smaller than Earth's. The forces between particles of regolith on Eros can be vastly more important than the force of gravity that acts on those particles, unlike the situation on Earth. Itokawa is even smaller, with a mass of about $4x10^{10}$ kg, much smaller than Eros.

A collapsed pile of ordinary baking flour shows many features characteristic of self-cohesion between the small constituent grains, such as large clumps and clods, that closely resemble the rubbly surfaces of asteroids. In the microgravity environments of those little worlds such self-cohesive forces might be at play among mm- to cm-scale rocky debris.

This is the problem that Dan and his colleagues face. We need to know how the surfaces and interiors of asteroids move and shift in microgravity in order to fully interpret spacecraft images and to understand how asteroids evolve over time. We also need to be able to either collect smaller asteroids or land on larger ones to use the minerals to support our efforts in exploring space. But studying these unfamiliar microgravity phenomena while burdened with Earth's gravity presents a number of challenges and limitations.

If You Want to Cook Something Up, Get to the Kitchen

The problem of looking at regolith on Earth – in Earth's 1 g gravity – is that the weight of the material is much larger than any forces acting between the particles of the material. One way that Dan's team gets around this problem is to use particles so small – fine powders – that the force of Earth's gravity is less that the forces between the particles of the powders. Cohesive forces such as 'van der Waals attractions' can exceed the gravitational force on very fine particles, thus mimicking the situation of larger particles in microgravity on an asteroid.

Dan's group has considered a number of fine powders for their asteroid regolith simulations, from common kitchen ingredients to high-tech materials. To investigate particles of various shapes and sizes, the group has studied the characteristics of common white and whole-wheat flour, which can be found in any kitchen. They studied these particles in a vacuum chamber at Ball Aerospace under varying degrees of dryness and wetness, heat and cold, all in an attempt to duplicate the structures and features imaged on Eros, Itokawa and other asteroids by NEAR-Shoemaker and other spacecraft.
The team also looked at glass microspheres, simulated lunar regolith material, Colorado desert sand, toner particles used in copy machines, and even pollen from a species of moss. They basically wanted to know what forces make these particles move, shift, and slide under various stresses. What they've found so far is illuminating – and they may have a model for asteroid regolith.

Failure is Not an Option – It's the Whole Point

In an article submitted for publication to the journal *Planetary and Space Science*, Dan and his group report their preliminary work with fine powders, which sheds light on the behaviour of asteroids. They performed a series of experiments looking at the failure behaviour of columns and piles of cohesive fine powders – in Earth's 1 g – as a proxy for regolith on asteroids composed of even millimetre- and centimetre-sized pebbles and cobbles moving in an asteroid's microgravity environment. Starting with symmetrical piles of fine powders and subjecting them to tilt or rotation, the team showed that the piles develop features similar to those observed on asteroids. They demonstrated features such as 'slide planes', finer cohesive structures, and 'fracture planes'. They also observed the formation of steep cliffs that looked like features often seen on asteroids.

The team's preliminary experimental results showed a good correlation with the numerical simulations they devised to describe them. It looks like the microstructure and particle size distribution of the regolith in large part determines the extent of cohesiveness between the particles. The team found better cohesion when they experimented with certain ratios of coarser particles and fine powders.

Dan believes that the wide range of qualitative features and behaviours in his team's fine powder models can reasonably approximate what is seen on the surface of an asteroid as it ages. This work has important implications for understanding the early evolution of our planet, preparing for future missions to asteroids, and even in helping to mitigate a potential asteroid collision with Earth. In any event, it's work that Dan and his group are seeking to expand upon with the help of grant funding for a three-year study of fine powder models of asteroid regolith.

The Ultimate Goal of Asteroid Research

'The problem here generally is that having grown up as a species and as individuals on a large planet with a substantial surface gravity we have no intuitive feel for what it's going to be like to interact with the geology of these things – other planets and asteroids – in microgravity,' says Dan. Of course, we know how to work in spacesuits and with tools in microgravity. We have all seen videos of astronauts in low-Earth orbit fixing the Hubble Space Telescope, for example, or assembling and maintaining the International Space Station. Humans have done geologic fieldwork on the dusty, rocky surface of the Moon. But, according to Dan, 'we've never had hands-on experience with both at the same time.' That's what we have to think about when we finally visit near-Earth asteroids like Eros or Itokawa. The experiments Dan and his group are doing are, in his words, 'a step toward helping to wrap our heads around some of the sometimes-counterintuitive properties and processes of the materials we're going to encounter on the surfaces of these little worlds.'

Meet the researcher

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Dr Dan Durda received his BS from the University of Michigan in 1987, an MS from the University of Florida in 1989, and a PhD from the University of Florida in 1993. Subsequently, he served as a Research Associate in the Lunar and Planetary Laboratory of the University of Arizona and then joined the Department of Space Studies at the Southwest Research Institute in Boulder, Colorado, as a postdoctoral fellow. Since 2001, Dr Durda has been a research scientist at the Southwest Research Institute, although he has also done a stint as Special Assistant to the Associate Administrator of the NASA Science Mission Directorate and served as Adjunct Professor in the Department of Sciences of the Front Range Community College in Westminster, Colorado.

Dr Durda's research interests include the collisional and dynamical evolution of main-belt and near-Earth asteroids, the search for vulcanoids inside the orbit of Mercury, the dynamics of Kuiper belt comets, and the physics of interplanetary dust. Dr Durda has authored or co-authored dozens of articles, both in peer-reviewed journals and other professional publications, as well as in general-interest publications popularising planetary science and human exploration of space. He was also the recipient of the American Astronomical Society's Division for Planetary Sciences 2015 Carl Sagan Medal 'for excellence in public communication in planetary science'. Dr Durda's own space art has appeared in many magazines and books and has been internationally exhibited. Dr Durda is also an instrument rated pilot, flying multiple airframes, and serves as a flight astronomer for the Southwest Universal Imaging System, an airborne astronomical camera system flown aboard NASA and military high-performance, high-altitude aircraft. He has also accumulated almost two hours' time in zero gravity conducting experiments on NASA's KC-135 Reduced Gravity Research Aircraft, famously known as the 'Vomit Comet'.

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FUNDING

The work summarised in this article was funded by a grant from the NASA Planetary Geology & Geophysics Program.

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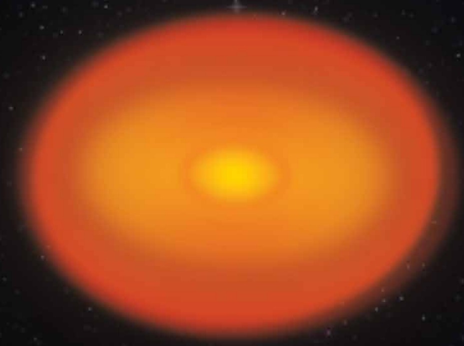
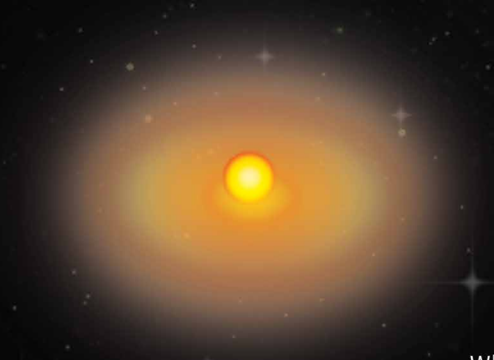
FORMATION OF THE SOLAR SYSTEM

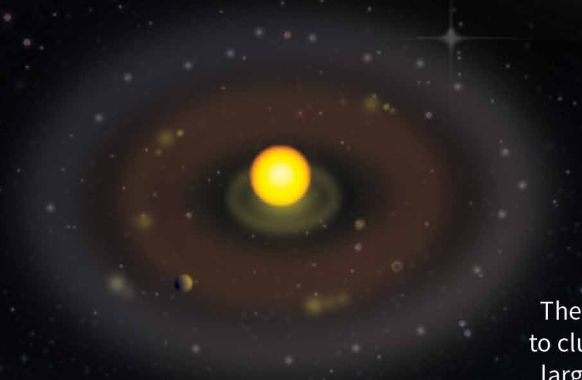
The solar system began to form about 4.6 billion years ago as a rotating cloud of dust containing mostly hydrogen.



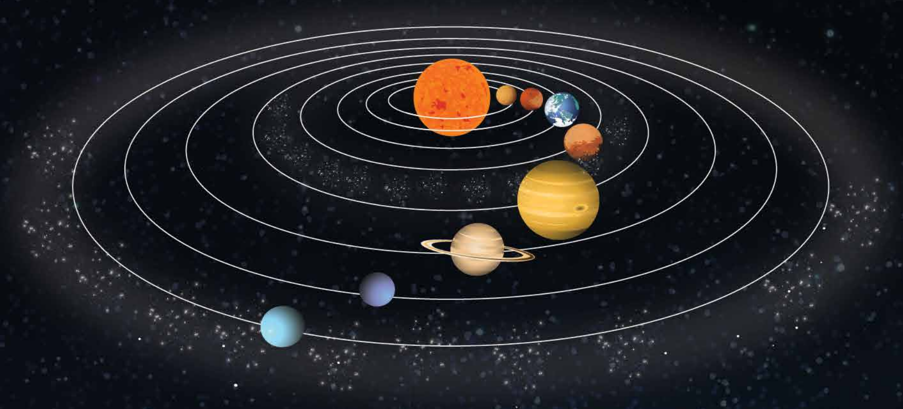
Part of the cloud started to collapse (possibly due to the shockwave from a supernova nearby), resulting in a flat spinning disk of dust and gas.



When enough material had fallen to the centre of the disk, the pressure was so great here that nuclear fusion could begin, and the Sun was born. 99.8% of all the material in the initial disk ended up in the Sun.



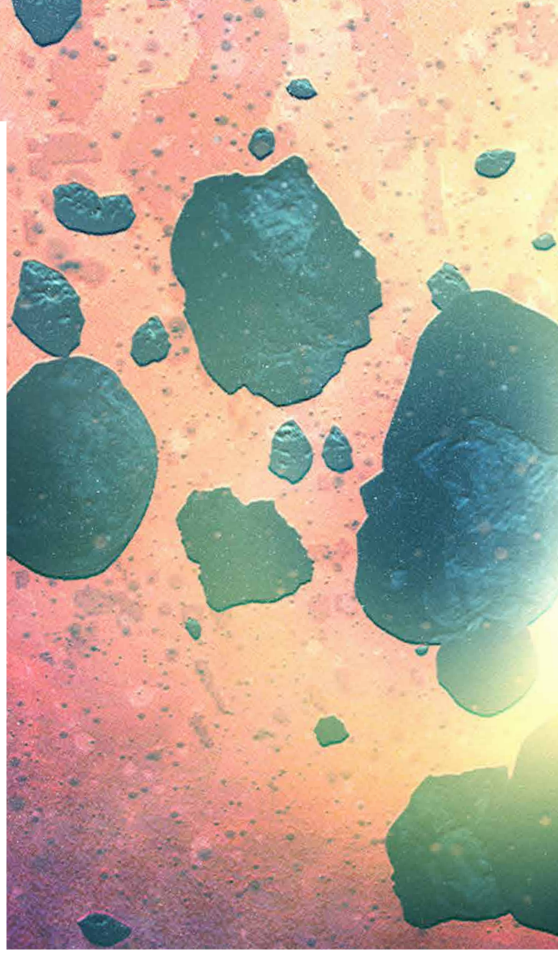
The remaining material started to clump together into larger and larger pieces, which went on to become planets, moons, dwarf planets, comets and asteroids.

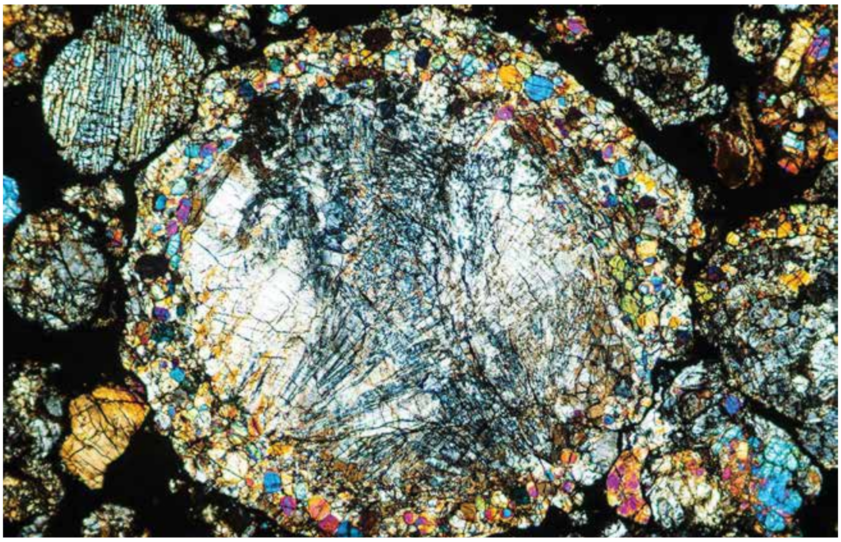


Gaseous and icy bodies couldn't survive close to the Sun, so they collected at further distances than the rocky planets.

REFINING THE THEORIES OF PLANET FORMATION

Science and philosophy are two of the most important pillars of human civilisation. But when it comes to the important questions, is there really much difference between them? Where do we come from? What is the meaning of life? Answers to such philosophical questions can often be scientific in nature, as shown by the work of **Dr Melissa Morris,** who is probing the early stages of how solar systems form.





CREDIT: Laurence Garvie

The Universe and Everything in It

Around 13.7 billion years ago, our Universe burst into being in a titanic event – the very space that we occupy came into existence in a 'flash' of extremely high energy and tremendous heat, before rapidly expanding outwards like an immense balloon. We call this event 'the Big Bang' and we owe our knowledge of it, in part, to Edwin Hubble. In 1929, Hubble discovered that the entire Universe was in a state of expansion and, when we run this process in reverse, the building blocks of every single thing that exists coalesces at a single point in space and time. From its outset, the Big Bang Theory was a controversial one. Many astronomers believed in an opposing idea – that of a 'steady state Universe' – and it wasn't until the accidental discovery of the Cosmic Microwave Background (CMB) radiation, that the Big Bang became widely accepted.

A large proportion of what we know about the beginning of the Universe is based on astronomical observation. Scientists consider what we know – such as the universal expansion discovered by Hubble – and try to fit their theories to these 'constraints'. When a theory can fit all of the known constraints of a system, it is accepted as the most likely explanation. That is, until a new constraint is discovered, or a better theory comes along. The discovery of the CMB radiation provided an additional constraint to the observed universal expansion – one which had been predicted by the Big Bang Theory – and signalled the end of the steady state idea that had been accepted for decades. It is in this manner that scientists build up models of all physical systems.

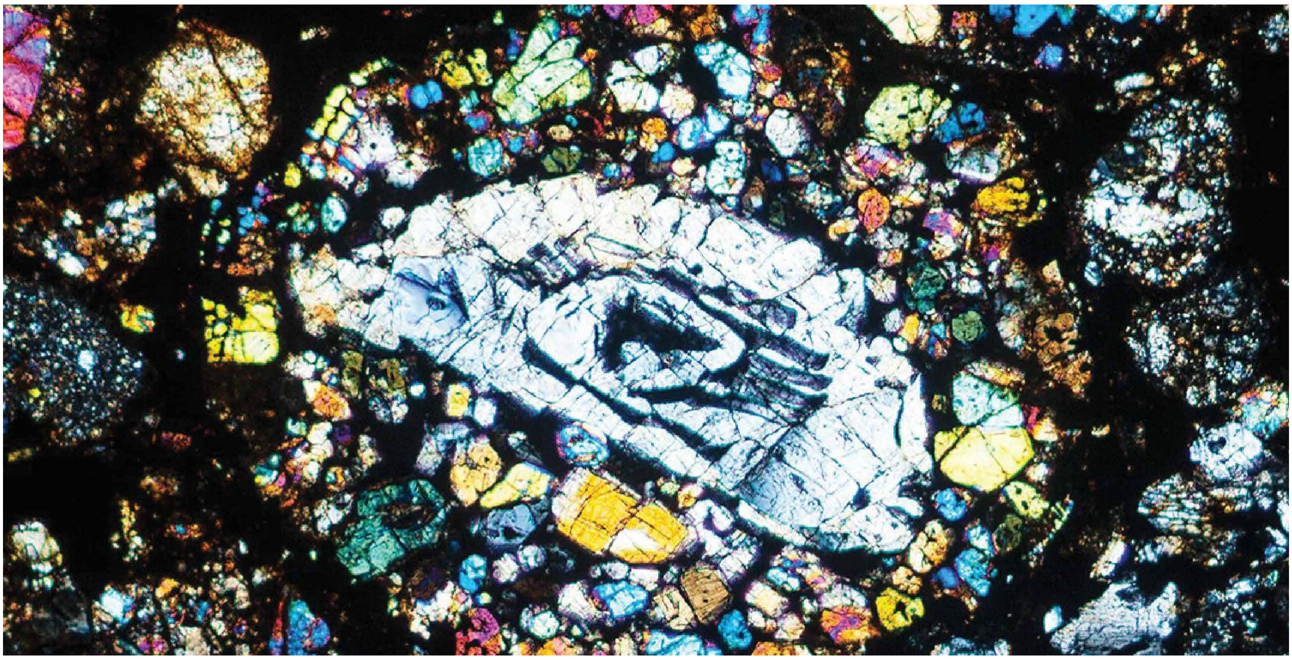
Although information from the early stages of the Universe is scarce, astronomers have managed to provide an account of the circumstances that eventually led to the formation of solar systems like our own. After rapidly expanding into space, the constituent particles of matter slowly began to clump together and form areas of higher density than the surrounding space. Due to the attractive effects of gravity, these higher-density areas pulled in more and more particles, forming large disks of gas and dust that rotated around a central axis. These enormous rotating disks, many of which are hundreds of thousands of light years across, are what we call galaxies today.

Within these galaxies, such as our own Milky Way, vast molecular clouds called nebulae started to collapse under the influence of their own gravity, ultimately leading to the formation of stars, such as our Sun. In the same manner that campers might rub sticks together to start a fire, the friction caused by atoms and dust rubbing together at the core of these rotating collapsed clouds kick-started a process known as thermonuclear fusion, giving rise to a star. The resulting disk of gas and dust rotating around this infant star is known to astronomers as a protoplanetary disk, and it is here that Dr Melissa Morris and her research team are focusing their expertise.

Protoplanetary Disks and Planet Formation

It is well-known amongst astronomers that protoplanetary disks are an integral part of planet formation – many systems that we can view with an optical telescope are currently in this stage and, using techniques such as spectroscopy, we can tell their molecular makeup. Spectroscopy is a method of

‘I try to figure out how planetary systems form – in particular, systems with planets that could support life.’



CREDIT: Laurence Garvie

analysing materials by shining light on, or through them, and measuring what light is reflected back or passes through. It’s impossible to shine light on gas and dust clouds located hundreds of lightyears away, so astronomers typically measure the light from the infant star, or another celestial source, after it passes through the protoplanetary disk.

Each chemical element interacts with light in a unique way based on its atomic structure – absorbing only certain frequencies (colours) of light. As many specific frequencies of light aren’t absorbed by a particular element, we end up with a ‘spectrum’ of light that shows weaker signals at the absorption frequencies, and stronger signals where light isn’t absorbed by the element. Each element in the periodic table has its own ‘optical fingerprint’ and spectroscopy is an extremely useful technique for distinguishing different types of matter throughout the Universe.

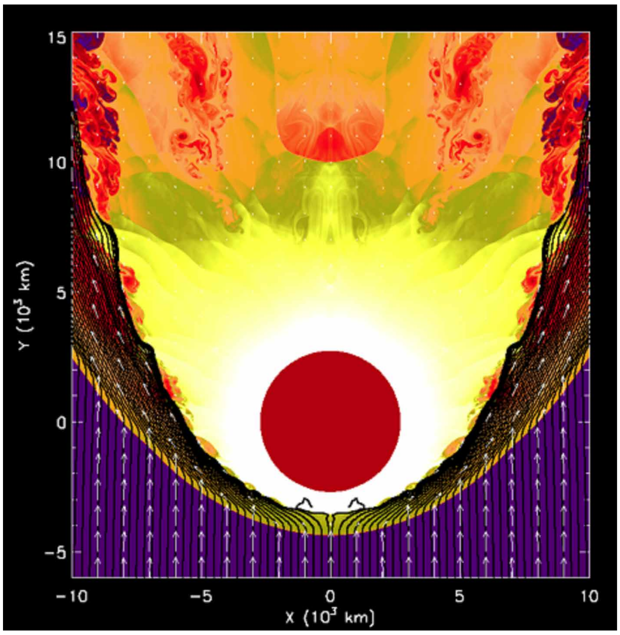
After a few hundred thousand years after the formation of a protoplanetary disk, it begins to change and larger bodies, such as asteroids, protoplanets, and planets, start to form from the dust and gas contained within the disk. This is a problem for astronomers, as techniques like spectroscopy are less effective when the composition of the disk changes from an evenly distributed gas and dust cloud, to a sparser dust cloud containing large solid formations, or ‘planetesimals’. In this situation, the use of spectroscopy as a constraint when modelling the system becomes ineffective – we no longer have enough information to model the system accurately. Our entire understanding of the formation of planets – and their growth – is dependent on our knowledge of the total mass of gas contained within a protoplanetary disk and how it develops over time. During the early stage described here, these quantities are poorly defined and, as a result, current models describing the development of our Solar System have large uncertainties. In order to better understand this stage in our history, astronomers seek out different constraints.

Digging into Meteorites for a Deeper Understanding

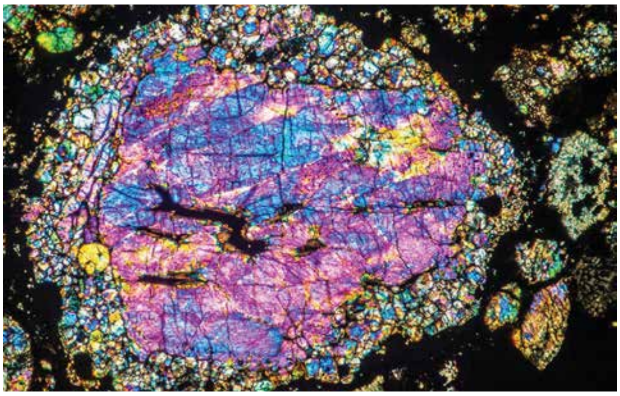
Chondrules are submillimetre-sized spheres of silicate rock that are found in large quantities in meteorites known as chondrites. Understanding how they form could help clear up some of the uncertainties that arise during the early protoplanetary disk stage in our Solar System. One explanation comes from the so-called ‘bow shock model’. Consider a ship sailing across a dark blue sea, or a rock sitting stubbornly in a stream. That apparently unchanging wave that forms on the boundary between ship and sea, rock and water, is a bow wave. Bow waves appear when the fast-moving water particles of the stream, or ocean, have to abruptly slow down when they encounter the front-facing surface of the rock, or ship. In a similar way, when a planetesimal moves through the protoplanetary disk, a shock wave forms at the front-facing surface. This is known as a ‘bow shock’.

The bow shock model demonstrates that chondrules can form under certain circumstances in the bow shock of a planetesimal, moving through its protoplanetary disk, as the relatively free particles of gas and dust bunch-up against its front face. Not only does this cause the particles to slow down relative to the planetesimal, it also causes a dramatic increase in the temperature of the material within the bow shock region. It is thought that this increase in temperature is what causes chondrules to form, by melting the dusty chondrule precursors as they pass the shock front. Until recently, models that simulate the formation of chondrules in this way indicated a cooling rate of around 10 thousand degrees Celsius per hour – far in excess of that needed to match the constraints on chondrule formation.

In her 2010 paper, *Thermal Histories of Chondrules in Solar Nebula Shocks*, Dr Morris updated the large-scale shock model – another shock model used to describe how



CREDIT: Melissa Morris



CREDIT: Laurence Garvie

chondrules might have formed through shocks caused by gravitational instabilities in the disk – by adding a further constraint: the inclusion of molecular line cooling due to water molecules. Molecular line cooling is similar to spectroscopy in that molecular transitions follow the same physical process as atomic transitions to emit or absorb radiation in the form of light, or heat. This transfer of radiation can contribute to cooling the gas, and as a result, can affect how fast newly-formed chondrules cool.

This apparently simple constraint added by Dr Morris and her team, based on extremely complicated mathematics, demonstrates that chondrule formation is, in fact, consistent with observational constraints. In their updated shock model, the team found that the cooling rates needed for chondrules to form was somewhere between 10 and 1000 degrees Celsius per hour, which is in line with what has been indicated by experimental reproduction of chondrules.

In 2011, another research team added a further constraint to the model of chondrule formation. They demonstrated that large planetesimals (around half the size of Earth) were present at the time that chondrules formed. Using this new information, Dr Morris and her team were able to model chondrule formation caused by the passage of protoplanetary disk matter in the bow shocks created by these large planetesimals. They demonstrated that, in principle, a small number of planetesimals could be responsible for producing all of the observed chondrules, without breaking any of the known constraints.

Until recently, all models describing the formation of chondrules made a simplified assumption – all chondrule precursors are the same size. Dr Morris and her team changed this with their paper, *The effect of multiple particle sizes on cooling rates of chondrules produced in large-scale shocks in the solar nebula*, where they demonstrated that if multiple different chondrule precursor sizes are taken into account, heating and cooling rates could be obtained that were in line with observational evidence.

Using samples of the metal-rich Isheyevo meteorite in their 2015 study, *New Insight into the Solar System's Transition Disk Phase provided by the Metal-rich Carbonaceous Chondrite Isheyevo*, Dr Morris' team went on to provide the first evidence of our own Solar System's transition phase. Found in a field in Russia in 2003, the Isheyevo meteorite has unique sedimentary layers of material, implying that it formed through some type of sedimentation process. By modelling this process, Dr Morris and her colleagues were able to show that the gas densities required to produce meteorites such as Isheyevo are consistent with those observed in transition disks, meaning that the studied samples provide the first physical evidence of our Solar System's own transition phase, when the disk went from one composed of mainly gas and fine-grained dust, to one with little gas (but some!) and larger solids.

Life by Proxy: The Search for Extra-Solar Water

In contrast to chondrules, phyllosilicates are minerals that form from the interaction of rock and water. It is a widely held belief in astronomy that where there's water, there might be life. It is, after all, one of the few constraints we have on our only example of a life-bearing planet – Earth.

In one of their earlier studies, Dr Morris and her colleagues showed that, due to the dust ejected from asteroid-asteroid collisions, phyllosilicates should be detectable in other solar systems if liquid water was present at some time. This provides astronomers with the tools for detecting water in solar systems other than our own, and could help focus our search for extra-terrestrial life.

What's Next?

'The logical next steps for my work are to continue to add more relevant physics and chemistry into my models to further constrain important processes in forming planetary systems, including our own,' says Dr Morris. In 2013, Dr Morris received funding from NASA for a project to investigate the possibility of chondrule formation in impact plumes – high-energy ejection of matter that occurs when two planetesimals or protoplanets collide. Another NASA-funded project she is involved with hopes to model the formation of 'igneous rims' around chondrules – a feature assumed to be the result of a second heating event in Solar System formation. Through this future work, Dr Morris and her team will provide yet more insight into the formation of our Solar System and, by analogy, other systems capable of sustaining life.

Our ability to query our own origin is what sets our species apart from all other known life. By pinning down the circumstances that led to the formation of our Solar System, Dr Morris and her team contribute greatly to our understanding of where we come from and what leads to the development of life. But whether we can ever fully comprehend our Universe in all its brilliance and beauty, remains a question for philosophers amongst us.

Meet the researcher

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Dr Melissa A. Morris received her BSc in physics, with a minor in astronomy, from Missouri State University in 2003. She then moved on to Arizona State University to complete a MSc (2007) in physics and a PhD (2009) in astrophysics. Currently at the Physics Department of the State University of New York at Cortland, her research interests include studying the formation of stars and planets by modelling extrasolar protoplanetary systems and the formation of early Solar System materials – such as those found in meteorites. Recently, her work has focused on chondrules – millimetre-sized spheres of igneous silicate which are found in large quantities throughout rocky meteorites known as chondrites. By modelling how these chondrules form, Dr Morris and her team have contributed multiple new insights into the formation of our Solar System. She has extensive experience teaching physics and astrophysics at a variety of universities and has been awarded multiple awards, including Excellence in Research, Scholarship and Outreach in 2015.

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FUNDING

NASA
TACC

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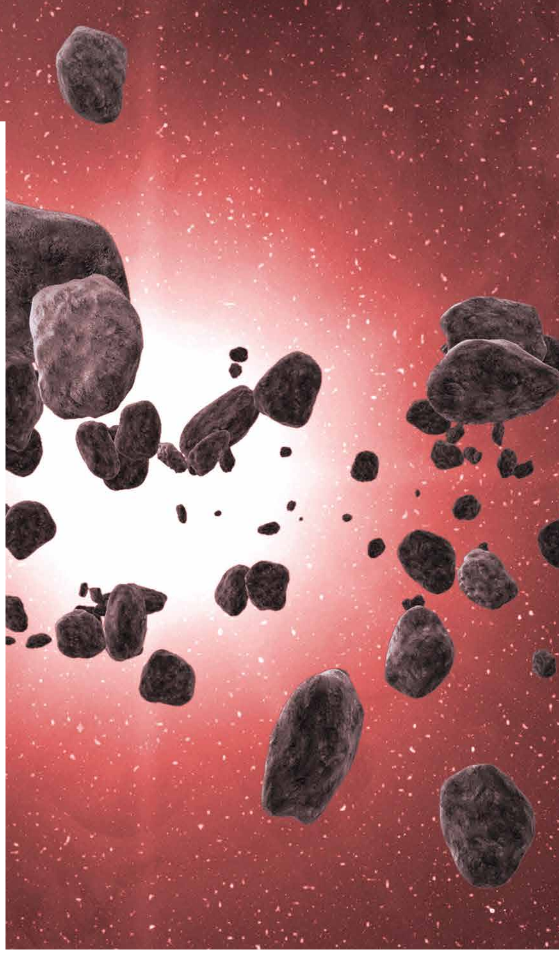
SUNY Cortland



UNDERSTANDING THE EARLY SOLAR SYSTEM THROUGH ISOTOPIC FINGERPRINTS

During the early stages of the solar system formation, the development of molecular organic and inorganic structures occurred through poorly documented mechanisms such as photochemistry or nuclear reactions. Directly probing such phenomena in the laboratory is almost impossible. However, isotopic compositions in lunar soils or in meteorites are chemical fingerprints, which **Dr François Robert** at the National Museum of Natural History, France, uses to resolve these unexplained phenomena.

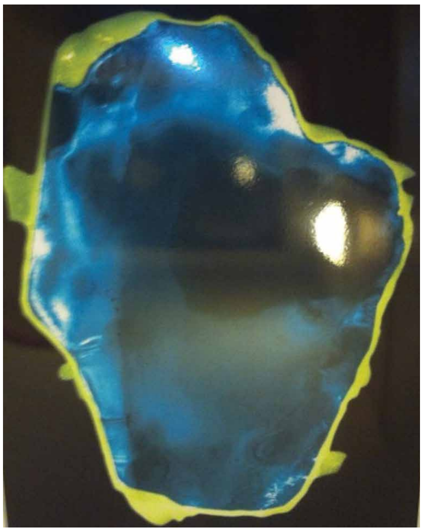
In the fields of geochemistry and cosmochemistry, the study of isotopic composition is used to understand fundamental formation processes of geo- and cosmo-materials. Each element can exist as several stable and unstable isotopes – with each isotope having a different mass. Isotopes of a particular element retain their atomic identity by possessing the same number of protons and electrons, but differ in the number of neutrons they hold in the nucleus. The electronic configurations of different isotopes of the same atom are thus identical, while the total mass of each atom, due to varying numbers of neutrons, is different. Therefore, the mechanisms responsible for variations in the relative abundance of each isotope are restricted to a small number of processes – hence their applicability in reconstructing past natural environments.

During the Sun's formation, a protosolar disk – a disk of high-density gas and grains – surrounds a dense core. These grains are composed of minerals now found within meteorites which retain the isotopic proportions that were present during their initial formation. Thus, meteorites are regarded as chemical archives of processes that governed the creation of the Sun and our solar system.

Dr François Robert has focused his scientific research, through analysing isotope compositions, on resolving the conditions of the formation, chemical composition and age of grains that make up meteorites and lunar soil. Dr Robert explains that 40 years ago when he started his PhD, there were 'no real theories on the conditions of the solar system formation' and that the field of study 'was essentially *terra incognita*'. Nowadays, exceptional technical progress has bridged some gaps between astronomy and geochemistry.

The Origin of Water on Earth

Water is one of the primary components that led to the emergence of life on Earth. However, there is no simple response to the question of where the water on Earth came from. There are three main potential sources of water on the Earth: comets, meteorites and the protosolar molecular hydrogen embedded deep in the Earth during its formation. Dr Robert and his colleagues started by analysing the isotopic variation of hydrogen in a meteorite sample. Hydrogen exists in two stable isotopes – hydrogen and deuterium. Hydrogen atoms contain just a single proton in their nucleus, while atoms of deuterium also possess a neutron. Dr Robert measured significant variations in the abundance of the two isotopes across the meteorite sample, and found multiple sub-micrometric areas that were rich in deuterium. Such an observation could not be recreated by any laboratory experiment or under natural terrestrial conditions. Following this discovery, he found that clusters of Insoluble Organic Matter (hereafter IOM) were the primary source of these deuterium-rich regions. In addition to IOM, meteorites contained ice yielding clay minerals during a high temperature episode of liquid water circulation in meteorite parent bodies. Dr Robert quantified the deuterium content in water that had been circulated in meteorites, and found this to be closely related to terrestrial seawater.



Lunar grain: the implantation of solar atoms has created an amorphous zone surrounding the grain (in yellow – false colour). Scale: 2x2 µm

When passing in close vicinity of the Sun, the ice surface of a comet vaporises, and scientists can measure the isotopic composition of this gaseous water. Such measurements have shown that, with few exceptions, the deuterium composition in water from a comet's tail is much higher than that measured for meteorites or terrestrial water. In contrast, the isotopic composition of hydrogen in the Sun (which is implanted in the Lunar soils by the solar wind), is much lower than that measured for meteorites or terrestrial water.

'My work is based on one analytical tool: the variations of stable isotope ratios of the volatile elements in natural environments – that is the fields of geochemistry and cosmochemistry'

Methane plasma

Therefore, several conclusions on the origin of water on Earth can start to be made from the observations made by Dr Robert and his colleagues on the deuterium concentration in comets, meteorites and terrestrial seawater. Firstly, comets are likely to have had a negligible contribution (less than 10%) to water on Earth. Secondly, the possible occurrence of the protosolar molecular hydrogen deep in the Earth is negligible in the Earth's water budget. Thirdly, most water on Earth probably came from the early addition of water-rich meteorites, present among the accreting bodies that formed the Earth. This last point currently remains a robust constraint in planetary formation models.

To understand the origin of the enrichment in deuterium in meteorite water, Dr Robert proposed that an isotope exchange reaction took place between the protosolar molecular hydrogen gas and the deuterium-rich interstellar water ice vaporised in the protosolar gas. He and his colleagues further confirmed this proposition by measuring the rates of this exchange in laboratory experiments, and by developing a 2D theoretical model of the protosolar disk, which highlighted a gradient of deuterium content between the deuterium-depleted centre to the deuterium-rich edges. Data on comets shows, with limited exceptions, that this result is qualitatively correct.

Growing Organic Compounds in Meteorites

There are several theories behind the origin of IOM in meteorites. One theory posits that this matter was created through gas/grain reactions at −200°C in interstellar space, while another proposes that it was formed from a carbon rich gas under intense UV fluxes within the centre of the protosolar disk. Dr Robert and his team recently demonstrated, through experimental deposition in a plasma of methane, that the latter explanation was indeed compatible with the origin of IOM in meteorites. The organic deposition of methane using microwave-assisted technology was shown to produce similar hydrogen isotopic anomalies as those observed in meteorites. Thus, the team concluded that methane breaks up into $CH_x\cdot$ radicals, which propagate reactions that lead to IOM formation in meteorites.

Several analytical approaches have shown that IOM in meteorites is enriched in deuterium compared with water. Dr Robert realised that in order to explain the origin of this, the structure of the IOM must first be resolved. He devoted a decade of research to elucidating the structure of the organic matter in meteorites. His team found that the structure comprised aromatic and aliphatic molecules and chemical linkages, including sulphide bridges (-S-), ester (-O-) and carboxylate (-O=C-O-) groups. 'We discovered that, at a molecular level, the internal isotopic compositions of the IOM (i.e. between aliphatic, aromatic and benzylic bounds) is also in an opposite distribution compared with thermodynamical predictions,' explains François Robert. A possible solution to this issue is the aforementioned condensation of radicals in plasma, for which the isotopic compositions of organic matter is not dictated by statistical situations.

Nuclear Reactions in the Solar System

During the formation of a new star, high energy hydrogen atoms are generated. When these hydrogen atoms subsequently react with nearby solid species, a series of nuclear events called spallation reactions can become initiated. Spallation reactions result in new elements being created through the break-up of heavier elements. Using an analytical instrument called a secondary ion mass spectrometer (SIMS), scientists can determine the isotopic composition of each element in a sample with sub-micrometric spatial resolution. The method works by separating fragmented and charged ions, according to their mass and charge.

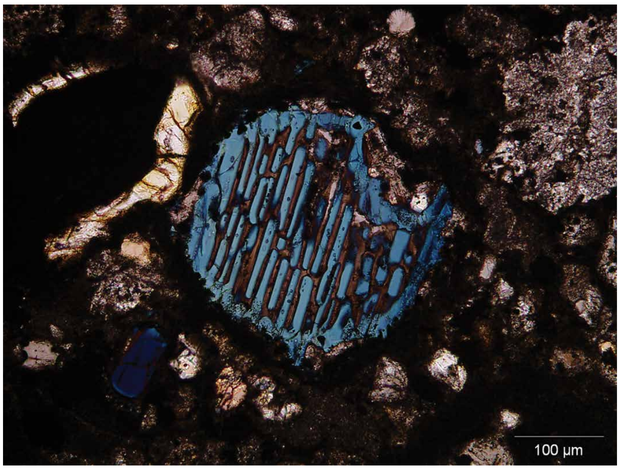
Dr Robert and his colleagues used SIMS to analyse the isotopic compositions of lithium and boron in meteorites. The unstable beryllium 10 isotope (^{10}Be) – containing four protons and six neutrons – is known to only be observed following a high-energy spallation reaction as it rapidly decays into the stable boron isotope ^{10}B – containing five protons and five neutrons. The team discovered an excess in the concentration of ^{10}B in a refractory mineral of a meteorite and showed that this high concentration is due to the decay of ^{10}Be. Therefore, spallation reactions were occurring in the close vicinity of our Sun during its formation.

Studying the isotopic composition of lunar soils can also shed light on the mechanisms behind element creation. Strong solar magnetic winds result in the expulsion of atoms that are implanted into lunar soils. Dr Robert and his colleagues reported a comparative analysis of nitrogen and lithium isotopic compositions within lunar soils and terrestrial materials. Nitrogen exists has two isotopes: ^{14}N and ^{15}N. After the team analysed the lunar soil and meteorite grains, they found that meteorites and planetary atmospheres are surprisingly much richer in ^{15}N than the Sun. The chemical or physical processes at the origin of this isotopic segregation of the volatile elements between the gas (presumably reflected by the Sun) and the solids (presumably reflected by meteorites and planetary atmosphere) remains enigmatic since that time.

Creating Extra-terrestrial Reactions in a Laboratory

Chemical reactions in both interstellar space and within protosolar disks occur under

NanoSims instrument, National Museum of Natural History



CREDIT: CNRS/MNHN – M. Bronchy (2014)

3.5-billion-year-old stromatolitic Chert – Sample from J.W. Schopf

extreme conditions. The ability to recreate such conditions within a laboratory, whilst remaining within acceptable health and safety standards, is no simple task!

Along with his colleagues, Dr Robert conducted a series of high temperature reactions of gaseous Ca-Mg-Si-O mixtures to quantitatively demonstrate the experimental conditions required for the mineral condensation from a solar composition.

Meteorites have a consistent but unique isotopic signature of oxygen. Since 1983, it is known that the synthesis of ozone (O_3) within the laboratory, yields a near identical isotopic signature. However, no consensus has emerged to account for this isotopic distribution. Dr Robert conducted a series of calculations on the isotope distribution of oxygen during ozone formation. 'We have proposed a possible origin for this effect which would be ultimately caused by the property of indistinguishable isotopes involved in collisional processes,' he explains. This signature is the most puzzling scientific problem raised by solar system materials.

Proposing Archean Sea Temperatures

Cherts are terrestrial sedimentary rocks made of almost pure silica, which cover the whole Precambrian era and date between 3.5 to 0.5 billion years old. Their oxygen and silicon isotope composition is believed to reflect the composition in the moments following their precipitation from seawater, and can therefore be used to figure out what the temperature of seawater was during the Archean and Precambrian time periods. Dr Robert and his colleagues measured these isotope compositions and developed a geochemical model to reconstruct seawater temperatures. Using this method, they propose that over the last 3500 million years, the temperature of seawater decreased from approximately 50°C to the present day mean value (about 10°C).

In addition to reconstructing the temperature variations of ancient oceans, the team also use the nitrogen isotopic compositions of organic matter in Cherts to identify the metabolic pathways of some ancient microorganisms that are fossilised within these siliceous rocks.

Weighing up Comet Fragments

Following a mission into space, material from a comet was brought back to Earth, and Dr Robert was given the opportunity by NASA to analyse its chemical composition. The National Museum of Natural History installed a NanoSIMS instrument, which is similar to a SIMS instrument but has a better spatial resolution. When measuring the isotopic distribution within a sample, surface areas of 1 square micrometre can be analysed, giving a unique and detailed chemical resolution of isotope distribution.

Using the NanoSIMS instrument, Dr Robert showed the chemical similarities and differences between inner (meteorites) and outer (comets) solar system material. The isotopic distribution within the cometary grains showed that some of them formed in close vicinity to the Sun, and were then transported to the edge of the protosolar disk. Condensation processes under lower temperature conditions at the edge of the disk would have caused the cooler grains to condense and form the comet.

Future Directions

Dr Robert intends to continue his work combining both experimental and theoretical approaches to predict the origin of isotopic distribution in solar system materials. He argues that 'a currently unrecognised physical process may be the origin of a common property that governs the isotopic variations in solar system matter'.

Meet the researcher

Dr François Robert
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Dr François Robert achieved his PhD in the field of cosmochemistry in 1982 at the Institut de Physique du Globe (IPG-P) France. Between 1983 and 1990, he undertook positions at the French Atomic Energy Commission (CEA) at Saclay, at Caltech, USA, and at the National Center for Scientific Research (CNRS), France. Dr Robert then became 'Director of Research' at the CNRS within the Laboratory of Stable Isotope Geochemistry (IPG-P). He moved to the Laboratoire de Minéralogie at the Museum National Histoire Naturelle (MNHN) in 1992. Between 2003 and 2015, Dr Robert was the Director of a new laboratory at the Museum, devoted to Cosmochemistry. He is a prominent researcher in his field, with research focuses including applications of stable isotopes in cosmochemistry, planetology and geochemistry, resolving the origin of water and organic molecules in the solar system and using both experimental and theoretical methods to study isotopic fractionation. Dr Robert is also the recipient of multiple prestigious awards, including the Leonard Medal in 2011 from the Meteoritical Society, for which Professor Robert was made a Fellow of in 2002, and also the CNRS Silver Medal.

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FUNDING

PNP Programme National de Planétologie (CNRS-INSU)
CNES (Centre National Etudes Spatiales – Exobiologie)
ANR (Agence National de la Recherche)
ERC (European Research Grant)

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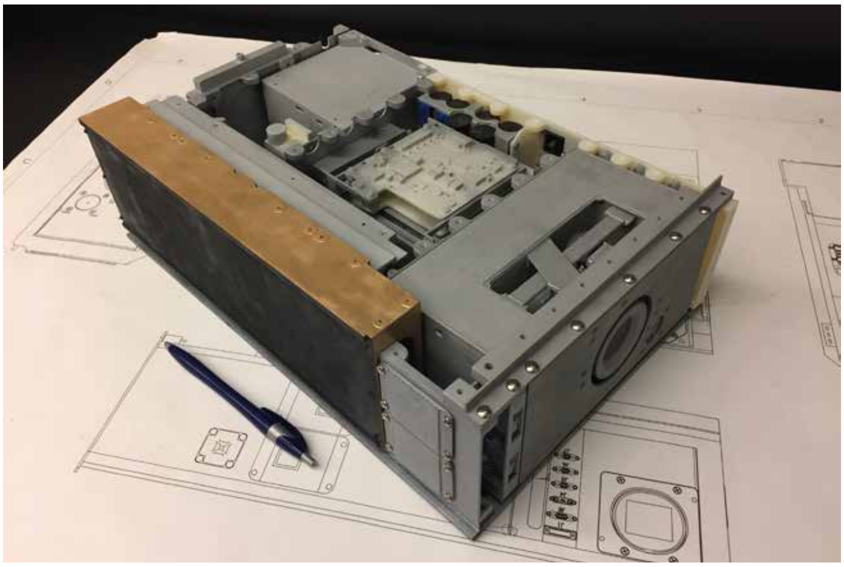
FINDING WATER IN THE MOON'S SHADOWS

The Moon's poles are enriched in hydrogen, a key component of water-ice, but there's still much to learn. **Dr Craig Hardgrove** and his colleagues at Arizona State University are leading the Lunar Polar Hydrogen Mapper (LunaH-Map) mission, which aims to discover how much water-ice is hidden in the permanently shadowed regions of the Moon.



Detecting Water

Although the presence of water-ice on the Moon was known to be theoretically possible, the impact of its actual discovery in 2009 still shocked many scientists. This revelation suggested that the origins and evolution of hydrogen in our solar system – an essential ingredient in water – were not understood, and existing spacecraft did not have the technology to resolve the conundrum.

In earlier space probes, devices that detect neutrons – uncharged subatomic particles found in most atoms – were used to reveal the existence of water-ice on the Moon. Galactic cosmic rays (high-energy protons) constantly bombard the Moon, and this process generates high-energy neutrons. As they pass through the upper metre of the Moon's surface, some of these neutrons interact with hydrogen atoms, and emerge from the Moon's surface with a characteristic energy that can be measured. Therefore, a higher concentration of neutrons with this specific energy (termed 'epithermal') tells scientists that hydrogen is present.

Several neutron detectors have shown that hydrogen atoms, bound to either hydroxyl ions (OH^-) or water molecules (H_2O), are more concentrated at the poles. However, up until now, existing space probes have not had the spatial resolution to resolve the small-scale areas of the south pole, where higher levels of hydrogen-bearing materials have previously been found. Previous missions were not able to unambiguously point to regions of the lunar south pole where ice was enriched, where we might want to direct future landers or missions towards exploring.

To solve this problem, a spacecraft would be needed that could fly low over the lunar south pole and detect neutrons over a region with a footprint of about fifteen square kilometres. Dr Craig Hardgrove was chosen to be the head of a team who would design such a spacecraft. The lunar south pole, inside the Shackleton Crater, was selected as the target.

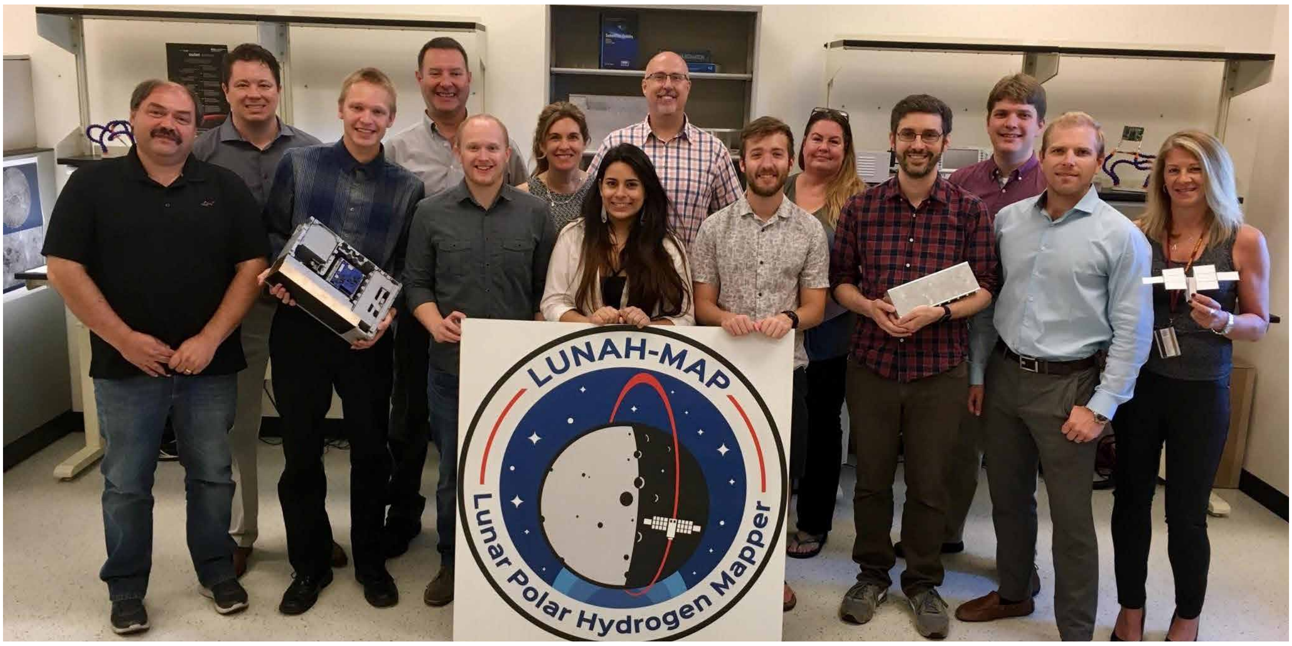
Dr Hardgrove and his team of colleagues and students at Arizona State University are leading the Lunar Polar Hydrogen Mapper (LunaH-Map) mission, which aims to probe these elusive polar regions. For this mission, the team decided to use a new type of neutron detector material, called an 'elpasolite scintillator', that is equally as efficient as previous neutron spectrometers and fits more readily in the team's new type of (tiny) spacecraft. The detector has been designed to be sensitive to neutrons with energies that best indicate an abundance of hydrogen.

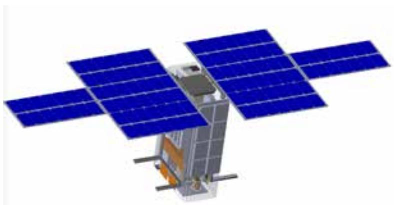
How Did Water Arrive?

Why water should exist on the lunar surface is not well understood, although experts have offered explanations on how it was produced and distributed to the poles. If scientists could understand how and why water is enriched at the Moon's poles they might discover it in similar regions elsewhere in the Solar System.

One way that hydrogen might have arrived is through the solar wind – the constant stream of charged particles emanating from the Sun. Earth's magnetic field thankfully deflects these high-energy particles, but the Moon's negligible magnetic field can't offer much protection. In this way, charged hydrogen atoms in the solar wind could react with oxygen in Moon rocks to form hydroxyl ions and possibly water, which could then migrate to the poles due to impacts, becoming trapped and eventually forming ice.

‘The people who work on this believe in it. They believe it’s something that should happen. They believe there will be more of these tiny spacecraft in the future and that this is a new model of exploration for NASA.’





Furthermore, impacts from objects such as comets and wet asteroids might have delivered water to the Moon. Outgassing from within the moon, evidenced by its fresh, unusual surfaces, could also be a source of water. Curiously, more recent missions have revealed that the poles of Mercury are enriched in water-ice but at much higher levels than the Moon. This is yet another mystery that a better understanding of the distribution and abundance of hydrogen within the lunar poles will help scientists address.

By measuring the concentrations of hydrogen at and around the lunar south pole, Dr Hardgrove and his team will help us to understand where this water might have come from. If they find that hydrogen exists in sufficient concentrations, this could have implications for how water was delivered to the inner solar system, and could point to regions for future human exploration missions to the Moon for life support and producing hydrogen fuel. In this way, the Moon could be used as a refuelling station for astronauts on their way to Mars or the moons of Jupiter.

LunaH-Map

Dr Hardgrove was appointed Principle Investigator in late 2015 for the innovative LunaH-Map mission, scheduled for the maiden launch of NASA’s new Space Launch System (SLS) Exploration Mission 1 (EM-1). This is the first planetary science mission designed, built and operated by Arizona State University, and LunaH-Map is billed as a high-risk but high-reward mission. The spacecraft itself is constructed from six ‘cube-satellites’ (6U, denoting six units) joined together, each having sides of just ten centimetres in length. On top of this, the entire 6U spacecraft has a maximum allowable mass of 14 kg – another challenging constraint for the designers.

Into this tiny space – roughly the volume of a shoebox – the team will cram two neutron detectors, directional ion thrusters to allow the spacecraft to be steered, iodine fuel, communication devices, electronics, power supplies and batteries, along with large external solar panels to capture energy from the Sun.

The neutron detectors will be shielded with a rare-earth metal called gadolinium. This will filter out low-energy neutrons, making the device more sensitive to the presence of hydrogen (and avoid complicating factors from other elements that absorb neutrons), especially hydrogen present in the top metre of the Moon’s surface. Indeed, the team’s neutron detectors are large relative to the spacecraft size, taking up about 200 square-centimetres of surface area, making them more sensitive than those used in any previous planetary science mission.

The Mission

The team’s mission will complete several pieces of a jigsaw, answering questions about the distribution and quantities of lunar water. If successful, it will significantly add to our knowledge of how water formed and evolved at the poles, and will help future missions that wish to exploit lunar water.

Upon deployment from SLS, LunaH-Map will use its iodine-ion-thrusters to position itself, to achieve a highly elliptical orbit with the closest point to the moon over the south pole at a height of 15 kilometres.

Achieving this semi-frozen elliptical orbit, so that the science can begin, will take some time, given the limitations of the ion thrusters. It will take up to 70 days for the spacecraft to be weakly captured by the

moon's gravity. Then, in around 470 days, LunaH-Map will achieve an elliptical orbit. At its farthest point in this orbit, the spacecraft will be 3,150 kilometres from the lunar surface (above the north pole), while its nearest point will be 15 kilometres (above the south pole).

Once this has been achieved, there will be a two-month science phase when neutron measurements will be made as the spacecraft flies by the south pole during each orbit. During this time, the spacecraft will map the distribution and quantity of hydrogen, as a proxy for water, within the permanently shadowed craters of the lunar south pole. It will also measure the availability of hydrogen within the top meter of the lunar surface, and assess whether this coverage is evenly distributed. During its scientific orbits, the spacecraft will cover the whole south pole region, including permanently shadowed areas around the target Shackleton crater.

Data will be stored in time 'bins', with a higher collection frequency as it flies over the south pole, which will be analysed on-board and prioritised for transmission back to Dr Hardgrove and the science team.

Finally, after the science data have been transmitted back to Earth and most of the fuel reserves consumed, LunaH-Map will crash into the lunar South Pole, perhaps within one of the permanently shadowed regions.

Science Objectives in Detail

LunaH-Map's neutron detectors will map the distribution of hydrogen within the south pole region of the Moon. When neutrons of the correct energy are detected, Dr Hardgrove and his team will know that hydrogen is present, and that means the presence of water.

Within the chosen flight path, the south pole being the closest point, the entire polar region will be examined. The spacecraft will gather data for several craters, including Shackleton, de Gerlache, Haworth, Sverdup, Faustini, Shoemaker, Nobile, Cabeus, Amundsen and Mean. Shackleton will be passed over in nearly all orbits, whilst Haworth and other craters will achieve only several passes due to the precession of LunaH-Map's orbit.

LunaH-Map will only measure neutrons that have interacted with hydrogen atoms, those with energies that fall within a certain range, as it passes over the lunar south pole. These measurements will be stored every few seconds, with each individual reading covering a square kilometre area of less than 10 kilometres. To calibrate these polar readings, the spacecraft will take measurements at the equator at a lower collection rate of about one hour per measurement. Using all of these data, the team will produce hydrogen abundance maps for an area of the south pole, 90 to

−85 degrees south, with each data point representing 15 square kilometres or less.

The next objective is to understand the concentration of hydrogen within a depth of 1 metre at the south pole. Dr Hardgrove's design allows the measurements taken by LunaH-Map as it passes over the poles to achieve this objective, because LunaH-Map's neutron detectors are extremely sensitive. Using the data collected, the team will create hydrogen maps at a scale of around the width of an average crater, or just like their abundance maps, around 15 square kilometres per data point.

No Pain, No Gain

Dr Hardgrove and his team have impressive goals and are combining the experience of the commercial small-satellite industry with the expertise and resources available at Arizona State University's School of Earth and Space Exploration. LunaH-Map's high-risk, high-reward mission stands to make significant and meaningful contributions to lunar science, and future space exploration.

Meet the researcher

Dr Craig Hardgrove
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Dr Craig Hardgrove received his PhD in Geology from the University of Tennessee in 2011 and is currently an Assistant Professor in the School of Earth and Space Exploration at Arizona State University. He is the Principal Investigator of the LunaH-Map mission, the first planetary science mission designed, built and operated by Arizona State University. He is also a Participating Scientist on the Mars Science Laboratory Curiosity Rover Dynamic Albedo of Neutrons (DAN) team and Principal Investigator of SINGR (Single Scintillator Neutron and Gamma-Ray Spectrometer) instrument development project. In addition, Dr Hardgrove has worked on many Mars rover and orbiter missions, including MER Spirit and Opportunity, MSL Curiosity, Mars Reconnaissance Orbiter-CTX, Mars-2020 Mastcam-Z. His research interests include planetary geochemistry, and the use of infrared remote sensing on planetary surfaces to understand sedimentary processes.

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FUNDING

NASA's Science Mission Directorate

WORKING IN SPACE: THE CHALLENGE FOR MARS AND BEYOND

Professor Karen Feigh and **Dr Matthew Miller** from the Georgia Institute of Technology examine what support will be required when astronauts need to work outside in deep space, where communication with Earth takes tens of minutes. Software engineer, **Cameron Pittman,** also joined the team to help develop functional prototypes so they can be tested in the lab and beyond.

Extravehicular Activity (or EVA) describes any work carried out by an astronaut outside a spacecraft, with common tasks including construction, inspecting payloads and making repairs. This work is carefully managed and controlled by NASA, and is one of the most prescriptive types of activity that astronauts carry out. Collectively, NASA astronauts have performed nearly 400 EVAs to date, over a quarter of which have encountered significant incidents such as crew injury, early termination or operational issues. Currently, astronauts and ground support personnel work closely together to ensure crew and vehicle safety, and where careful planning and execution minimises unnecessary risks.

Professor Karen Feigh and Dr Matthew Miller at the Georgia Institute of Technology wanted to gain a better understanding of how NASA manages EVAs, so that they could evaluate how the process might be improved for deep-space missions, such as manned missions to Mars where real-time communication with mission control on Earth is not possible. Of particular interest to them was the use of intelligent and automated 'decision support' tools to provide appropriate timely support to astronauts carrying out an EVA.

Understanding EVAs

To achieve their goals, Professor Feigh and Dr Miller needed to become familiar with the processes that NASA uses to control EVA, and the key roles played by individuals and groups both on the ground and in space – inside and outside the spacecraft.

The only way to achieve this was to spend time at NASA, gaining first-hand insight from experts and witnessing EVAs as they took place. As part of his doctoral studies funded by NASA's own Space Technology Research Fellowship program, Dr Miller spent forty weeks over a four-year period working with teams at NASA's Johnson Space Centre in Houston, Texas, where he developed close technical relationships with EVA operations experts.

To gain an even deeper understanding, Dr Miller was involved in three International Space Station EVAs, plus a simulation training exercise that amounted to over thirty hours of cumulative observation. To complement this, he also examined archive footage of historical EVAs, including that of the Apollo lunar surface operations, and comprehensively reviewed previously published research and development efforts regarding EVAs. The culmination of these efforts resulted in the modelling of the underlying constraints that shape EVA operations.

Early in the project, Dr Miller discovered that the EVA work environment was highly social, with effective communication between many different team members being a vital component. The EVA team involved experts located at different sites using many detailed work artefacts and information systems. He found that any given EVA was riddled with uncertainties, as controllers often needed to act as problem solvers despite the fact that the activities are carefully planned and executed.

Adding Rigour

Professor Feigh and Dr Miller not only needed a comprehensive and extensible understanding of how a present-day EVA is conducted, but they also needed to translate and reimagine EVAs in a future of deep-space missions. For this, the team leveraged perspectives from the discipline of 'cognitive systems engineering', which emphasises understanding the confluence of human operators and


CREDIT: D.S.S. Lim

their associated technologies and work components that make up a complex system.

This scheme provided tools that allowed the team to examine, in a top-down and structured manner, the work performed, information flows and underlying constraints that shape EVA operations. Ultimately, it would help them derive the requirements necessary to influence their final goal: to create a prototype decision support system to improve the way that EVA operations would be performed during deep-space missions.

Important Findings

The team found that the EVA work environment is shaped by two major considerations: the distribution of knowledge across EVA operators and systems, and the harsh environments experienced by the space flight crew.

During an EVA, the extravehicular (EV) crew members are outside the spacecraft and are constrained by the spacesuit that keeps them alive, and the tools and robotic aids that help them accomplish their tasks. Because of these constraints and the heavy physical strain on the EV crew member, the intravehicular (IV) crew members – unsuited astronauts located inside the spacecraft – are positioned to help ease the burden of various aspects of EVA execution. Under present-day EVA operations at the International Space Station, an IV crew member controls the robotic assets to support EV tasks. The mission control centre (MCC) on Earth coordinates every part of the EVA, and is in constant communication with both the EV and IV crew.

Within the MCC, a large team of controllers is dedicated to EVA support, occupying three primary 'console' positions: systems, task and airlock. These three positions are supported by dozens of other team members called 'back room' controllers. Messages for both the EV and IV crew are condensed and transferred among the ground flight team and relayed through the 'Ground IV' – one of only two people allowed to communicate directly with the crew during EVA. As evidenced through this architecture, EVA operations relies on the wealth of technical, systems and operations knowledge that exists within MCC to ensure mission success.

As human exploration takes the crew farther from Earth, the communication latency between the MCC and the crew will grow to as much as 20 minutes for a one-way transmission to destinations such as Mars. As a result, MCC guidance will be inherently limited. Therefore, the only way to maintain successful EVA operations is to shift the work of the MCC to the space flight crew to deal with the moment by moment challenges that arise during EVAs.

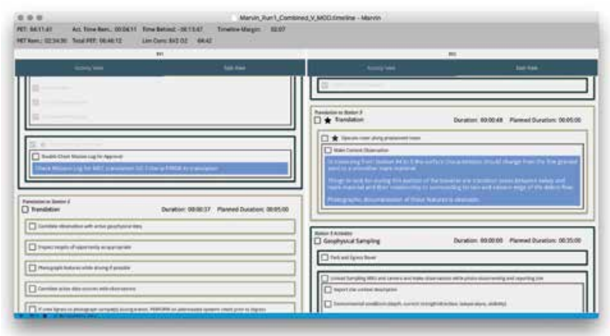
The IV crew members are ideally situated to take on those additional responsibilities. The challenge now becomes effectively translating the work functions of many personnel in MCC to a single operator in a deep-space setting. One solution is to develop technology that can take on those additional responsibilities to provide the IV crew similar operational insight currently available at the MCC.

Decision Support System

Dr Miller and Professor Feigh's comprehensive analysis of both current EVA operations and those envisaged for deep-space missions allowed them to derive the necessary systems requirements to guide the development of an EVA decision support system. Specifically, they developed a series of cognitive work and information relationship requirements that are unique to the development of systems designed to aid human cognition.

The team wanted to design a computer system that could assist the IV crew with managing high-priority tasks (previously assigned to MCC personnel): detailed life support system monitoring and managing EVA timeline progress. During EVAs, tracking and altering these aspects significantly impact safety and productivity. Other, less realised features of future EVA, such as future spacecraft, spacesuits, hardware, communication infrastructure would need to be considered in future work.

CREDIT: Andrew Hara



Therefore, Professor Feigh and Dr Miller decided to focus their efforts on the life support system and timeline management functions when developing their prototypes. To do this, they called on the skills of an experienced software engineer, Cameron Pittman.

Basic and Advanced Prototyping

Pittman gave his time freely to help develop the decision support system prototypes, of which there were two: Baseline and Advanced.

The team incorporated present-day serviceable EVA processes and technologies into their Baseline prototype, focusing on three main areas: life support system monitoring, timeline material and communication. A defining characteristic of this prototype is that it primarily supports the IV operator and envisions how the IV workstation might look if we were to take existing technologies to Mars tomorrow.

The Baseline prototype combined the various present-day EVA work artefacts for an IV operator to utilise. It included a summary of the timeline and detailed EVA procedures, which were provided in the form of paper timelines and schedules, with minimal alterations on current EVA practices. This prototype also supported two different types of communication – audio and text. A digital audio communication channel was provided between the EV and IV operators, and a simulated five-minute latency text communication client, on loan from the NASA Ames Playbook team, was included between the IV operator and the MCC.

The team's second prototype – the Advanced decision support prototype – demonstrated how new designs could be leveraged to support the IV operator's new role in the EVA process. In particular, the team developed a novel timeline management tool that is integrated with life support monitoring, to create a system they called Marvin – a reference to the intelligent robot in Douglas Adam's Hitchhiker's Guide to the Galaxy. When designing this Advanced prototype, Pittman and Miller worked together to develop a design solution to managing tasks on the EVA timeline – a non-trivial task that represented a major shift in technology and practice.

Marvin consisted of three focus areas: life support monitoring, timeline task management and communication systems with information integration and automatic task progress calculations to reduce the burden on the IV crew.

The team describes their current design as a 'dark cockpit', where the display remains 'dark' or quiet unless an alert is triggered. Their Advanced prototype assumes that only audio communication would be used between the EV and IV crew, and that there would be time-delayed text communication between the MCC and the IV crew.

Proof of the Pudding

The team's use of cognitive systems engineering helped frame two phases to test their Baseline and Advanced prototypes. The first involved three large-scale NASA analogue research programs that simulated future EVA operations and informed their second, more controlled, laboratory evaluation environment, where participants would test the prototype in a simulated laboratory experiment.

The Baseline prototype represents current EVA processes and technologies, and so allowed users to identify potential deficiencies in the design. This prototype was designed to adhere as closely as possible to today's MCC. When managing the EVA tasks during the laboratory evaluation, 64% of the participants rated the Baseline as only 'Slightly' effective, indicating that there were substantial opportunities for improvement.

The team's Advanced prototype, however, represents a first step towards improving support for the IV operator, particularly when managing the timeline of the tasks that need to be carried out while also monitoring a wealth of life support system data. The participants rated this prototype as 'very' or 'extremely' effective in a number of key areas regarding timeline and life support system management. It was clear to the team that this was just a start, and significant improvements to data displays would be possible in future designs.

Participants in the laboratory tests were easily able to use the new timeline management features to track the progress of EV crew. They appreciated the ability to 'click-off' steps as they were completed, which produced accurate moment-to-moment estimates of timeline margin and progress. As a result, the IV operator could focus on communicating with the crew without the need to perform mental timeline math calculations. Unsurprisingly, they commented that this new way of working was much better than having to use paper-based tools.

Nearly all measures of user performance yielded significant differences between the prototype designs, in favour of the team's Advanced decision support system.

The team recognises that trying to improve EVA operations is a massive undertaking that will require a huge investment of effort. Their work has shown that incremental improvements are possible and with the appropriate articulation of meaningful requirements that guide technology development, we will be able to meet the challenges facing future space explorers as they venture deeper into our Solar System.

Meet the researchers

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Professor Karen Feigh was awarded her PhD in Industrial and Systems Engineering from Georgia Institute of Technology in 2008. Subsequently, she became an Assistant Professor at the Institute in the School of Aerospace Engineering, where she is now an Associate Professor. She is currently Principle Investigator on a number of important contracts, including Proactive Decision Support Through Information Modification for the US Office of Naval Research, and Objective Function Allocation Method for Human-Automation/Robotic Interaction and Technologies for Disruption Management in Mixed Initiative Schedule for Human Space Flight for NASA.

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Matthew J. Miller received his PhD in Aerospace Engineering from Georgia Institute of Technology, Atlanta, GA in 2017. He is currently an Exploration Research Engineer at Jacobs Engineering, Inc. at the NASA Johnson Space Center, researching advanced state of the art human spaceflight extravehicular activity flight operations by leveraging cognitive systems engineering practices. Dr Miller has participated in three separate NASA analogue research programs, accumulating over 175+ hours of simulated future EVA operations experience. He served as an EVA Team Member and Flight Controller, where he contributed to the development and execution of mission objectives, research design, and EVA timelines.

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Cameron W Pittman is an experienced Software Engineer who graduated with a MA in Teaching from Belmont University in 2011 and a BA in physics from Vanderbilt University in 2009. He is currently employed by Udacity as Full Stack Software Engineer, where he focuses on helping students get feedback on their projects. Amongst other projects, he augments and scales tools that analyse student projects and provide feedback automatically. Cameron also maintains and improves Udacity's infrastructure and services that connect students with graders.

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FUNDING

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ASTRONOMY

THE EVOLVING UNIVERSE

For centuries, scientists believed that the Universe had always existed in an unchanging form, in a theory referred to as the Steady State Universe. However, in 1927, a Belgian scientist called George Lemaitre proposed that the Universe instead had a beginning – and had originated as a single point, which he dubbed the 'Primeval Atom'.

Although the term 'Big Bang theory' was coined by the astronomer Fred Hoyle in an attempt to belittle the idea, Lemaitre's theory is exceptional in explaining a range of phenomena, such as cosmological expansion and the cosmic microwave background – the afterglow of the Big Bang. Indeed, the Big Bang theory has now come to be the prevailing cosmological model for the Universe.

The theory proposes that approximately 13.8 billion years ago, all the matter in the Universe violently emerged from a single, miniscule point of infinite density – called a 'singularity'. As matter rapidly burst from this point at an unimaginable speed, space itself was created, along with time. Between 10^{-33} and 10^{-32} seconds after the initial burst, the linear dimensions of space had expanded by a factor of 10^{26} – or a hundred trillion trillion – during the so-called 'inflationary epoch'.

Because of this rapid inflation, the Universe cooled from 10^{27} degrees Celsius down to a balmy 10^{22} (or billion trillion) degrees. Upon further rapid cooling, the four fundamental forces – gravity, the strong interaction, the weak interaction and electromagnetism – emerged as distinct forces, but energies were still too high at this point for protons and neutrons to form, with matter existing instead as a soup of fundamental particles.

When protons, neutrons and their antimatter counterparts did finally form, sometime between a millionth of a second and a second after the Big Bang, they annihilated each other. Luckily for us, however, there was slightly more matter than anti-matter, and so some matter remained. Within the next few minutes, the temperature had cooled to such a degree that some light atomic nuclei could form, but it would take another 300,000 years before energies were sufficiently low that these nuclei could capture electrons, filling the Universe with clouds of hydrogen and helium gas.

Rather than this matter being evenly spread, there were slight fluctuations in density throughout the Universe. This was again fortunate for us, as slightly denser regions could pull more matter towards them, ultimately leading to the formation of the galaxies, stars and planets we know today.

In the first article of this section, we meet Dr Romeel Davé, formerly of the University of the Western Cape, who has recently been appointed as the Chair of Physics at the University of Edinburgh. Dr Davé and his colleagues elucidate the fine details of how our observable Universe evolved from shortly after the Big Bang until now. By using advanced computational simulations, some of which take months to run, the team are working to answer some of the most basic questions about our visible Universe, such as why galaxies exist in the multiple shapes and sizes we see, what regulates the growth of galaxies and black holes and when were the first stars and galaxies formed.

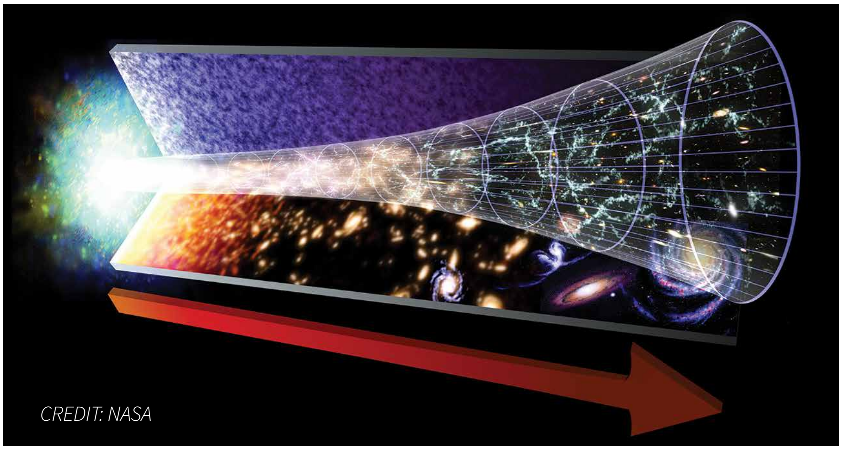
Also working to understand why astronomical structures look the way they do are Drs Marc Pound, Jave Kane, David Martinez and Bruce Remington of the University of Maryland and Lawrence Livermore National Laboratory (LLNL). In the next article of this section, we highlight this team's work into understanding the formation of the iconic Eagle Nebula Pillars – elongated clouds of gas and dust that stretch over five lightyears. To test their theory of how these vast structures came to be, the researchers decided to recreate the conditions that formed the pillars in a lab using a powerful laser at LLNL. In their experiment, this laser was used to mimic the high-intensity radiation emitted by energetic young stars in the Eagle Nebula, creating foam structures that represented the Eagle Pillars – but were 10^{38} times smaller! In their future work, the team would also like to explore how magnetic fields could have influenced the formation of these majestic structures.

And speaking of magnetic fields, our third article in this section explores the magnetic behaviour of our Sun. Here, we meet Dr Mark Giampapa and his colleagues at the National Solar Observatory, who are working to understand how the magnetic activity of the Sun evolves and how it will behave in the future. To do this, the team explores the behaviour of similar stars in our galaxy, as a way of predicting the full range of activity that our Sun may produce in the future.

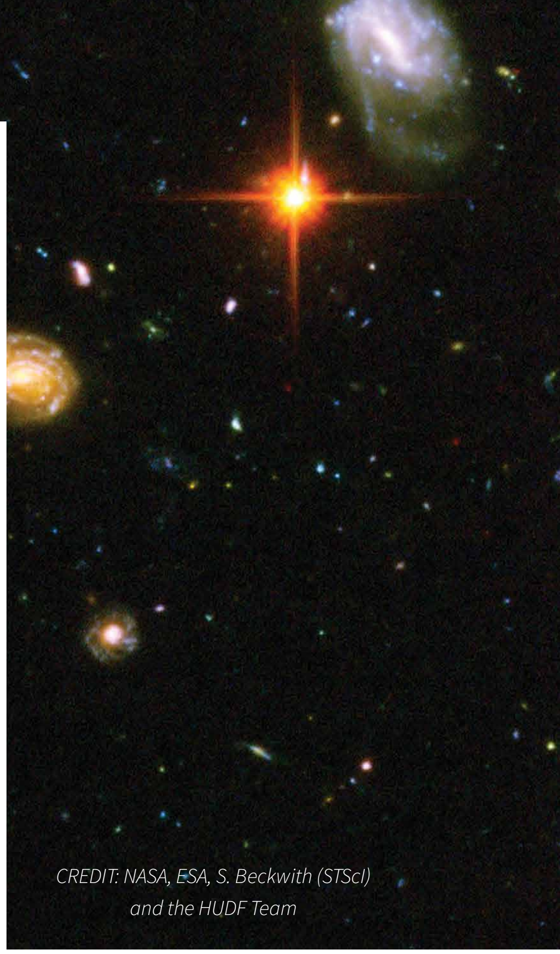
Also interested in the magnetic fields of stars and other astronomical objects is Dr Robert Mutel of the University of Iowa. In the final exciting article of this edition, we discuss how Dr Mutel gathers information about the magnetic fields of stars, planets and even the black holes at the centres of active galaxies by looking at their radio emissions.

PUTTING THE UNIVERSE IN A COMPUTER

Galaxy formation theorist **Dr Romeel Davé** and his team at the University of the Western Cape use high-performance supercomputer simulations to answer basic questions about the evolution of galaxies and our visible Universe.



CREDIT: NASA



CREDIT: NASA, ESA, S. Beckwith (STScI) and the HUDF Team

Humans have always been mesmerised by the night skies, and strived to understand our place in this vast Universe. Our current understanding suggests the beginning of our observable Universe occurred in a Big Bang – an unimaginably hot and dense state that expanded rapidly, creating matter out of nothing but tiny quantum fluctuations. Over the nearly 14 billion years that followed, the inexorable pull of gravity grew these fluctuations into the hundreds of billions of galaxies that we can observe today. Our most sophisticated telescopes such as the Hubble Space Telescope can see galaxies far out in space and commensurately back in time, back even into the first billion years of existence. Stunning images show a fascinatingly complex and rich population of galaxies, including majestic spirals like our Milky Way, formless ellipticals, and chaotic irregulars. To scientists like Dr Davé at the University of the Western Cape, this prompts the fundamental question: How did all this come to be?

As powerful as they are, telescopes merely take snapshots at an instant in time – human lifetimes are too short to directly watch the Universe evolve. This is where Dr Davé and his colleagues step in. Dr Davé's team builds sophisticated computer programs that aim to simulate the Universe from the Big Bang until today. The goal is to reproduce the dizzying range of observations seen with advancing optical, radio, X-ray, and other telescopes, armed with nothing but the laws of physics and powerful supercomputers. Ultimately, this would allow us to make a movie of how our Universe evolved from the Big Bang until today, connecting humans to the beginnings of time within a single cosmic origins story.

Making Models

Cosmologists currently estimate that about 70% of the Universe is made up of dark energy, a quarter is dark matter, and only about 5% is visible or so-called 'baryonic' matter. This baryonic matter includes everything we ordinarily think of as 'matter', or as Dr Davé explains, 'everything made up of elements in the periodic table.' While the nature of dark matter and dark energy remain fascinating mysteries, Dr Davé tells us that his work is focused more on questions regarding the evolution of the visible parts of the Universe. So, his work is primarily concerned with just 5% of the mass-energy in the Universe, but 'it's the interesting 5%, because it's the stuff that makes up galaxies, stars, planets, and us!'

Dr Davé was always interested in computer programming and numerical modelling. Although it is only in the past decade or so that computer simulations incorporating baryonic matter have emerged as a mature and valued approach, he has been developing and running such simulations since the 1990s, and pioneered some of the approaches still used today. 'I could see early on that computer modelling was going to grow into an important force in the field because of the complexity of the physical systems involved,' he says.

The underlying reason for this, Dr Davé argues, is that unlike Earth-bound lab scientists who can control their experiments, astronomers can't even reach their distant experimental subjects – galaxies, stars and planets – much less control them. 'It's a classic blind men and the elephant story,' explains Dr Davé. 'Telescopes can see different aspects of different objects at different times, but it takes computer models to synthesise all these disparate data into a single cohesive elephant.'

Early in his career, Dr Davé worked on aspects of cosmology such as dark matter and dark energy. While he maintains an interest in these areas, he finds studying baryonic matter to be a much richer endeavour. 'This is our story, the story of how we and everything we see got here,' he says. 'Virtually every culture or religion has its own origin myth. We astronomers are developing science's version of an origin myth – but unlike any that has come before, one that is testable, observationally verifiable, and grounded in the principles of physics.'

Simulating the Universe from the Start

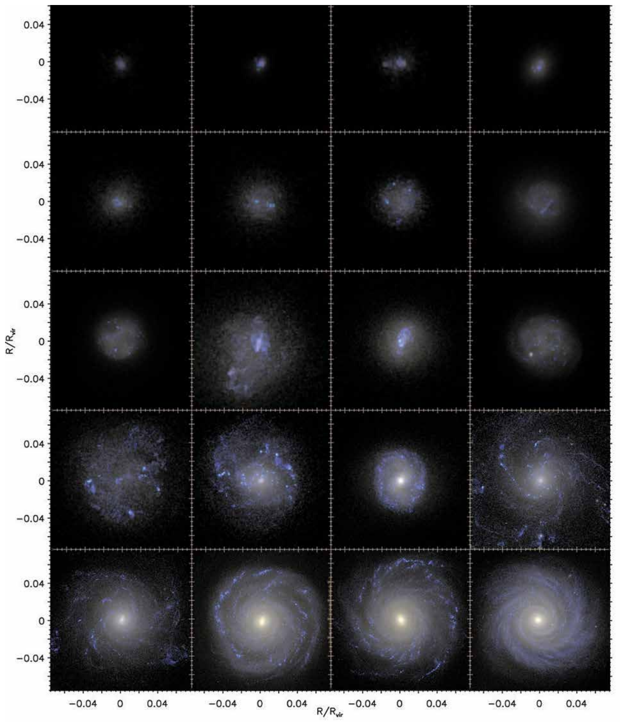
Dr Davé likes to distil the aim of his research down to a basic question: 'Why does the Universe look the way it does?' To answer this question, he takes an empiricist's approach. He begins with the well-established initial conditions shortly after the Big Bang, adds in the laws of physics, sprinkles on some complicated physical processes such as the formation of stars and black holes, and throws this all into a computer. A single simulation can take months to run using thousands of CPU cores, but what comes out at the end is a rich and dynamic movie of the Universe and its evolution across all of time that can be tested against observations covering the full electromagnetic spectrum. For many observations, the simulations agree well with the empirical data, in which case Dr Davé says he 'dives into them to try and understand the fundamental physical processes that drive such agreement.' Often, though, his models disagree with observations. It is such disagreements that are most valuable, because this tells him that the model is missing some key component, or that a baseline assumption is incorrect. He must then come up with a new hypothesis, guided by physical intuition and observations, insert it into the model, and the process stars over. With each iteration, Dr Davé's simulations more closely reproduce observations of the real Universe, and become an ever more viable description of why the Universe looks the way it does.

Galaxy formation simulations must account for a Universe that includes a complex collection of physics such as star formation, black hole accretion, gas dynamics, and dark matter and dark energy that establish the galactic distribution within the Cosmic Web – the vast network of dark matter that houses all galaxies. To cover all these bases, Dr Davé's simulations include physics from classical dynamics, thermodynamics, chemistry, relativity, radiative processes and quantum mechanics, along with aspects of computer science such as hardware-optimised algorithm development and parallel computing. According to Dr Davé, the diversity of knowledge required is one of the most entertaining aspects of his work. 'To be a galaxy formation theorist, you have to be something of a physics dilettante, knowing a little bit about great many topics.' he says. 'I'm constantly having to learn about things I never thought I'd have to know, which is great fun.'

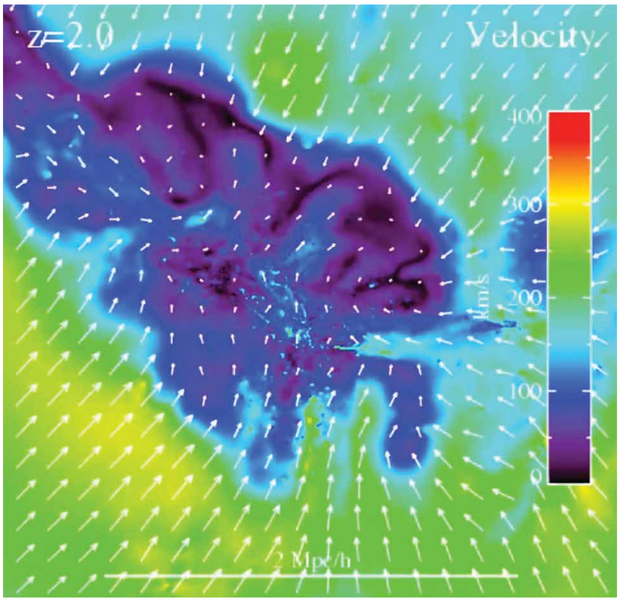
A major recent accomplishment of Dr Davé's group is the development of a suite of cosmological simulations they call MUFASA. 'MUFASA represents a re-think of how we play this game,' argues Dr Davé. 'It synthesises knowledge from simulations at multiple scales together with analytic modelling to yield among the closest agreement with data that any galaxy formation model has yet achieved.' Despite pushing the state of the art, Dr Davé admits that MUFASA remains far from reproducing all available observations, and even shows some vexing disagreements. 'We've made huge progress, but it's hard to overstate how far we have yet to go to build a fully successful model,' he says.

By synthesising this knowledge and applying his computer skills, Dr Davé says he is attempting to answer some of the most basic questions about our visible Universe: Why do galaxies exist in the multiple shapes, colours, and sizes we see? What regulates the growth of galaxies and their black holes? When were the first stars and galaxies formed and what did they look like? What lies between

CREDIT: NASA, ESA, S. Beckwith (STScI) and the HUDF Team



CREDIT: C. Christensen (Grinnell)



CREDIT: B. Oppenheimer (Colorado)

galaxies in the Cosmic Web? To him and many of his colleagues, these are some of the most fundamental questions in modern astrophysics, questions that are driving billions of dollars in investments into future astronomical facilities such as the James Webb Space Telescope.

The Universe as a Living System

Despite only recently coming to the fore as a major tool in understanding our Universe, computer simulations like those of Dr Davé's group have already been transformative in our basic picture of how galaxies form and grow. 'Before simulations,' Dr Davé explains, 'galaxies were thought of as island universes, solitary and set apart, having little interaction with their surroundings.'

Simulations changed all this. Generically, simulations forwarded a new paradigm that Dr Davé and fellow Professor Andrew Baker (Rutgers) dubbed 'the baryon cycle'. In his view, Dr Davé likens galaxies to living beings in ecosystems on Earth. Galaxies obtain fuel from their surroundings, some of which is transformed into visible stars, and some of it is ejected back out of the galaxy, later to be recycled back in. This is the cycle of baryonic matter in and out of galaxies. A galaxy's properties are then influenced not only by the nature of its birth location, but also by the way in which this cosmic ecosystem nurtures their growth. As with many biological systems, the relative importance of nature versus nurture remains an open question in galaxy evolution.

This new baryon cycle paradigm of galaxy evolution is the primary focus of Dr Davé's work. 'Even though a galaxy might look serene, it is in fact a roiling pot of energy that continually spews mass and energy into its surroundings, while at the same time pulling in fresh material owing to its gravity,' he explains. Dr Davé's view is that understanding how the baryon cycle operates is tantamount to understanding galaxy evolution, and by extension, the visible Universe.

The most pressing current questions surround how galaxies manage to eject huge amounts of matter back into surrounding space. Immense energy is required to do this, which might come from exploding supernovae, black holes, winds from massive stars, or cosmic rays, but exactly which of these are at work and how they operate remains unclear. Dr Davé and his colleagues aim to develop, as he puts it, 'new technologies, techniques, and telescopes to directly detect and measure the baryon cycle as it happens.' By combining such measurements with advancing simulations such as MUFASA, the team hopes to better understand the diversity of galaxies arising in various environments, much like biologists aim to understand the diversity of life on Earth arising in various habitats.

Moving on While Looking Back

Dr Davé's life is evolving forward much like his simulations, as he is in the process of moving to the University of Edinburgh to take up the Chair of Physics. There, he intends to put together a world-class group of scientists working in numerical simulations of galaxy formation and related issues in cosmology. 'At the Royal Observatory in Edinburgh there are already experts in simulations of the first stars and black holes on small scales, and cosmology on large-scales,' he explains. The latter refers to Professor John Peacock, who literally wrote the book on Cosmology – the standard textbook Cosmological Physics. Dr Davé expects that his galaxy formation models will help bridge the gap between small and large scale phenomena. He envisions Edinburgh to be a 'one-stop-shop for all astrophysical simulations of galaxies, from the smallest first objects to massive clusters today.'
Dr Davé's main research will be based on the MUFASA simulation project that he assembled over his years in South Africa. 'I have had a wonderful and rich experience in Cape Town over the last few years helping South Africa to emerge as an important player on the international astronomy scene.' South African astronomers are currently building the world's greatest radio telescope – the Square Kilometre Array. Dr Davé says he plans to continue to be heavily involved in South Africa's growth and emergence, but at the same time he is excited to join one of the UK's preeminent astronomical centres at the Institute for Astronomy in Edinburgh. With computers becoming ever more powerful and incredible new telescopes on the way, Dr Davé is enthusiastic about the prospect of discovering fascinating new insights into how galaxies, black holes, and intergalactic gas evolve over time, and doing his part to piece together the story our cosmic origins.

Meet the researcher

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Dr Romeel Davé received his Bachelor's degree in Physics from the University of California at Berkeley and a Master's degree in Physics from the California Institute of Technology. He then pursued graduate work at the University of California in Santa Cruz, obtaining his PhD in Astronomy & Astrophysics in 1998. Following this, he was awarded a Lyman J. Spitzer Fellowship at the Princeton Department of Astrophysics, and subsequently a Hubble Fellowship at the Steward Observatory, before securing a faculty position in Astronomy at the University of Arizona in 2003. In 2013, Dr Davé joined the Department of Physics of the University of the Western Cape, where he is now the South African Research Chair in Cosmology with Multi-Wavelength Data. Dr Davé's research interests include numerical studies of galactic evolution, the intergalactic medium, large-scale galactic structure, reionisation, and general cosmology. His career highlights include writing the world's first parallel hydrodynamics code for galaxy formation, developing the first cohesive model connecting the evolution of galaxies and the intergalactic medium, and investigating the nature of the Universe's so-called 'missing baryons'. Dr Davé has authored or co-authored over 170 articles published in peer-reviewed journals garnering over 18,000 citations, and is regularly invited to give keynote or plenary talks at international conferences. With his wife Dr. Jarita Holbrook, he has co-produced prize-winning documentaries 'Hubble's Diverse Universe' (2009) and 'Black Suns: An Astrophysics Adventure' (2017).

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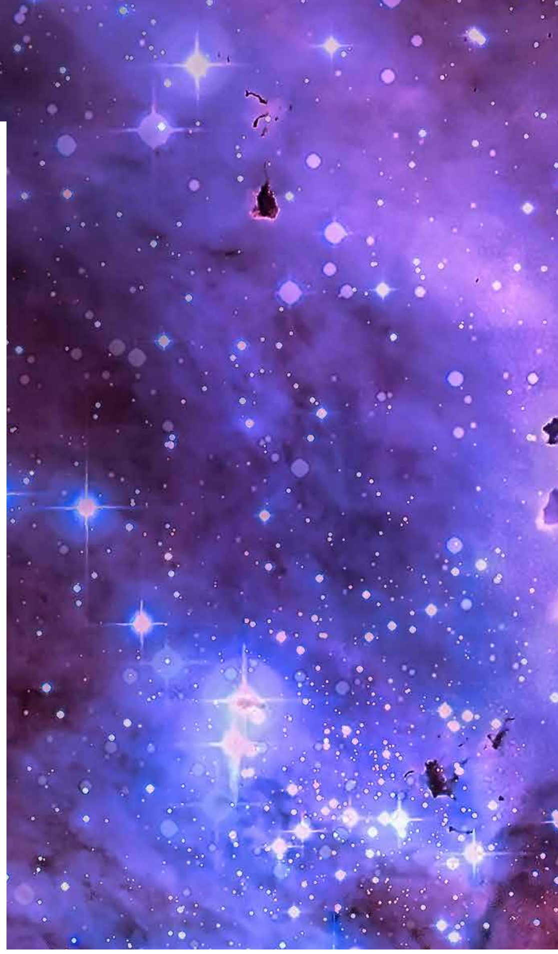
FUNDING

NSF
NASA
South African National Research Foundation
UK Royal Society

CREATING THE EAGLE NEBULA PILLARS IN THE LAB



The ‘Pillars of Creation’ is one of the most iconic images ever taken by the Hubble Space Telescope, but the processes that formed these colossal tendrils of the Eagle Nebula are still not entirely understood. To test emerging theories, **Drs Marc Pound, Jave Kane, David Martinez** and **Bruce Remington** are using the National Ignition Facility, at Lawrence Livermore National Laboratory (LLNL) in Livermore, California, to recreate the conditions that formed the pillars, on a much smaller scale.

Situated some 6,200 lightyears from our Solar System, the Eagle Nebula contains a number of clouds composed of interstellar gas and dust. On a cosmic timescale, these clouds don’t stay around for long, as denser areas formed inside the cloud collapse under their own gravity, giving birth to new stars. The material is so plentiful that massive O-type stars – those up to 90 times the mass of our Sun – can form. These stars burn hot and bright, emitting ultraviolet radiation at extremely high intensities.

This ultraviolet radiation from a young O-type star gets absorbed by the cloud material surrounding the new hot star. Hydrogen atoms on the outer surface of the cloud become ionised by the radiation, and ‘photoevaporate’ away from the cloud towards the hot star, forming a low-density gas between the star and the cloud. A localised high-pressure region is thus created near the surface of the cloud through a process called the ‘rocket effect’, where the photoevaporated ions correspond to the ‘exhaust’. The net result is a shock wave launched through the cloud, pushing the cloud away from the star.

Made famous by the Hubble Telescope’s iconic image, the ‘Pillars of Creation’ or ‘Eagle Pillars’ are elongated clouds of gas and dust stretching five lightyears, which are situated within the Eagle Nebula. The cloud that originally came to form these pillars contained clumps of denser material, which hadn’t yet collapsed to form stars. While shock waves pushed lower density cloud material away, the dense clumps ultimately stayed in place, as shock waves travelled through them much more slowly.

The clumps, therefore, provided a safe haven from both the intense radiation from the star and the resulting shock waves from photoevaporation of the clump, allowing gas and dust to collect behind them, forming pillars. This scenario is the basis of the so-called ‘shielding model’ of formation of the Eagle pillars.

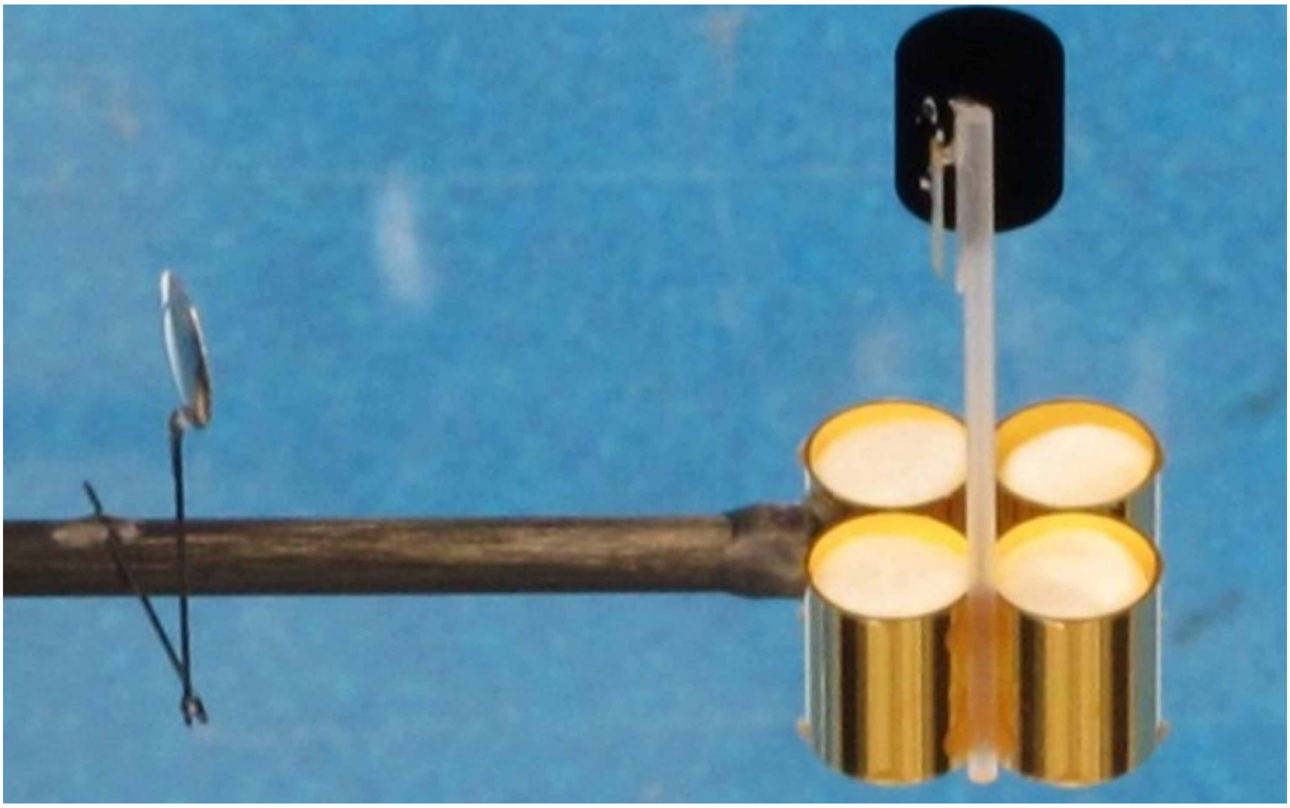
‘High mass stars will disrupt the clouds through powerful streams of high energy photons (particles of light) that break apart the molecules and ionise the gas,’ explains Dr Marc Pound, of the University of Maryland. ‘The Eagle Pillars and features like them are a particularly dynamic manifestation of this interaction as the photons sculpt the dense gas, and push it into elongated shapes.’ The shielding model is one interpretation of the early formation of the Eagle Pillars, but Dr Pound and his colleagues, Drs Jave Kane, David Martinez and Bruce Remington at the Lawrence Livermore National Laboratory, believe there is more involved with the structures that we observe today.

Introducing the Cometary Model

The four researchers think that as an initial shock wave wrapped around behind a clump of material, it gained a lateral component, causing it to collide with itself when it reached the axis of one of the pillars. Material travelling with the shock wave rebounded off the pillar’s axis, while also moving away from the clump and cooling by radiation and expansion. There are a number of effects, such as the 3D nature of this interaction, that make the situation slightly more complicated. Thus, the team propose a far more comprehensive model.

‘At later times, material that is photoevaporated from the clump, or released when the shock exits the clump, collects behind the clump, creating a second, late-time source of material for the pillar,’ the researchers claim in their report. ‘This process of the clump releasing material downstream is the beginning of the formation of a secondary, “cometary” structure.’ This secondary source of material maintains the continuous, elongated structures that we see in the Eagle Pillars today.

This cometary model gets its name from its similarity with the tails of comets. The centres of comets emit particles that are ‘blown down stream’ by solar winds, leaving a ‘tail’ that continually points away from the Sun. Similarly, although on a much larger scale, material from the clumps in the Eagle Pillars is released in a ‘tail’ that points away from the pillar-forming star. Drs Pound, Kane, Martinez and Remington suggest that this process may be what created the structures that we see in the Eagle Pillars today, but unfortunately, they can’t confirm it solely from direct astronomical observations. To test their theory, they decided to recreate the conditions that formed the pillars inside an experimental laboratory. To do this, they would need a radiation source powerful enough to play the role of the intense radiation given off by massive, young stars.



The Eagle experimental setup. The NIF laser beams hit the interiors of the hollow gold cylinders from below, which produces intense thermal x-rays out the tops, to simulate the powerful ultraviolet radiation given off by massive, young stars. This intense, protracted source of x-rays irradiates the foam target above.

The Laser that Simulates Starlight

About an hour's drive from San Francisco is a resource capable of meeting the team's requirements. The National Ignition Facility (NIF), located at the Lawrence Livermore National Laboratory (LLNL), contains a 192-beam laser that can deliver an energy of 2 megajoules – equivalent to the energy given off by half a kilogram of TNT – to an area of just a few square millimetres. The facility allows a select number of scientists to conduct their own research there each year. 'The NIF Discovery Science program allocates 8% of its facility time to basic science, based on an international call for proposals,' says Dr Remington, 'Through this program, new regimes of science are being experimentally studied at NIF.'

This facility has previously been used to recreate extreme astrophysical conditions in the lab. In 2014, a team of researchers led by Dr Ray Smith at LLNL wished to recreate the extremely high densities of material found in the cores of giant planets, such as Saturn. To do this, they fired the laser onto the inner surface of a gold cylinder called a 'hohlraum' that was 6 mm in diameter, with a small diamond plate mounted over a hole in the wall of the hohlraum. When hit by the laser, the hohlraum produced high-intensity bursts of x-ray photons – photons of even higher energy than ultraviolet photons.

When the x-ray photons hit the diamond, they generated intense photoevaporation (ablation), which resulted in a pressure of 5 terapascals – 50 million times larger than the Earth's atmospheric pressure. The impact created a compression wave inside the diamond – compressing it to almost a quarter of its original size and four times its density. This artificially high density gave the scientists a brief glimpse into the interiors of massive objects in space.

Another experiment at the NIF, conducted by a team of scientists including Drs Hye-Sook Park and Hans Rinderknecht from LLNL and Frederico Fiuza from SLAC, used the NIF

Simulated image (right) of the evolved target show similar evolution to the data (left). The dark band at the top of the image is the shock in the low-density foam and is moving up, away from the radiation source. The shock colliding behind the clump created a triangular band near the top of the image. At the bottom of the image is the dense clump and above the clump is a shock, moving away from the column of plasma.

laser to irradiate two pieces of foil separated by a few millimetres. Each piece of foil generated high speed (~1000 km/s) flows of plasma (highly charged matter), which interacted with each other at the midplane between the foils. As the two plasmas collided, bursts of subatomic particles called protons and neutrons were generated, as well as x-rays. The presence of these particles suggested that strong heating was occurring at the midplane between the foils, which over time allowed deuterium (a type of hydrogen atom containing one proton and one neutron) to undergo nuclear reactions.

These nuclear reactions implied extremely high temperatures, and suggested the formation of a shock. But the plasma densities were too low for a conventional ('collisional') shock to form. This meant that a 'collisionless' shock had formed, much like astrophysical shocks that exist in supernovae (exploding stars) and other energetic astrophysical phenomena. This observation showed the scientists that thin shockwaves were forming in each collective plasma flow, without the flows interacting with each other by direct two-body particle collisions.

Conducting experiments with the NIF laser is an exacting process, and Dr Park and her team needed to be confident that their experimental setup would yield high quality scientific results. To do this, they used a simulation code named HYDRA, developed at LLNL to predict the outcome of the plasma collision and interactions. Similarly, the recent experiments devised by Drs Pound, Kane, Martinez and Remington to examine the cometary model of pillar formation would rely on HYDRA simulations over many months of preparations to avoid costly mistakes.

Pillars of Foam

In the team's Eagle experiment, the NIF laser was used to create high-intensity radiation, corresponding to that emitted by young O-type stars in the Eagle Nebula. They used a similar gold cylinder setup as that used in Dr Ray Smith's experiment, creating an intense, long-duration burst of x-rays to fire at their target. The NIF laser would do the job nicely, but the target itself required some more thought.

The team's setup could only fire x-rays at an area of a few square millimetres – around 10^{38} times smaller than the real Eagle Pillars! In earlier experiments, they embedded 'clumps' of solid material inside 'clouds' of foam a few millimetres across, representing the structure from which the pillars were formed. When the x-ray photons hit the outer surface of the target, a layer of foam particles was photoevaporated (ablated), in reaction to which a shock wave was launched into the foam. On timescales of 20 nanoseconds (20 billionths of a second), the foam formed into elongated pillars behind the clump, consistent with the shielding model.

These foam targets were incredibly intricate and delicate to make, yet they were vaporised with each shot of the laser. To make sure every shot counted, the researchers used the HYDRA computer code to predict the speed and density of the plasma flow at different points in the structure as it evolved. They could then compare their predictions with real observations of the speeds and densities of gas and dust in the Eagle Pillars, allowing them to perfect the design of the target.

The team's early experiments showed mature foam pillars forming on shorter timescales, consistent with the shielding model. The next step was to adapt the target to test their predictions about the cometary model from a clump embedded in a larger cloud. For this to work, the x-rays would need to last long enough for the shockwave to pass through the clump, allowing the photoevaporated material to collect behind it. The clump itself would also need to be adapted to dynamically add plasma to the pillar after the shock wave had passed through it.

To do this, the researchers adapted the shape and design by adding more x-ray producing gold cylinders that were then illuminated in sequence, lengthening the timescale of the x-ray pulse representing the hot, young O-star to 60 nanoseconds – long enough for cometary structures to form. For the clump, they used a series of denser foam disks, which became successively less dense away from the x-ray source. When the shock wave exited the back side, the clump contributed plasma to the earlier-formed pillar.

So far, the researcher's results have been promising for the cometary model, with the beginnings of cometary structures being observed in the foam pillars after 60 nanoseconds. In the future, they would like to adapt the clumps to more realistically represent those in the Eagle Pillars. This would involve creating spherical clumps that become denser towards the middle – a difficult task that is only now becoming possible with improvements in 3D printing technology.

Dr Pound would also like to explore how magnetic fields could have influenced the formation of the Eagle Pillars. 'Strong magnetic field lines could provide a "tension" that forces the gas to expand in a certain direction and prevent it from expanding in another,' he explains. 'Alternatively, a weak magnetic field would get swept along as the gas moves. We have proposed astronomical observations to measure the existing magnetic field in the Eagle Pillars using NASA's SOFIA airborne observatory. The results of these observations will guide the design a new generation of lab experiments that include the addition of a magnetic field.' Whichever direction the research takes, it's intriguing to think that we can make genuine advances towards understanding astrophysical processes, by recreating them on scales we can measure from the comfort of a lab.

Meet the researchers

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Dr Marc Pound is a principal research scientist at the University of Maryland, where he primarily studies molecular gas clouds and star formation. He completed his PhD in astronomy at the University of Maryland in 1994, after working as a radio astronomer at AT&T Bell Laboratories. He worked as a postdoctoral fellow at the University of California at Berkeley, before returning to Maryland in 1997. Outside of his research, Dr Pound develops software for astronomers using the Atacama Large Millimeter Array, and is involved many university committees on campus, aiming to improve career opportunities for non-tenured faculty members.

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Dr Bruce Remington is a staff physicist at the Lawrence Livermore National Laboratory, where he has worked since 1988. He is now the program leader for Discovery Science at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). Dr Remington received his PhD in experimental heavy-ion nuclear physics from Michigan State University in 1986, and his research has since focused on using lasers to study plasma hydrodynamics, high pressure materials science, and laboratory astrophysics.

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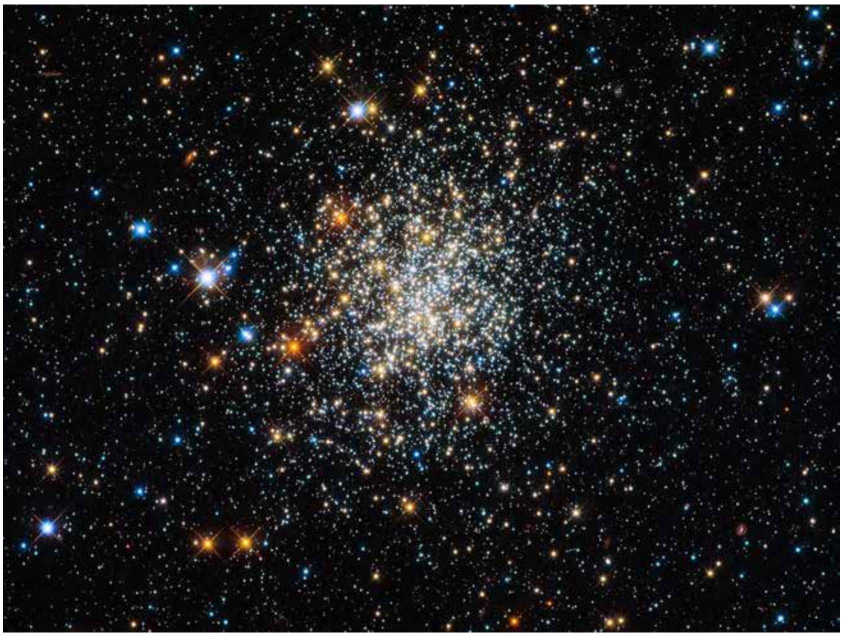
FUNDING

US Department of Energy
US National Science Foundation
National Aeronautics and Space Administration

STUDYING OUR CHANGING SUN BY GETTING TO KNOW ITS RELATIVES

Astrophysicist **Dr Mark Giampapa** of the National Solar Observatory with his team from astronomical centres in the US and Europe try to understand how the magnetic activity of the Sun evolves and how it will behave in the future. The team does this by exploring the characteristics of similar stars in the distant cosmos and using them as a measuring stick for the Sun's variability in the form of spots and flares over time.



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Looking at the Universe today, yesterday and tomorrow, both here in our galactic neighbourhood and out to the distant regions of space, the stars and nebulae seem to act in much the same way. However, this characteristic of uniformity over space and time helps Dr Mark Giampapa and his fellow astrophysicists at the National Solar Observatory explore the interior of the Sun, what it's made of, and the origin of its vast array of variability we see such as spots, flares, and other manifestations of magnetic field-related phenomena.

'The scientific motivation for my work is to gain insight on what our Sun may do next and what it may have done in the past,' Dr Giampapa explains. He says there are a number of ways scientists approach this topic. One angle is to study the Sun's past history – to examine the geological record here on Earth for traces of the Sun's magnetic activity, or to search through historical records for solar observations around the world. This can give us an idea of the Sun's past, at least as far as our data allow us to see.

Scientists can also directly measure solar activity prospectively, using high-precision instruments both on the ground and in space. 'Such data, combined with sophisticated computer modelling techniques, let us probe the structure of the Sun from its deep interior to just below its surface,' says Dr Giampapa. He and his group, however, prefer a different strategy – looking at distant stars that are similar to our Sun.

It turns out that our Sun is not very unusual in the Universe, except for the fact that, as Dr Giampapa puts it, 'the Sun has a solar system with a planet that has life on it asking questions about the universe.' However, there are countless stars in the Universe that are similar to the Sun, which don't happen to host pesky, questioning humans (as far as we know). Our Sun is what scientists call a yellow dwarf star – stars that are generally about 0.85 to 1.14 times the mass of our Sun and are energised primarily by the fusion of hydrogen atoms into helium atoms.

Yellow dwarf stars tend to emit particular frequencies (energies) of light according to the number of atoms of a given element and the conditions of the atmosphere, such as temperature and pressure. One pattern of specific frequencies emitted by these stars is called the Ca II H and K emissions. These signature emissions are due to calcium ions moving from high-energy states to low-energy states, releasing energy in the form of light. In other words, at the specific heat and composition of our Sun, some of the light emitted has characteristic frequencies that can be measured – a type of a starlight fingerprint.

Ca II H and K emissions arise from a special part of the Sun's atmosphere called the chromosphere. The chromosphere is just above the visible 'surface' or photosphere of the Sun, and is actually hotter than the

‘The scientific motivation for my work is to gain insight on what our Sun may do next and what it may have done in the past’

underlying regions. Why it is hotter instead of cooler is a long-standing mystery, but solar physicists believe that energy from nearby magnetic fields heats the chromosphere and the overlying corona, which is even hotter.

Similarly-sized stars – such as yellow dwarves – can be expected to have similar spectral fingerprints. Although only about 5% of the stars in our galaxy are very similar to our Sun, this still equates to billions of candidates. Therefore, that what happens to these stars during their lives can also be expected to happen to our Sun. According to Dr Giampapa, ‘I observe stars like our own Sun to learn about the full range of activity our Sun may produce.’ In other words, looking across the Milky Way at stars similar to our Sun may enable Dr Giampapa’s team to predict what our Sun will do in the near future.

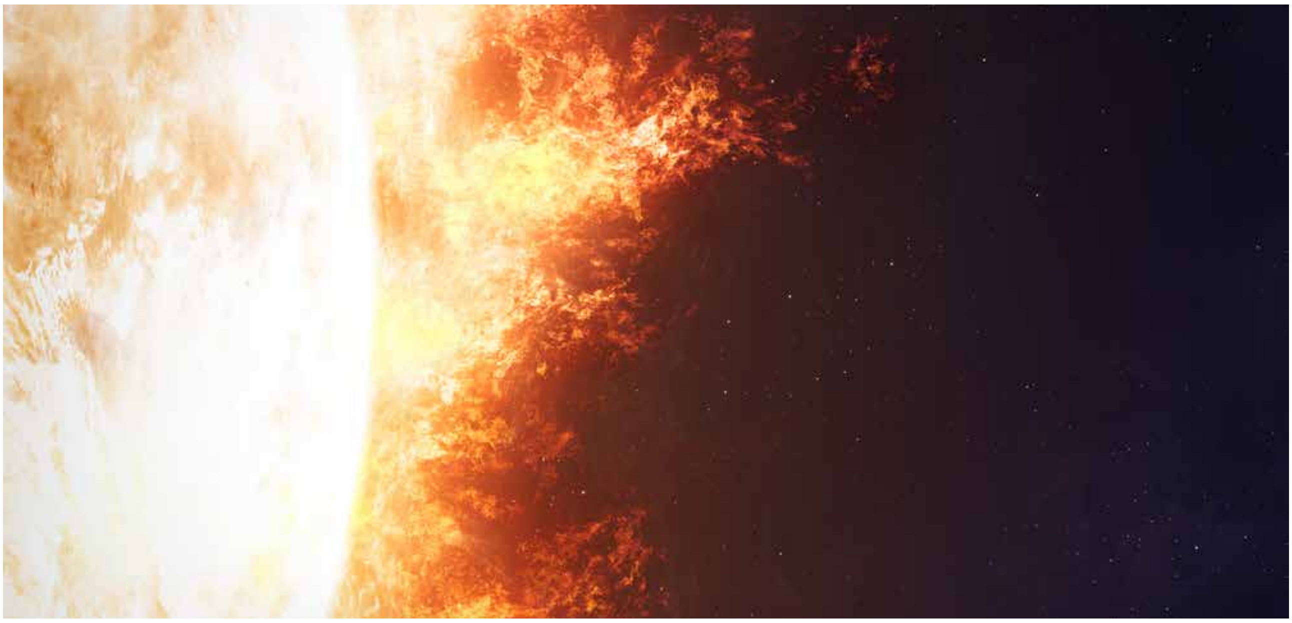
Our Sun’s Close Relatives

When searching for stars like our Sun, Dr Giampapa and his colleagues look for stars that have physical and chemical similarities to the Sun, what they call ‘solar twins’. Forty years of searching has yielded a number of candidates, but Dr Giampapa’s new favourites reside in a star cluster called Messier 67, or M67. Dr Giampapa’s team is particularly interested in M67 as it contains numerous stars that are about the same age and composition as our Sun.

The team has investigated M67 closely with ground-based telescopes at the WIYN Observatory (operated by the NOAO) and comparison observations of the Sun-as-a-star with the McMath-Pierce Solar Telescope Facility – previously operated by the National Solar Observatory. Their data, published in The Astrophysical Journal, revealed that of 60 sun-like stars they identified in M67, two-thirds of them had H and K emissions within the same range as our Sun. ‘Since these solar-like stars of M67 would be expected to be in different phases of their individual sunspot cycles, we can learn about the potential full range of activity that our Sun may exhibit at its current age by studying these stars,’ says Dr Giampapa. In fact, other researchers from Sweden and Canada actually identified one of these stars – M67-1194 – as having emissions almost identical to the Sun’s. It was also about the same age, about 4 billion years – a virtual solar twin! Remarkably, an Italian scientist called Anna Brucalassi and her collaborators discovered an exoplanet orbiting around this solar twin, with a mass at least a third that of Jupiter.

Dr Giampapa’s team also took notice of those stars that were not in the two-thirds that matched the Sun. There were some with emissions whose chromospheric energies were too high or too low compared to the Sun. They wanted to know whether these stars had higher (or lower) energy output due to some variation in the stars’ magnetic energy, such as increased (or decreased) sunspot activity, or was it perhaps something else, like a variation in stellar rotation.

The team wanted to understand whether there was something about the increased or decreased magnetic activity that could possibly be analogised to our Sun during periods in recorded history. For example, had similar fluctuations occurred in our Sun, which may have led to historic warming or cooling intervals, such as the extended period of high solar activity that coincided with the Medieval Warm Epoch? In other words, if the higher activity of some M67 sun-like stars was due to increased rotational speed, then that perhaps wouldn’t be applicable to the Sun – as the Sun can’t suddenly start rotating faster. But if the increased energy output was due to



increased sunspot activity or flares, then that may be something to think about. In either case, Dr Giampapa and his team wanted the answer and they found it.

In another paper published in The Astrophysical Journal, Dr Giampapa and his colleagues reported their data from 15 sun-like stars in M67 that they observed using the European Southern Observatory's Very Large Telescope ('VLT') located high in the mountains of Paranal, Chile. They employed what is called the 'Ultraviolet Visual Echelle Spectrograph' – the UVES – an advanced machine that can see very weak stellar signals.

Using the VLT, the team collected energy data on the sun-like stars of interest and compared this data with the same energy fingerprint of the Sun, by collecting light that reflected off Jupiter's moon Ganymede. Much of Ganymede is covered with water ice, so it serves as a good reflector of the Sun's light. It is also at a good distance from Earth, allowing scientists to get an idea of what the Sun might look like from distant space. The team's comparison showed that stars with a fingerprint similar to that of the Sun were rotating at similar speeds. On the other hand, stars with higher magnetic energies were rotating at higher speeds. Basically, because these stars were rotating faster than the Sun, they were producing more magnetic activity due to sunspots and flares.

Why these stars are rotating faster at an age near that of the Sun is yet to be determined. Perhaps it has something to do with their size, or perhaps it has to do with the magnetic properties of their atmospheres. Whatever it is, it's something for Dr Giampapa and his team to investigate further, perhaps by looking at a broader sample of sun-like stars, some that are a little warmer or a little cooler, or a little larger or a little smaller, and correlating other parameters with those of the Sun. As we've learned from other explorers of the unknown: 'The truth is out there'. And Dr Giampapa is hot on its trail.

The Next Steps in Solar Research

In 2009, NASA launched the Kepler spacecraft to search for other planets capable of sustaining life. With a powerful Schmidt telescope located in stable Earth orbit, Kepler scoured the heavens for years and produced exciting data on thousands of planets orbiting hundreds of stars in our galaxy. But like all machines, Kepler started to wear out and lost a couple of its reaction wheels, so it can't remain stable enough to continue its original mission.

In an effort to make use of its remaining capability, Kepler was repurposed by NASA and turned into a veritable guest observatory. Kepler's new mission – termed 'K2' – is to be let out to planetary, stellar, extragalactic, and solar system scientists. Scientists can submit proposals for what they want Kepler to photograph, and if it's feasible, they might get some time on the telescope. Dr Giampapa and his colleagues are already on board.

'The kind of data we can obtain with K2 on the solar-type stars in M67 would have been impossible to obtain on the ground in terms of quality and uninterrupted continuity over a period of about 75 days,' says Dr Giampapa. He should know – he's tried it from more than one high-powered land-based telescope. His team has a K2 project coming up to look at some of the same sun-like stars in M67 to add to the data they have already collected. They can then extend the investigation of the brightness variability of the stars to even higher precisions than are possible with Earth-based systems.

'We are also planning to use large telescopes, such as the LBT (Large Binocular Telescope) in Arizona and the VLT in Chile, coupled with their powerful spectrographs, to measure more accurately the activity parameters that characterise the "Suns of M67",' explains Dr Giampapa. Since M67 is at a near-equatorial location in the sky, this makes it accessible to Earth-based telescopes in both hemispheres. But at about 2700 light years away, Dr Giampapa says that the sun-type stars in M67 are relatively faint. Therefore, using a space telescope such as K2 is ideal for acquiring much higher-quality data as it orbits above Earth, and thus avoids a lot of the interference associated with the atmosphere.

Ideally, Dr Giampapa wants to organise a dedicated program with suitable instruments to monitor this cluster several times a month, to trace the sunspot cycles of these stars and compare them to those of our Sun. 'This kind of program will become more feasible as robotic telescope technology advances and costs for moderate-aperture facilities decline,' he says. In this way, we can begin to better understand the array of phenomena exhibited by humanity's most important star, by understanding the lives of its closest relatives.

Meet the researcher

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Dr Mark Giampapa received his PhD in Astronomy from the University of Arizona in 1980. After this, Dr Giampapa carried out postdoctoral research at the Harvard-Smithsonian Centre for Astrophysics from 1980 to 1982. Since 1997, Dr Giampapa has been a tenured astronomer at the National Solar Observatory, as well as an Adjunct Astronomer & Lecturer in Astronomy at the University of Arizona. The National Solar Observatory is managed for the National Science Foundation in the United States by the Association of Universities for Research in Astronomy. Dr Giampapa's research interests include stellar dynamos, stellar cycles and magnetic activity, exoplanet system characterisation, and asteroseismology. He is currently interested specifically in unravelling the past and future evolution of the Sun through studying similar-sized stars at various distances from the Earth. Dr Giampapa has authored or co-authored nearly 200 articles, both in peer-reviewed journals and other professional publications. He is also a member of American Astronomical Society, including its Solar Physics Division, as well as the International Astronomical Union. Aside from his interest in outer space, Dr Giampapa also enjoys being closer to Earth as a certified private pilot, rated for single engine aircraft.

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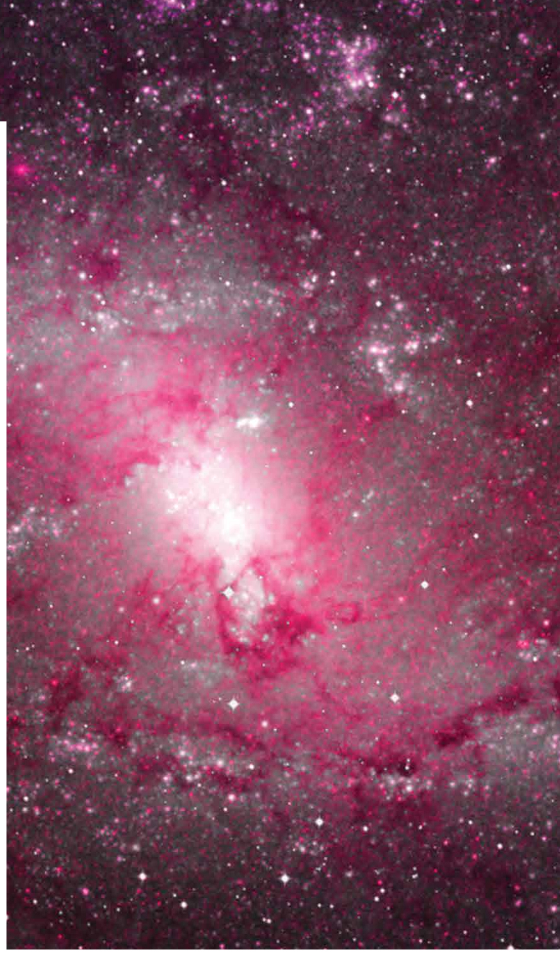
FUNDING

National Science Foundation
NASA



CREATING RADIO MAPS OF THE UNIVERSE

For thousands of years, humans have been fascinated by what lies beyond our own planet. One of the ways to study the most distant objects in our universe is using radio telescopes. By studying radiation emitted in the radio band of the electromagnetic spectrum, scientists can determine the magnetic field strength, gas density and energy content of planets, stars and galaxies. Astronomer **Dr Robert Mutel** has been using these techniques for decades, and has recently discovered ways to map a star's magnetic field using radio emission.

The Mystic Barber

Professor Robert Mutel, Professor of Astronomy at the University of Iowa, has been interested in astronomy for a long time. 'As with most children, I was fascinated by the stars and especially the idea of extra-terrestrials,' he says. 'This sounds strange, but at the age of 11 or 12, I met a barber in NYC where I lived that called himself the Mystic Barber.

'He claimed to communicate with aliens using a tin-foil helmet device on his head. I was doubtful, but I decided to try to find UFO spacecraft by staying up all night lying in a lawn chair and recording every strange light I saw. That was the start of my career as an astronomer!'

Although he is yet to discover aliens, Professor Mutel has been studying planets, stars and galaxies using radio emission for decades. As an undergraduate majoring in Physics at Cornell, he witnessed the excitement and fierce debates surrounding pulsars, which had just been discovered in England. At the same time, the rapidly rotating stars were being observed with much better precision at Arecibo Observatory, the world's largest radio telescope, which Cornell operated.

'The astrophysics seminars were like attending a World Cup game,' Professor Mutel says, 'with intense intellectual fervour and a sense that history was being made. I was hooked, and decided to attend graduate school and become an astronomer.'

Creating Radio Maps

'Most of my research has focussed on understanding astrophysical plasmas in a variety of environments,' Professor Mutel says. 'I study mostly radio emission from these plasmas, usually with radio interferometers that provide highly detailed "radio maps" of the emission.'

A basic astronomical interferometer uses two telescopes, but they can be made up of arrays of multiple telescopes. They work together to provide a higher resolution image, through the superposition of signals gathered by each telescope. The advantage of this technique is it can theoretically produce images similar to those of a much bigger telescope. For a single telescope to produce an image of the same quality as that of an array, it would have to have an aperture equal to the separation between the component telescopes. Professor Mutel and his team use a type of interferometry called very long baseline interferometry (VLBI), where the baselines, or distance between component telescopes, exceed 10,000 km.

By studying spectral characteristics, time variations, and spatial extent of emissions, researchers can determine physical properties, such as gas density, magnetic field strength, and energy content of both the gas and magnetic field. These in turn provide clues to the possible ways the parent object was formed – which could be a galaxy, planet or star – and what its probable life cycle will be.

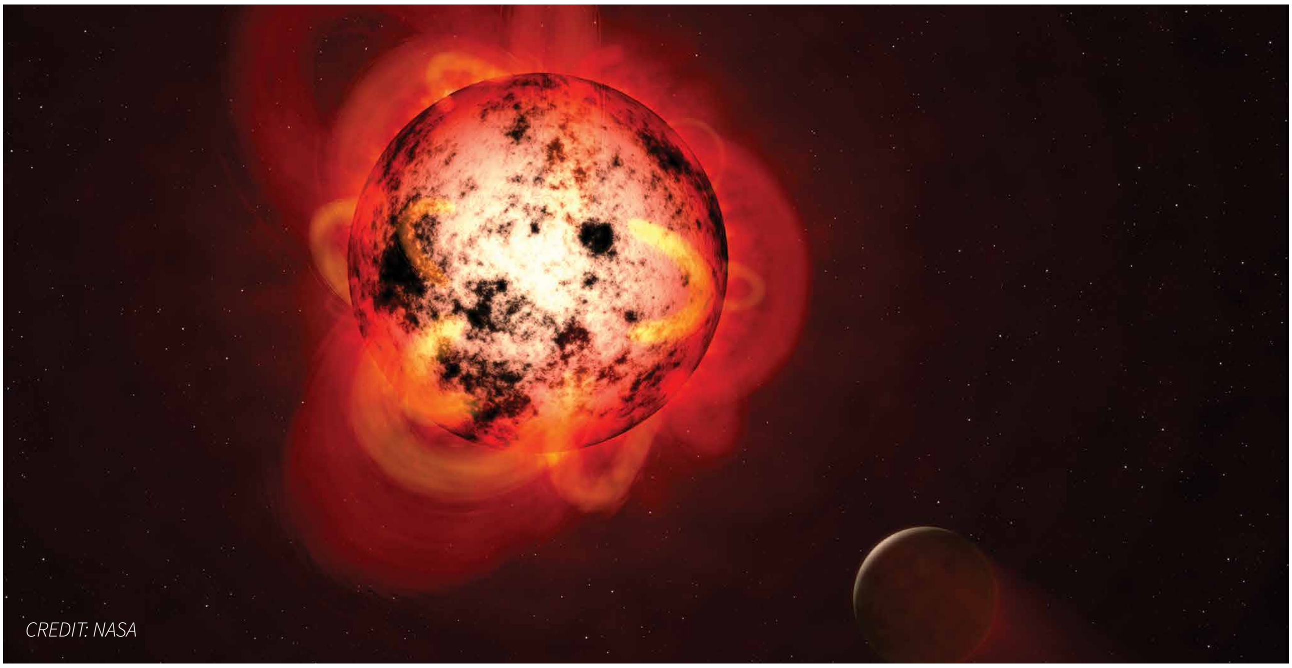
Professor Mutel started off his career looking at 'active galaxies'. This refers to galaxies

whose centres contain a massive black hole, which produces intense beams of radio emission.

Later Professor Mutel moved onto studying planets, including the magnetic fields of planets in our solar system. He found that the magnetospheres of Earth, Jupiter, Saturn, Uranus, and Neptune produce intense radio waves through a process called the electron cyclotron maser instability (ECMI).

'We built the first radio interferometer in space that precisely determined the location of these emissions, which turned out to be above the auroral regions of the Earth,' Professor Mutel

‘We use the VLBA, a global array of radio telescopes, to map locations of stellar radio emission with a precision of less than one milliarcsecond, the equivalent of being able to read a newspaper in London from New York’



CREDIT: NASA

explains. ‘In fact, the Earth’s aurorae and ECMI radio emission are two manifestations of the same phenomenon.’

Recently, Professor Mutel and his research team have been studying the radio emission from stars. In particular, they have been learning how to gather information about the magnetosphere of stars from its radio emission. ‘We use the VLBA, a global array of radio telescopes, to map the radio emission location with a precision of less than one millisecond, the equivalent of being able to read a newspaper in London from New York,’ Professor Mutel tells us. In recent studies, his team have done so with two particular classes of stars called active binaries and ultra-cool dwarfs.

Investigating Active Binaries

Active binaries are pairs of stars that orbit each other, meaning that their brightness varies from our viewpoint on Earth. These stars are interesting because stars in short-period binary systems often show signs of enhanced magnetic activity. These can include persistent photospheric spots, ultraviolet chromospheric emission, X-ray emission from hot coronae, and non-thermal radio emission.

In a 2010 study, Professor Mutel and his group looked at the first of these active binaries ever to be discovered. The system called ‘Algol’, also known as the ‘Demon star’, is a system of three stars thought to have first been documented by the ancient Egyptians 3,200 years ago. The Demon star has been a source of intrigue for astronomers ever since, and is one of the best-documented binary stars as a result.

Two of the three stars in this system are in a very close binary orbit, with one of the stars eclipsing the other every 2.86 days. This blocks the companion’s light for a total of six hours each eclipse, causing a noticeable dip in its light that can be observed even without a telescope. Professor Mutel and his team studied the Alogl binary system to understand more about its magnetic activity. They found that the cooler component had a large coronal loop extending out of its surface oriented toward its companion star. This hints that a persistent magnetic field structure, with an asymmetric shape, is aligned between the stars.

A year later, Professor Mutel and his team published another paper, this time looking once again at Algol, and also another triple star system called UX Arietis, located in the northern zodiacal constellation of Aries. Both star systems are made up of two larger stars orbiting each other, with another, less-massive star orbiting the close binary pair. In this paper, the scientists pinned down the exact orbits of both systems of orbiting stars, using an array of eleven telescopes located across the globe from Hawaii to Germany. They also found an interesting feature on UX Arietis based on the radio signals they gathered. After noticing a single, partially resolved emission region, they deduced that the signal was likely to be associated with a persistent polar spot observed optically using Doppler imaging.

Two years ago, Professor Mutel and a team published a paper looking at another active binary star system, this one called HR 5110. They used a global radio interferometer to study the binary system over six observing periods spanning 26 days. The team was trying to determine the exact location of radio emission within the binary system. They wanted to see if it came from a single active star, or from a region of magnetic interaction between the stars. The results pointed towards there being a single active component on one of the stars, instead of interactions between stars.

Exploring Ultra-Cool Dwarf Stars

More recently, Professor Mutel has moved on to investigating another, completely different type of star known as an ultra-cool dwarf. Ultra-cool dwarf stars are very small, about one tenth the radius of the Sun, and have effective surface temperatures of less than half of the Sun's surface temperature. This means that they are barely hot enough for nuclear fusion to occur. Surprisingly, many ultra-cool dwarf stars emit intense, highly polarised pulsed radio emission, making them extremely interesting to Professor Mutel and his team.

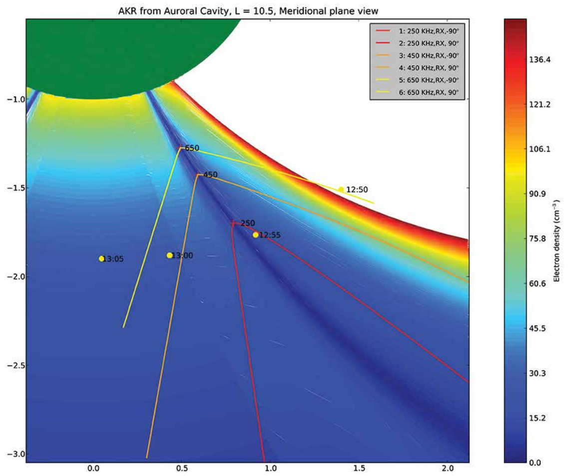
'These stars have ECMI emission, just like the Earth, and it is also highly beamed, like a pulsar or a rotating lighthouse,' Professor Mutel says. 'This causes the star, which is spinning about once every few hours, to emit short pulses of radio emission as seen from Earth.'

By modelling the frequency-time structure of the pulses, the scientists can infer where the emission is located on the star's surface and the strength of the magnetic field. 'In other words, we can make an image of the star's active regions, this is analogous to taking a conventional optical image of the Sun's sunspots on its surface,' he says. The technique, which he referred to as 'spectral tomography' is analogous to creating a three-dimensional image of the brain using time-sliced images from a medical CT scanner.

Professor Mutel has recently been awarded a three-year grant from the National Science Foundation (NSF) to continue this work. He hopes to study the dynamical spectra of more of these low-mass ultra-cool dwarf stars that exhibit pulsed radio emission. Then, he and his team hope to use these studies to come up with detailed models of the stars' magnetospheres.

Moving from Radio to Optical

After forging a career from investigating radio signals, Professor Mutel



is hoping to take a slightly different direction with his research in the future. 'After a long career studying mostly astrophysical radio emission, I am now pursuing some research using optical telescopes,' he explains.

Professor Mutel built the Iowa Robotic Observatory (IRO) in Arizona, a small but powerful robotic optical telescope, almost 20 years ago, and now he is hoping to use this experience towards building a new optical instrument. 'A graduate student and I recently applied for a patent for an innovative new miniaturised optical spectrometer,' he says.

The optical observations are not going to completely take over his time, however. 'Of course, I am not abandoning my radio studies, but new intellectual challenges are what started my career – I suppose that's what I have always enjoyed.'

Meet the researcher

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Since 1986, Professor Robert L. Mutel has been a Professor of Astronomy at the University of Iowa. He obtained his BA in Physics at Cornell University in 1968 and a PhD in Astrophysics at University of Colorado in 1975. In 2015, he received the University of Iowa Hancher-Finkbine Faculty Award and Medallion for teaching and research excellence. Mutel Peak in Antarctica is named in honour of his Antarctic magnetospheric research and service. He is also the director of the Iowa Robotic Observatory.

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FUNDING

National Science Foundation
Carver Trust
NASA

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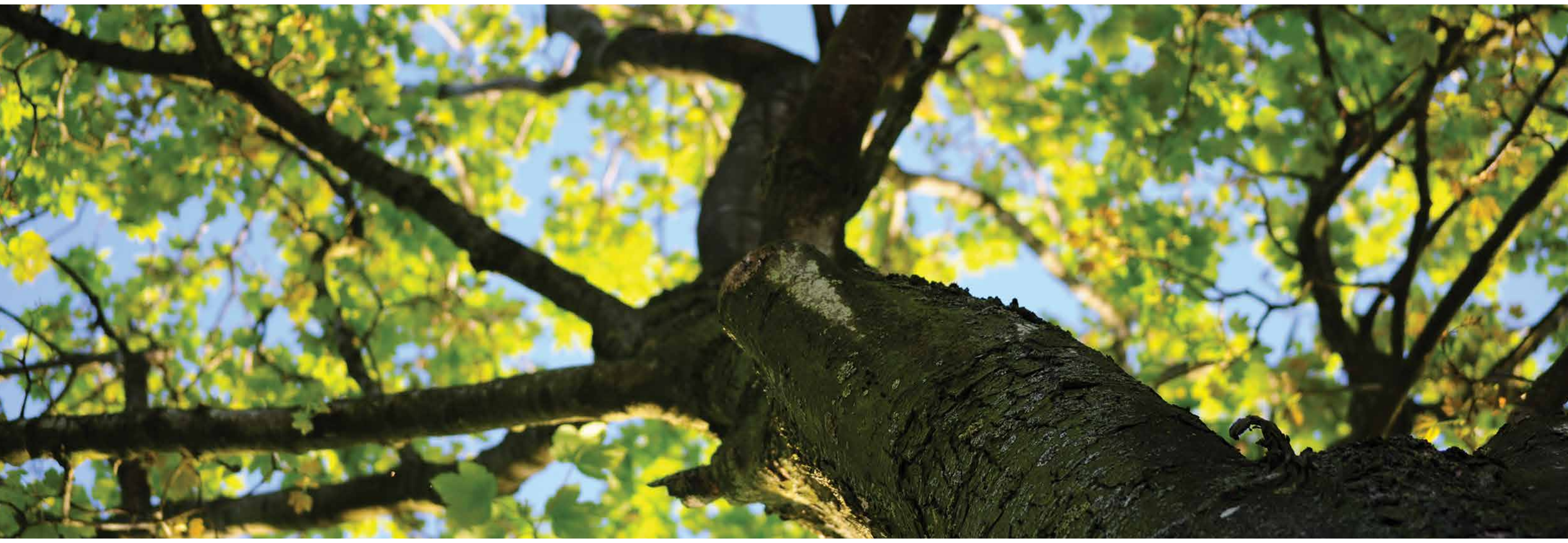
The University of Iowa

Trees for Cities
Breathing life into your neighbourhood



WHO WE ARE

Trees for Cities is the only charity working on an international scale to create greener cities. Since 1993, we have engaged over 70,000 people to plant over 650,000 urban trees in parks, streets, schools and housing estates across the UK, as well as internationally, revitalising these areas and improving the lives of the people who live in them. We strengthen communities through volunteering opportunities and inspire children to grow and eat good food and to connect with nature.

WHAT WE DO AND WHY WE DO IT

We focus on planting trees and greening community spaces where the social and environmental impact on local people is greatest. In London this might mean planting trees to clean the air or transforming unused community spaces into vibrant green areas, making our communities happier and healthier places to live, whilst in Nairobi it's planting fruit trees for food and sustainable livelihoods.

HELP US PLANT A MILLION URBAN TREES BY 2020

To date we have planted over 650,000 trees in cities. We have now set ourselves an ambitious new target to strive to plant 1 million urban trees by 2020. Help us meet this exciting new milestone...

CORPORATE PARTNERSHIPS AT
www.treesforcities.org/corporate-services/

DONATE ONLINE AT
www.treesforcities.org/donate/

FIND OUT HOW TO GET INVOLVED AT
www.treesforcities.org/get-involved/

MISSION

- Planting trees and greening cities worldwide.

VALUES

- **People-led:** Although our reach is global, we value the importance of a local focus. We always work through and within local communities to strengthen them and empower their members.
- **Quality-driven:** Both the quantity and quality of the trees we plant are at the forefront of our planning so that we constantly strive to maximise the impact of our projects to the environment and society.
- **Delivery-focused:** We are an organisation that gets things done. What we talk about, we do – effectively, efficiently and on-time.

WHY TREES MATTER

- Trees help our environment and the impact of climate change:
- They remove 4m tonnes of carbon from the UK atmosphere each year (Forestry Commission 2010)
- They can cool the air by 2 - 8 degrees C
- Trees absorb water, lowering stress on storm water drains and mitigating flood risk
- A single mature oak tree can host up to 423 different species of invertebrates that support birds and mammals
- Each year Trees for Cities plant around 65,000 trees in cities worldwide, revitalising cities and enhancing the lives of the people that live in them