physicsworld
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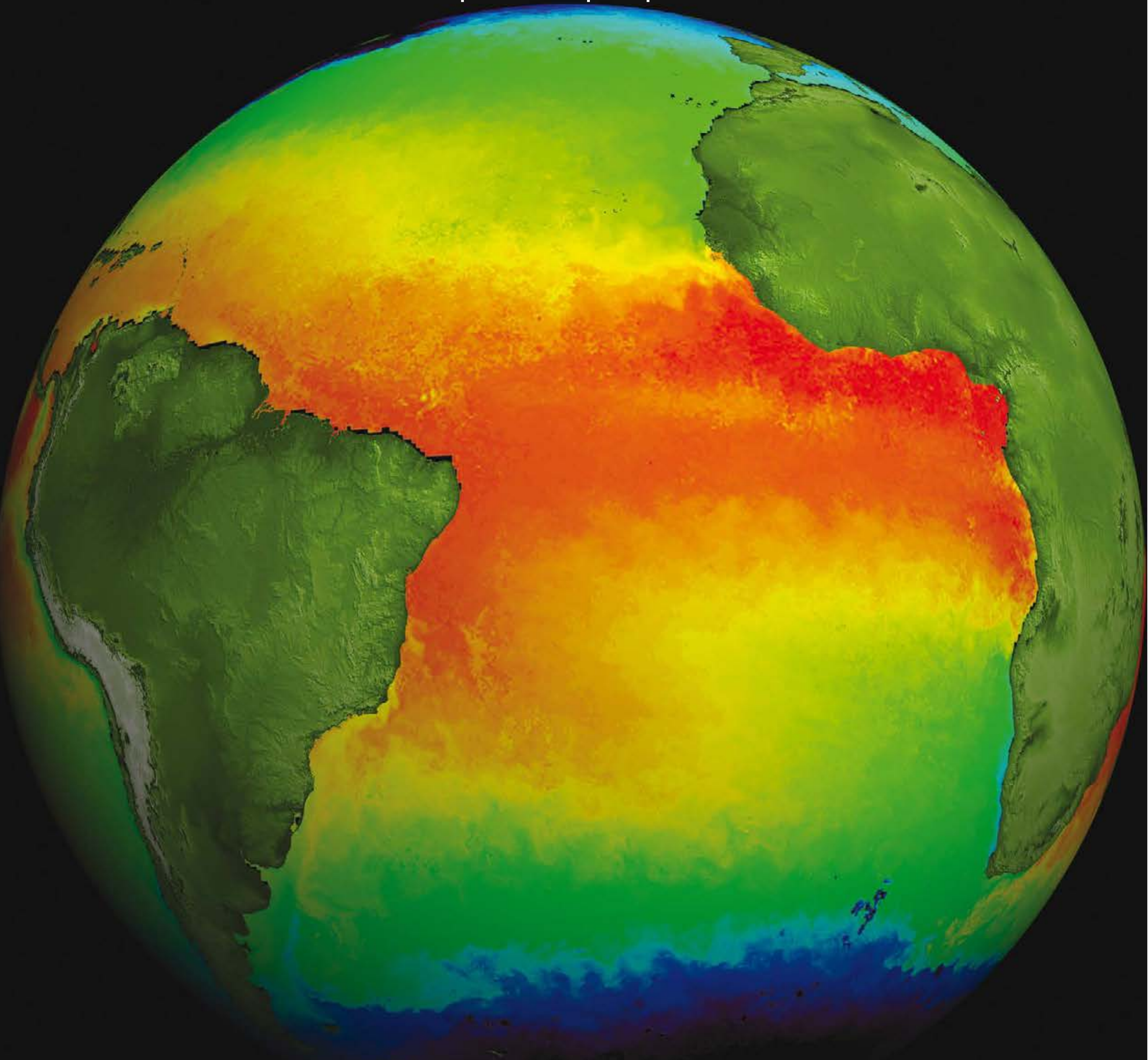
Volume 25 No 3 March 2012

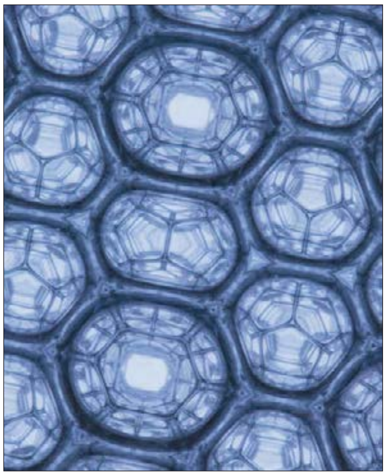
# PHYSICS AND THE EARTH

Our planet in perspective



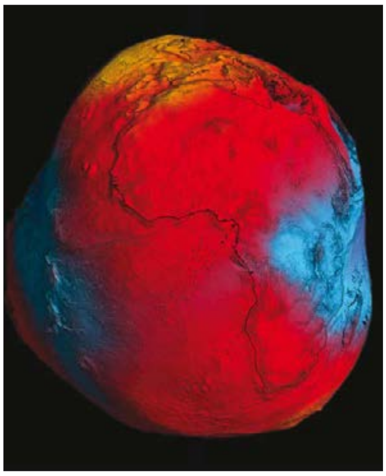
# physicsworld

Ruggero Gabbrielli



Spot on – creating the "ideal foam" 5

ESA/HPF/DLR



Potato-shaped – Earth's gravity map 30–35

**On the cover**
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*Physics World* is published monthly as 12 issues per annual volume by IOP Publishing Ltd, Temple Circus, Temple Way, Bristol BS1 6BE, UK

**United States Postal Identification Statement**
*Physics World* (ISSN 0953-8585) is published monthly by IOP Publishing Ltd, Temple Circus, Temple Way, Bristol BS1 6BE, UK. Air freight and mailing in the USA by Publications Expediting, Inc., 200 Meacham Ave, Elmont NY 11003. Periodicals postage at Jamaica NY 11431.
US Postmaster: send address changes to *Physics World*, American Institute of Physics, Suite 1NO1, 2 Huntington Quadrangle, Melville, NY 11747-4502



## Physics and the Earth

# Quanta

## For the record

**By the end of my second term, we will have the first permanent base on the Moon**

*US Republican presidential candidate* **Newt Gingrich** *speaking at a campaign rally in Florida*

Gingrich says he wants Americans to "think boldly about the future" and for the country to have the capacity in space that the "Chinese and Russians will never come anywhere close to matching".

**We already have a word for those who clamour to send Americans back to the Moon: lunatics**

**Robert Park** *from the University of Maryland in his* What's New *bulletin*

Park says that Gingrich's plans are not only very expensive, but also "insane".

**We live in a world where it's quite all right to be proudly ignorant of Faraday or Einstein**

*CERN director-general* **Rolf-Dieter Heuer** *speaking at the World Economic Forum in Davos, Switzerland*

Heuer says science faces a challenge to reverse "a trend in society towards scientific apathy, and even antagonism".

**I would hate it to come down to a shootout**

**Thomas Ludlam**, *chair of the physics department at the Brookhaven National Laboratory, New York, quoted in* Science

Ludlam was commenting on budget difficulties at the US Department of Energy, which may have to choose between continuing to run the Relativistic Heavy Ion Collider at Brookhaven or building the $615m Facility for Rare Isotope Beams at Michigan State University.

**Particle physics? I don't think so. The whole place was a front for snowboarders**

*Comedian* **Ben Miller** *writing in* Eureka!

Miller says that the Large Hadron Collider at CERN is really just a smokescreen for physicists wanting to get some time on Alpine slopes.

**Nobody had cut the weeds. It looked so sad**

**Jill Tarter**, *an astronomer at the SETI Institute in Mountain View, California, quoted in the* New York Times

Tarter was commenting after astronomers returned to the Hat Creek Observatory in California, which reopened thanks to private donations plugging budget cuts at the University of California, Berkeley.

## Seen and heard

Nuclear Decommissioning Authority

### Nuclear gnashers

Cleaning up a redundant nuclear plant is usually a very serious business. But workers decommissioning the Dounreay site in northern Scotland could be in for a surprise after news emerged that deep inside the plant's iconic sphere lies half a set of false teeth. According to the February issue of *Dounreay News*, the dentures belonged to a colleague of retired engineer Don Ryan, who worked on the site from 1961 until 1994. Speaking as part of an oral-history project recording the memories of workers at the site, Ryan revealed that the colleague "just happened to be leaning on rails beside the instrument panels, facing outwards towards the spherical steel 'wall' " when he sneezed "quite energetically". Half a set of false teeth then disappeared from view "under the influence of gravity and the internal sphere slope" before the choppers "rattled down to the never-visited bottom-sphere skirt". Ryan adds that the colleague even tried claiming for his gnashers, but the UK Atomic Energy Authority, which then ran the site, "rebuffed [this] in firm administrative terms".

### Bet you can't win?

Are you looking to make a cool $100 000? If so, Scott Aaronson has a challenge for you. The mathematical physicist at the Massachusetts Institute of Technology is offering this princely sum to anyone who can convince him that scalable quantum computers are impossible. This might seem like easy money – after all, physicists have struggled for years to build even the most primitive quantum processors, and scaling these up to make a working quantum computer seems a tall order. But Aaronson is not talking about hardware – instead, he wants you to disprove the underlying quantum physics that would make a quantum computer tick. "This is a bet on the validity of quantum mechanics as it's currently understood," he explains. Aaronson is confident he can raise the money and he even thinks it would be well spent, because disproving some or all or quantum mechanics would lead to a revolution in physics. As *Physics World* went to press, Aaronson had not yet received any serious entries but, with no time limit on the challenge, it's time to start thinking.

### Meteoric wine

"Earthy", "floral", "oaky". Wine tasters are known for their rich vocabulary when describing different wines but now they can add "hints of meteorite" to their repertoire. That is because UK astronomer Ian Hutcheon has released a wine that is aged with a lump of 4.5-billion-year-old meteorite. Dubbed Meteorito, the extraterrestrial wine was created at Hutcheon's Tremonte Vineyard in Chile using Cabernet Sauvignon grapes picked in April 2010. These underwent "malolactic fermentation" for 12 months in a wooden barrel containing the meteorite, before being blended with other batches. The three-inch meteorite apparently belongs to a US collector and is believed to have crashed into the Atacama Desert in northern Chile around 6000 years ago. About 10 000 litres of the meteor-aged wine have been made but if you want to get your hands on a splash, then you will need to make a trip to the Centro Astronomico Tagua in Chile – an observatory Hutcheon established in 2007.

iStockphoto/DarrenMower

### Fringe science

Physicists in the UK have taken the whole concept of "fringe science" to a new level by studying that hairstyle of choice for men and women of a certain disposition – the ponytail. Raymond Goldstein of the University of Cambridge, Robin Ball of the University of Warwick and Patrick Warren from shampoo-maker Unilever claim that the shape of a ponytail is defined by a competition between gravity, the elasticity of individual hairs and their mutual interactions (*Phys. Rev. Lett.* **108** 078101). And because a ponytail can contain as many as 100 000 hairs, the problem is best addressed using statistical physics. The researchers derived an "equation of state" for a ponytail that includes what they dub a "Rapunzel number" – a dimensionless measure of ponytail length. The equation was then used to predict how the shape of a ponytail varies with length, with a real ponytail requiring an additional term that reflects hair getting frizzier as it grows longer. Why anyone would want a ponytail in the first place, however, remains unanswered.

# Frontiers

## In brief

**Cool sun could host habitable planet**
An international team of scientists has discovered a potentially habitable super-Earth orbiting within the habitable zone of a cool star that is a member of a triple-star system located about 22 light-years away. This is the fourth exoplanet found within the habitable zone of a star – the first was found last May – and its discovery demonstrates that habitable planets could form in more varied environments than previously thought. The new planet receives 90% of the light that the Earth receives but because the light is infrared, a higher percentage of this energy must be absorbed by the planet. The researchers believe that the planet absorbs about the same amount of energy from its star as the Earth absorbs from the Sun, meaning that the surface temperature is similar to that on Earth, which in turn suggests that liquid water could exist on the planet's surface. However, further information about the planet will be needed to confirm this hypothesis.

**Frequency comb reaches extreme ultraviolet**
Physicists in the US have created an optical frequency comb that, for the first time, operates in the extreme ultraviolet (XUV). The comb, which could be used to look for tiny variations in the fine-structure constant, consists of a train of laser pulses with peaks that are evenly paced in frequency, like the teeth on a comb. It was created using a high-power laser to make an intense infrared comb within an optical cavity. The cavity was then filled with xenon gas, which gets ionized by the laser, liberating electrons that are accelerated and emit pulses of XUV light. These pulses bounce back and forth in the cavity to create XUV combs in the 40–120 nm wavelength range. The team used the comb to study specific atomic transitions in argon and neon at wavelengths of 82 and 63 nm, respectively.

**Heating cools a semiconductor**
Laser cooling has been used on a solid film of semiconductor for the first time, reducing its temperature to a chilly 4 K. In the study, researchers from Denmark reduced the vibrations of a thin-film semiconductor membrane placed in an optical cavity so that it captures light between two reflectors. The semiconductor absorbs the photons, exciting them to electrons that then fall back to a lower energy before releasing that energy as heat. This changes the length of the cavity, which in turn cools the semiconductor. The team suggests that with future developments, the semiconductor's temperature could be chilled further so that its vibrations are reduced almost to the quantum ground state in at least one direction.

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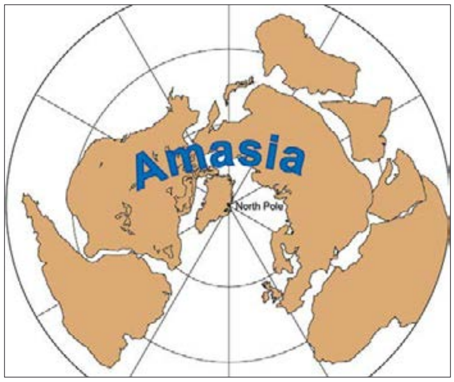
## How supercontinents are born



R Mitchell *et al.*, *Nature*

**Merged** Amasia: the next supercontinent.

Geophysicists in the US have developed a model that may have finally solved the riddle of how supercontinents form. The model suggests that each new supercontinent assembles a quarter of the way around the globe from the centre of the previous supercontinent. Projecting their model into the future, it indicates that the next supercontinent – "Amasia" – will form as a merger of the Americas and Asia via the Arctic Ocean.

The collision of continents into one huge landmass – and their subsequent drifting apart – is thought to have occurred several times during the Earth's history, in a cycle of 300–500 million years. Rifting and drifting occurs at subduction zones – areas on the planet where two tectonic plates move towards one another and one slides under the other. The last supercontinent, Pangaea, began to disintegrate about 200 million years ago and two competing hypotheses have previously tried to explain how a new supercontinent would form.

The first says that the continents will continue to drift apart as they do today, with the Atlantic Ocean continuing to widen – eventually bringing together North America and Asia. In this "extroversion model", the new supercontinent would be situated on the opposite side of the globe to its predecessor. The second idea is that the continents at some point do a U-turn and drift back towards their starting position. This "introversion model" relies on new subduction zones opening up that would allow the Atlantic oceanic crust to sink back beneath the continents, closing off the Atlantic Ocean and forming a new supercontinent in the same location as Pangaea.

However, as neither of these models successfully explains all of the features of previous supercontinent transitions, geophysicists at Yale University, led by Ross Mitchell, have now developed a different model that they say provides a better fit for past data. In their "orthoversion model", after a supercontinent breaks up, the continents initially drift apart but become trapped within a north–south band of subduction – a relic of the previous supercontinent. The new supercontinent forms in this band, one-quarter of the way around the Earth or at 90° from the centre of its predecessor.

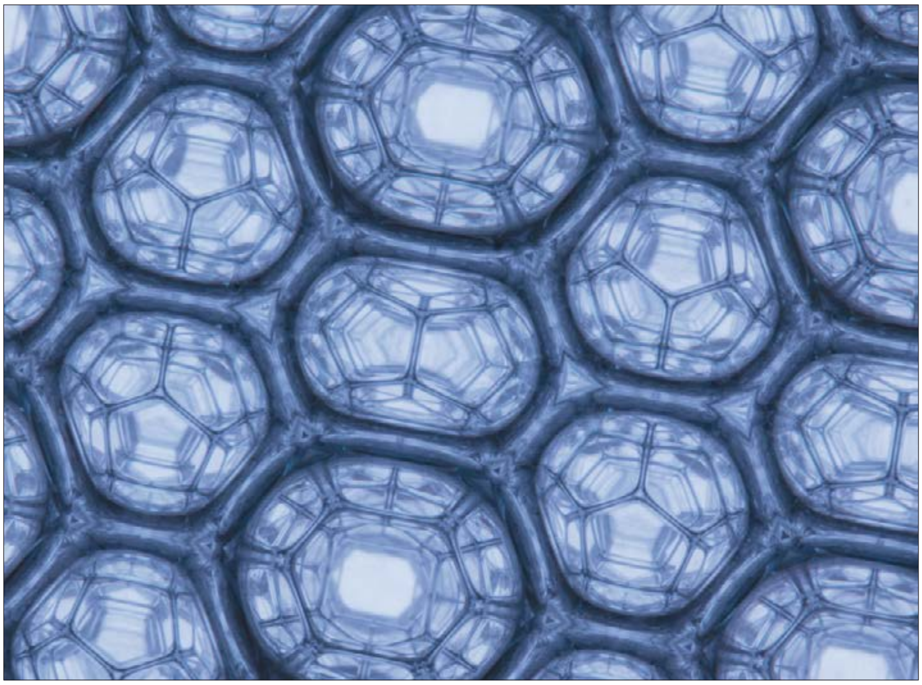
To test their model, the researchers used paleomagnetic data – records of the Earth's magnetic field preserved in rocks – to study variations in the rotation of the planet with respect to its spin axis. Their analysis reveals an angle of 87° between Pangaea and its predecessor Rodinia, and an angle of 88° between Rodinia and its predecessor Nuna. From this, the researchers inferred that the new model best describes supercontinent transitions (*Nature* **482** 208).

## Filters of the future

Researchers at Manchester University in the UK, led by Nobel-prize-winner Andre Geim, have made an ultrathin membrane from graphene oxide that appears to be highly permeable to water while being impermeable to all other liquids and gases. Graphene oxide is like ordinary graphene, which was co-discovered by Geim in 2004, but is covered with molecules, such as hydroxyl groups. Each membrane consists of millions of small flakes of graphene oxide stacked on top of each other, with nanometre-sized capillaries between the flakes.

Geim and colleagues found that water passes through the graphene-oxide membrane extremely fast, while all other gases and liquids are completely blocked by it. According to the team, water is able to flow through the capillaries with minimal friction. Indeed, the water diffuses though the graphene-oxide sheets so quickly that it is as if it were passing through air.

The researchers say the membranes are impermeable to other substances because the graphene-oxide sheets are arranged such that there is only room for one layer of water molecules. So when water passes through the capillaries, it blocks them and does not allow any other substance to go through. And if there is no water, the capillaries shrink and do not let any other substances through. The new property could lead to much more efficient water filters or a way of removing water from a mixture or container while retaining all the other ingredients (*Science* **334** 422).



Ruggero Gabbrielli

## Getting to the froth of the matter

The foam in this image might have been made using everyday Fairy Liquid detergent, but it is also the first ever example of a "Weaire–Phelan foam", which physicists believe is the lowest energy structure for a foam formed of equal-volume bubbles. The first theoretical concept for an "ideal foam" of equal-sized bubbles was developed by Lord Kelvin back in 1887 and was considered to be the ideal until 1994, when Trinity College Dublin physicist Denis Weaire and his student Robert Phelan identified from computer simulations that a foam at an even lower energy should exist. The Weaire–Phelan foam is a complex 3D structure of two kinds of equal-volume polyhedral bubbles, and is 0.3% lower in energy than the Kelvin foam. Making one proved tricky, however, until Ruggero Gabbrielli from the University of Trento in Italy realized that the problem lay with the shape of the containers used, and so designed a receptacle with walls of an intricate form that encourage and accommodate the Weaire–Phelan bubbles. The foam is created by placing the special template in a simple solution of water and Fairy Liquid, with bubbles introduced by releasing nitrogen gas from a glass capillary. The resulting foam was backlit and photographed using a digital SLR camera. The samples that were produced comprised up to 1500 bubbles (*Phil. Mag. Lett.* 10.1080/09500839.2011.645898).

## Why spider webs endure

The incredible robustness of spider webs, which lets them survive even the fiercest of storms, is down to a feature of the silk that localizes damage to small sections of the web. That is the finding of researchers based in the US and Italy, who claim that this property of spider silk could help civil engineers to devise more robust structures.

Spider silk is known to have a greater tensile strength than high-grade steel. But previous studies have not explained how spider webs can remain relatively intact after being subjected to extreme loading such as hurricane-strength winds. A team led by Markus Buehler from the Massachusetts Institute of Technology now says it has an answer after combining modelling with experiment to relate the nanoscale properties of spider silk to the large-scale integrity of spider webs.

A spider's silk is made from basic proteins, including some that form thin, planar crystals called beta sheets. When stress is applied to a strand of this silk, the sheets slide across each other, until the silk eventually ruptures. To examine this process of structural failure, Buehler's team developed an atomic-scale simulation of silk from the *Nephila clavipes* – a species of golden orb-web spider native to the warmer regions of the Americas. It revealed that when the spider silk is subjected to an applied load, its stiffness varies in a nonlinear fashion. Under light stresses, the silk responds fairly uniformly by softening and spreading the load across the entire web. But at high stresses, the material becomes stiffer near the applied load but remains soft elsewhere in the web.

When the failure point is eventually reached, the stiff silk ruptures, but only in the region where the load was applied. In this way, the web is effectively sacrificing only a small section, which can then be repaired by the spider (*Nature* **482** 72).

### Innovation

## Raman technique peers into cabin baggage

Every seasoned flyer knows better than to carry a large bottle of shampoo, perfume or even champagne in their hand luggage. But all that might change, thanks to researchers in the UK who have developed a scanner that can be used at airports to screen liquids in opaque or translucent bottles. The device could allow the ban on liquids of more than 100 ml in hand luggage to be lifted as early as 2013.

The scanner uses a technology known as spatially offset Raman spectroscopy (SORS), which was invented and developed by Pavel Matousek and collaborators at the Rutherford Appleton Laboratory in the UK in 2004. A variation on conventional Raman technology, it provides a chemical analysis deep within a sample and can be used to scan everything from bone beneath skin and drugs in plastic packages to liquids in opaque bottles. The new scanner is known as the INSIGHT100 and was developed by Cobalt Light Systems – a company founded by Matousek in 2006 to exploit the SORS technique.

Conventional Raman spectroscopy relies on the inelastic backscattering of photons as light interacts with matter. Normally, the scattered photons are detected from the same spot on the sample that has been illuminated. The problem is that Raman signals from surface layers tend to dominate those signals from within the sample.

To get around this issue, the researchers collect photons from a spot a few millimetres away from the illuminated area – a "spatially offset" spot. This works because photons migrate from the illuminated spot and travel through the body of the sample. Thus, SORS delivers a smaller surface signal and a sharper signal from deeper within the sample, while always being non-invasive.

The current ban on liquids of more than 100 ml in hand luggage can only be lifted when airports are able to screen liquids quickly and without opening containers. While X-ray scanners currently do that job, they produce high false-alarm rates, which slow the screening process. Cobalt claims that the false-alarm rate with the INSIGHT100 is considerably lower, at 1% or less, and that the scanner can screen individual bottles in less than 5 s and also provide a high chemical specificity with all types of containers in a variety of sizes. The scanner has already passed the stringent testing procedure necessary to allow it to be trialled and is now being used at an undisclosed number of major European airports. Matousek points out that the scanner is to be used in parallel with X-ray scanners as it "complements the existing technology".


*Conditions apply. See tda.gov.uk/conditions for full details.

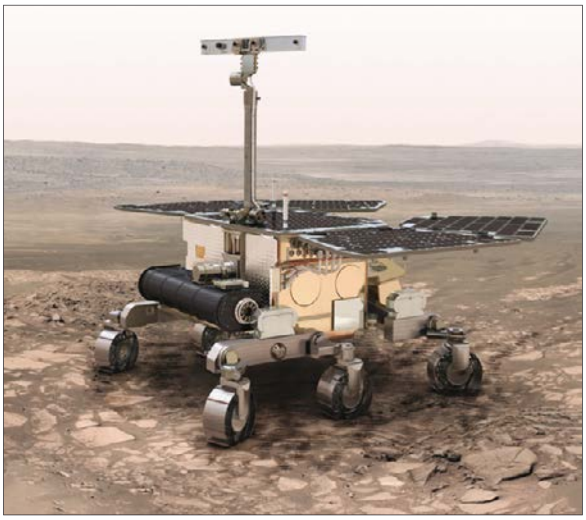
# News & Analysis

## Mars mission in doubt as US pulls out

The future of a joint US and European mission to Mars is uncertain after NASA told the European Space Agency (ESA) that it is pulling out of the €850m ExoMars venture. The US withdrawal comes following the US president's budget request, released last month, which sees NASA's $1.5bn planetary-science budget slashed by 21%, with Mars exploration receiving $360m – a 39% cut from 2012 levels. ESA is now in discussion with the Russian space agency Roscosmos about ExoMars's future.

ExoMars, which is supposed to launch in 2018, consists of two parts. The idea is to launch a Trace Gas Orbiter in 2016 to orbit Mars and map the red planet for sources of methane and other gases. Two years later, an ExoMars rover, weighing almost 300 kg, would be launched to search for possible signs of life on Mars, characterize the water and geochemical distribution of the surface, and identify any hazards for future manned missions to the planet.

While NASA's overall 2013 budget is similar to 2012 – roughly $17.7bn – the agency still needs to pay for its flagship James Webb Space Telescope (JWST) mission, the costs of which are expected to balloon from $476.8m in 2011 to $659m in 2014. It is this hike that has resulted in the need for cuts elsewhere in the programme and the cancelling of NASA's involvement in ExoMars. NASA administrator Charles Bolden said in a statement that the agency would instead "develop an integrated strategy to ensure that the next steps for Mars exploration will support science as well as human-exploration goals, and potentially take advantage of the 2018–2020 exploration window".



ESA

**Down and out** Budget constraints mean that NASA will pull out of the €850m ExoMars mission, which was set to launch its first stage in 2016.

The president's budget request still has to pass through Congress, which is unlikely to be easy in an election year. However, regardless of what budget emerges, severe cutbacks will have to be made. "Having just been involved in a near-death experience for the JWST, I am very sympathetic to the feelings of my scientist colleagues who are dealing with the cancellation of a key Mars mission," says astronomer Garth Illingworth, who is chair of the JSWT advisory committee. "I am particularly concerned that these cuts are affecting our international partners significantly."

Meanwhile, a report by the National Research Council recommends the US makes a £20m contribution to ESA's Euclid dark-energy mission. Euclid, to be launched in 2019, will map the large-scale distribution of dark matter and characterize the properties of dark energy. The committee says that the US should still go ahead with building the Wide-Field Infrared Survey Telescope, to be launched in 2020, which would search for dark energy as well as search for exoplanets. "NASA involvement in Euclid is, I hope, a start to renewed international collaborations," adds Illingworth.

**Michael Banks**

**Russia**

## Plans unveiled to reincarnate Phobos-Grunt

**Russia has announced it may launch a second mission to Mars's moon Phobos after its original Phobos-Grunt mission ended in disaster in January when scientists lost contact with the craft and it crashed back down to Earth. Lev Zelenyi, director of the Institute of Space Research at the Russian Academy of Sciences, which was behind the Phobos-Grunt mission, told a press conference in Moscow that a new spacecraft, named provisionally as Phobos-Grunt 2, could be launched in 2018.**

**The timing of the new mission is designed to take advantage of a launch window when Mars will be particularly close to the Earth. Such windows occur roughly every 26 months, but the next window in 2013 does not leave enough time to prepare for the new mission, while the 2016 window coincides with Russia's planned lunar projects.**

Roscosmos

**Second time lucky?** Russia may launch a successor to the failed Phobos-Grunt mission to Mars' moon Phobos.

**Zelenyi says the new mission will be a pared-down version of Phobos-Grunt, retaining the control systems from the original design but with less instrumentation and simpler rovers for exploring the surface of Phobos. However, he cautions that the plans for the new mission are still in the very early stages. "Nothing has been decided yet," he told *Physics World*. Indeed, Roscosmos, the Russian federal space agency, has been in discussions with the European Space Agency (ESA) since late last year about participating in the ExoMars mission – another mission to the red planet that is set for 2016 (see above). "If no deal is reached [with ESA], we will repeat the attempt [to launch a Phobos mission]," says Roscosmos boss Vladimir Popovkin.**

**Meanwhile, following intense speculation about why Phobos-Grunt failed, an official report has concluded that a computer malfunction, possibly caused by a burst of cosmic radiation or defective microchips, was to blame. Phobos-Grunt's failure also affected China, which had its own Yinghuo-1 orbiter aboard the craft. Wu Ji, director-general of the National Space Science Centre of the Chinese Academy of Sciences, told *China Daily* last month that the country has had to rethink its plans for Mars exploration, with a new mission in 2016 at the earliest.**

**Simon Perks**

India

# Blacklisted former space boss protests at 'witch hunt'

The Indian government has blacklisted four top space scientists for alleged "procedural lapses" when negotiating a $250m deal for the leasing of two communications satellites to an Indian private company. The four scientists include G Madhavan Nair, former head of the Indian Space Research Organization (ISRO), who guided ISRO in launching the country's first mission to the Moon in 2008. The others are K R Sridhara Murthi, former head of the Antrix Corporation in Bangalore, K N Shankara, former head of the ISRO Satellite Centre in Bangalore, and A Bhaskaranarayana, former director of ISRO's satellite-communications programmes. All four, who have been banned for life from holding any government positions, deny any wrongdoing.

The controversy dates back to 2005 when Antrix – ISRO's commercial arm – signed a deal with Bangalore-based Devas Multimedia Private Limited to build two high-powered communications satellites that would deliver India with multimedia and information services, even to those in remote areas. On 17 February 2011, however, the government cancelled the contract citing "increased strategic needs". It then appointed two internal investigation committees – the first led by B K Chaturvedi, a former cabinet secretary, and the next by Pratyush Sinha, a former Central Vigilance Commissioner – to look into the situation. In a statement on ISRO's website, Sinha's report says "We conclude that there have been not only serious administrative and procedural lapses, but also suggestion of collusive behaviour on the part of certain individuals."


Pallava Bagla

**Lunar pioneer** G Madhavan Nair, former head of the Indian Space Research Organization, guided the agency in launching the country's first mission to the Moon.

Nair claims he did nothing wrong and that no rules of government were violated, but the key sticking point is that he and others apparently did not inform the government in writing that ISRO was manufacturing and leasing communications transponders to a private company and that the spectrum was sold too cheaply. To date, neither ISRO nor Devas Multimedia has been accused by the government of any wrongdoing.

Nair claims that the scientists have been subjected to "a witch hunt". He now wants Indian prime minister Manmohan Singh to put a hold on implementing the ban. "The condemnation and tarnishing of the images of these scientists is beyond all comprehension and against the principles of natural justice," Nair wrote in a letter to Singh. "The four scientists have given their sweat and blood to the country…they virtually gave the Moon to the country." Nair adds that no formal enquiry has been conducted and the four have not been "given any chance to present or defend the case". The matter is now being heard in India's Supreme Court.

**Pallava Bagla**
New Delhi

South America

# Theoretical-physics hub opens in Brazil

**A new centre for theoretical physics has opened in Brazil that aims to become one of the leading research institutes in South America. The centre – named after the renowned International Centre for Theoretical Physics (ICTP) in Trieste, Italy – will be located at Universidade Estadual Paulista (UNESP) in Sao Paulo. Known as the ICTP South American Institute for Fundamental Research (ICTP-SAIFR), the new centre was officially opened on 6 February in a ceremony attended by the president of the Brazilian Academy of Science, Jacob Palis, as well as Peter Goddard, director of Institute for Advanced Study, Princeton, US.**

**The ICTP-SAIFR has been created in a collaboration between the ICTP, UNESP and the Sao Paulo Research Funding Agency. Its activities are modelled on those of the ICTP and will begin with the centre holding international schools and workshops. Among the first events will be a workshop on gravity and string theory in May and a school on astrophysics and cosmology in July.**

**A meeting of minds** Physicists including ICTP director Fernando Quevedo, fourth from right, at the opening of the ICTP South American Institute for Fundamental Research in Sao Paolo.

**Initially, there will be five permanent researchers as well as a director, who is the Brazilian physicist Nathan Berkovits. The centre expects to support about a dozen postdoc positions per year as well as playing host to a number of international visitors and students. With a budget of about $1m per year, the institute will also have an active visitors' programme. "We very much hope that this will be only the beginning of a great new project that will increase the scientific level of the region and that will play a major role in international scientific collaboration," Fernando Quevedo, director of the ICTP in Trieste, told *Physics World*. "I have the highest hopes [for this institute]."**

**Berkovits says that the idea for the institute emerged eight years ago but accelerated once Quevedo became director of the ICTP in 2009. "The ICTP was crucial for the creation of this institute," says Berkovits. "It is, of course, exciting and a great challenge to start this new institute." The opening of the new centre is part of a five-year plan to expand the ICTP into other countries, especially in the developing world. "Brazil, India and China are playing a more relevant role worldwide," says Quevedo. "The scientific level of Brazil is very high and a centre located there can therefore play the same role for South America that the ICTP has already been playing worldwide."**

**Michael Banks**

**Japan**

# Cosmology centre secures long-term future

The future of one of Japan's leading cosmological-research centres appears safe after it was awarded a massive $7.5m cash boost from the US-based Kavli Foundation. The Institute for the Physics and Mathematics of the Universe, which is based at the University of Tokyo, becomes the first centre in Japan to be supported by the foundation. There are now a total of 16 Kavli institutes around the world, including 10 in the US, three in Europe and two in China.

Set up in 2007, the centre will now be known as the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU). It seeks to tackle some of the biggest questions in physics, such as the origin, evolution and fate of the universe, as well as the nature of dark matter and dark energy. The work is carried out on an interdisciplinary basis by more than 200 researchers, including theoretical and experimental physicists, mathematicians and astronomers.

The new money is a vital boost for the institute, which was set up as part of a Japanese initiative to attract scientists from abroad to work in the country. A total of five institutes were founded under the country's World Premier International (WPI) programme, each of which was promised $10m a year for a decade and told to recruit 30% of its researchers from overseas. However, in early 2010 the Japanese government cut the WPI's budget by 22%, raising question marks about the IPMU's long-term future. Plans for two new WPI institutes were then axed, leaving the IPMU with a smaller, but still problematic, 3.6% budget cut.

Kavli IPMU

**A promising future** The five-floor main building of the Kavli Institute for the Physics and Mathematics of the Universe in Tokyo was completed in 2009.

Hitoshi Murayama, director of the IPMU, says that the support from the Kavli Foundation will now help the institute to keep going even when the WPI funding runs out. "The return [from the endowment] is nowhere close to the current funding level, but it is a start," he told *Physics World*. Murayama is confident that the Kavli cash will also bring "prestige and international visibility [that] should help the institute to attract and recruit more scientists". Murayama himself was lured back to Japan to run the IPMU after almost 15 years in the US at the University of California, Berkeley. Currently, some 56% of the IPMU's staff are non-Japanese.

The Kavli Foundation, based in California, was set up in 2000 by the Norwegian-born physicist and philanthropist Fred Kavli. It sponsors research in astrophysics, nanoscience, neuroscience and theoretical physics. It also awards three prestigious $1m prizes each year as well as funding workshops, symposia, Kavli professorships and a programme for science journalists. "I hope that our support of science in Japan can demonstrate that the quest for knowledge has no boundaries, and that finding the answers to some of science's biggest and most fundamental questions requires international collaboration," says Kavli.

**Matin Durrani**

**Research**

# Manchester set to bid for new Graphene Institute

The University of Manchester in the UK has been invited to be the sole bidder for a new £45m Graphene Institute, which would be housed on the university's campus. Around £38m of the funding will be provided by the UK's Engineering and Physical Sciences Research Council, which says that the institute's main aim will be to "lead the commercialization of graphene through the development of applications, building on the strength of UK research in this field". The rest of the cash is expected to come from the university and also from private investment.

Manchester physicist Andre Geim, who shared the 2010 Nobel Prize for Physics with his colleague Konstantin Novoselov for their work on graphene, says that it is the right time for the UK to invest in this area because countries such as Singapore and South Korea are already doing so. However, Geim has mixed feelings about the new institute and its bent towards commercialization. "My strength has always been in curiosity-driven research, [and] this funding pushes me hard in the direction of the commercialization of graphene research," Geim told *Physics World*. "I was not really looking forward to this new funding. I consider it not as a favour by [the government] but as an extra burden I was asked to carry."

James King-Holmes/Science Photo Library

**Blessing or burden?** Nobel laureate Andre Geim has mixed views about a new institute to commercialize graphene.

A University of Manchester spokesperson says that even at this early stage various companies are showing an interest in working together with the institute's researchers to commercialize graphene, including Samsung, which already has a strong graphene-research programme. Details are scarce about what the new building will look like or when it will open. However, the 40 or so researchers who currently work at the university on graphene are expected to transfer to the new facility, with more scientists then being hired once the institute is open at a date yet to be fixed.

**Kulvinder Singh Chadha**

Publishing

# US bill seeks to overturn NIH research-archiving rule

A bipartisan bill introduced in the US House of Representatives aims to reverse 2008 legislation that requires recipients of National Institutes of Health (NIH) grants to make copies of their peer-reviewed papers freely available online. Introduced in December and sponsored by California Republican Darrell Issa and New York Democrat Carolyn Maloney, the New Research Works Act could limit public access to privately published research, including that funded by the government.

The current legislation means that NIH-funded scientists have to place their papers in the National Library of Medicine's repository, which is free to access for the public. Supporters of the new bill, which would scrap that requirement, include the Association of American Publishers (AAP), whose members includes several publishers of scholarly journals. They argue that the bill is necessary because the process of peer-reviewing and publishing research involves significant financial outlay. "America's professional and scholarly publishers are making more research available to more people through more channels than ever before in our history," the association noted in a statement. "The Research Works Act ensures the sustainability of this industry."


**Change of course** A US bill aims to reverse current legislation that NIH-funded scientists have to place their research in the National Library of Medicine's repository, which is free to access for the public.

However, the bill only has a relatively small chance of passage this year. Indeed, some of the AAP's academic members, including the University of California Press, have come out in opposition. The American Institute of Physics (AIP) – an umbrella group for physical-science societies – and the American Physical Society (APS), both of which publish peer-reviewed journals, have also stated their opposition to the new act. "The proposed legislation is counterproductive to current efforts and not needed at this time," said the AIP in a statement.

"We always allow authors to publish our version of their papers on their and their institutions' websites without embargo," Gene Sprouse, the APS's editor-in-chief, told *Physics World*. "We have 500 libraries signed up to our library initiative, which makes the complete contents of our journals from 1893 to today available to anyone who visits the libraries physically. And starting last year we have made our articles freely available in high schools."

Meanwhile, as *Physics World* went to press, more than 6000 researchers had signed a petition pledging not to publish in Elsevier's journals or to act as a referee or editor for the publisher. They say that peer review is carried out by voluntary, unpaid academics and that the publications serve largely to line the pockets of the publishing company. In response to the boycott, initiated by University of Cambridge mathematician Timothy Gowers, Elsevier declared that it was "proud of the way we have been able to work in partnership with the research community to make real and sustainable contributions to science".

**Peter Gwynne**
Boston, MA

Industry

# Philips and BASF put a new spin on the car roof

At first glance it may look more like a fancy paint job but a new car roof designed by researchers at Philips and chemical giant BASF has the unusual property of giving drivers and passengers a clear view by day before turning into an interior light at night. The roof contains 129 glass hexagons containing organic light-emitting diodes (OLEDs) that are transparent during the day but can generate light when it is dark. The OLEDs are shown here in the roof of a prototype electric Daimler Smart Car.

OLEDs are light-emitting diodes (LEDs) in which the luminescent layer is a film of organic compounds that emits light in response to an electric current. Unlike LEDs, they can emit light from their entire surface area – which creates "softer" light than LEDs. They are already used in rigid form in some display screens and also in interior design, such as in glass table tops.


**Clear view** Organic light-emitting diodes make this car roof be transparent by day but light up at night.

BASF remains tight-lipped about its OLED material, except to say that it has developed dyes and other "organo-chemical" materials that are "used in the development and manufacturing of OLEDs by Philips". The OLEDs are built into glass panes that also contain embedded solar cells, which generate electricity during the day and then store that energy in the car's lithium-ion batteries. This energy is used to power the OLEDs to illuminate the car's interior at night.

It is not certain when the technology might be ready for commercial production and neither BASF nor Philips has said how efficient these OLEDs are. While regular LEDs turn only about 20% of supplied electricity into light (the same as a conventional incandescent light bulb), firms developing OLEDs – especially for electronic gadgets – are still trying to reduce power consumption. For example, Osram – a subsidiary of Siemens – last month claimed to have developed a bendable plastic OLED ribbon that yields 32 lumens per watt (lm/W), which compares with just 10–20 lm/W for a halogen bulb.

**Mark Halper**

Nuclear waste

# US urged to develop new strategy for nuclear waste

The US's failure to get to grips with the long-term storage of nuclear waste has been "damaging and costly", according to the final report by the Blue Ribbon Commission on America's Nuclear Future. The commission's report contains several recommendations, including the need for any future repository to first obtain local consent for any waste facilities. It also says an independent organization should be set up solely dedicated to overseeing the US's nuclear-waste management.

The work of the commission, which consisted of politicians, scientists and engineers, gained particular relevance last year when US President Barack Obama halted work on the planned repository in Yucca Mountain, Nevada. First mooted in the 1980s, the repository was to have stored the US's spent nuclear fuel and high-level radioactive waste.

While the state of Nevada has now vetoed a repository, other states might accept one. "There has been local support in Carlsbad, New Mexico, which already hosts the Waste Isolation Pilot Plant," says commission member Ernest Moniz, director of the Massachusetts Institute of Technology Energy Initiative. "There is no physical reason why a new repository has to come tomorrow or the day after, but what we need fairly urgently is to adopt the overall strategy that the commission has put forward."

US energy secretary Steven Chu, who set up the commission, welcomed the report as "a critical step toward finding a sustainable approach to disposing of used nuclear fuel and nuclear waste". At the request of Congress, Chu's department will now within the next six months develop a strategy for handling spent nuclear fuel and other waste.

**Peter Gwynne**
Boston, MA


Department of Energy

**Waste woes** Work on developing Yucca Mountain into a long-term repository for nuclear waste was scrapped last year by US President Barack Obama.

Space

# Japan plans successor to asteroid mission

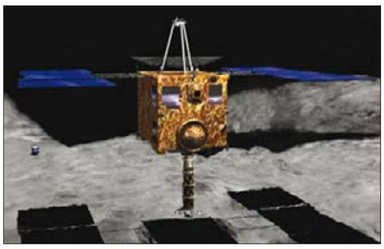
**Japan has announced it is to launch a second asteroid sample-return mission following the success of the Hayabusa craft, which in 2010 returned the first samples ever obtained from the surface of an asteroid. The Space Activities Commission, which governs funding for the Japanese space programme, formally approved the Hayabusa-2 mission in late January. The Japanese firm NEC, which built parts of the original Hayabusa mission, has also announced that it has started designing the communications system and an infrared camera for the Hayabusa-2 craft.**

**Weighing almost 600 kg and costing around $200m, Hayabusa-2 will land on 1999 JU3 – an almost spherical asteroid that is 920 m in diameter and is thought to contain organic matter and hydrated minerals. Hayabusa-2 will attempt to find out where such organic matter and water originated from and how they are related to life and ocean water on Earth.**

**The Japanese Space Agency, JAXA, plans to launch the craft in 2014 when the asteroid's path will be closest to Earth, eventually reaching the body by the middle of 2018. The craft will then land on the asteroid and stay there for around 18 months to retrieve samples before beginning its return to Earth at the end of 2019.**

**While the original Hayabusa mission only scraped the surface of the asteroid it landed on, Hayabusa-2 will instead release a 2 kg impactor before touching down. The impactor will hit the asteroid's surface and make a small crater several metres in diameter. Hayabusa-2 will then land in the crater and collect samples from within the asteroid.**

**Michael Banks**


JAXA

**New and improved** Hayabusa-2 will follow in the footsteps of Hayabusa-1 (pictured), which in 2010 successfully retrieved the first samples ever from the surface of an asteroid.

# Sidebands

### Nobel trio back US neutrino facility

A group of 43 theoretical physicists in the US – including the Nobel laureates Sheldon Glashow, Steven Weinberg and Frank Wilczek – have expressed support for a key component of the proposed $1.3bn Long Baseline Neutrino Experiment (LBNE). The experiment would involve sending an intense beam of neutrinos that are created at Fermilab to a large detector deep inside South Dakota's Homestake mine, lying some 1300 km away. In a letter sent to the US Department of Energy (DOE), the theorists praised the "high discovery potential" of such an underground detector, noting it could be used to study symmetry violation in neutrinos, to search for proton decays and to perform sensitive studies of neutrinos emitted in supernova explosions. The signatories say that the facility's flexibility means it is "urgently needed" even in a time of budget constraints. The support is likely to boost the LBNE's chances of passing a funding review later this summer, when DOE officials are expected to decide whether the project will go ahead.

### CERN ramps up collision energy

CERN has announced that it will increase the energy of proton–proton collisions at the Large Hadron Collider (LHC) from 7 TeV to 8 TeV per beam. The move to a higher energy later this year should help make it clearer whether the Higgs boson has been found with a mass of about 125 GeV, as was suggested in December 2011. Meanwhile, Ximo Poveda of the ATLAS experiment delivered a talk at CERN last month on the latest search for supersymmetry (SUSY). Many physicists hope the LHC will confirm SUSY's central prediction that for each of the Standard Model particles there exists a heavier "sparticle" sibling. Poveda reported on the search for several supersymmetric partners of various quarks and leptons – squarks and sleptons – called the stop, stau and sbottom. However, so far ATLAS has seen "nothing beyond the Standard Model".

### UK physics numbers jump by 8.3%

Applications to study physics at UK universities have shot up by around 8.3%, according to figures from the Universities and Colleges Admissions Service. This year 24 934 students have applied to do a physics course in the UK – up by 2000 on last year's figures. The boost for physics is in stark contrast to the overall 8.7% decline in university applicants across the UK, which is thought to be caused by tuition fees rising to a maximum of £9000 per year for students studying in England.

Q&A

# Understanding the element of life

A new 10-year project funded by the Alfred Sloan Foundation aims to understand how carbon interacts deep within the Earth, and may even answer how life started out. Michael Banks talks to **Robert Hazen**, director of the Deep Carbon Observatory

**So what is the Deep Carbon Observatory?**
The Deep Carbon Observatory (DCO) is a 10-year international programme, which began in 2009, with the object of achieving a transformational understanding of carbon – that is, its biological, chemical and physical role in the Earth, from crust to core. The DCO is co-ordinated from the Carnegie Institution in Washington, DC, where I am based, consisting of about 1000 researchers in 40 countries.

**How did you get funding from the Alfred Sloan Foundation for this programme?**
The Alfred Sloan Foundation is a philanthropic, not-for-profit institution. It had just finished the census for marine life, attempting to classify all ocean life, and so was looking for a new 10-year project. One of its programme officers heard me talk about the origins of life at a conference and asked me about the possibility of Sloan sponsoring a study looking into whether life originated deep within the Earth rather than at its surface.

**So you went ahead with that suggestion?**
I thought that topic alone was too narrow to support a large effort, although it is a very important question. However, I thought about doing a study of how carbon operates within our planet. I wrote a proposal that was accepted by an external committee set up by the Alfred Sloan Foundation.

**How much funding will the DCO receive from the foundation?**
Our approach is that researchers come to us with ideas and then we help to set up collaborations to tackle the issues. There is no set amount, but we expect to fund research to the tune of about $5m per year. We do not see ourselves as a $50m research agency but rather as using Sloan funds to leverage much bigger things. In order to get going fast, we initially provided seed funding for 30–40 projects with about 200 researchers. The next aspect is to get researchers to think about setting up much bigger and longer-term research programmes.


Evan Cantrell

**Asking the big questions**
The 10-year Deep Carbon Observatory programme, led by Robert Hazen, will attempt to fully understand how the Earth uses carbon.

**Why carbon?**
Carbon is an astonishing element. Because it has the widest range of bonding environments, it forms materials with the most extreme range of properties, from the hardest – diamond – to the softest – graphite. Carbon forms biological materials, so it is the molecule of life. As we know, it also has tremendous implications for the environment. And yet we do not even have a clear idea how much carbon there is in the Earth.

We do not even have a clear idea how much carbon there is in the Earth

**Why is it called the "Deep" Carbon Observatory?**
We wanted to make it clear that we are not looking at climate issues, ocean carbon or carbon sequestration. We are studying carbon from a few metres under the ground to thousands of kilometres inside the Earth. The carbon cycle has been intensely studied over the last few decades but the part of the cycle that lies beneath the surface has been largely ignored.

**What are some issues you are tackling?**
A fundamental part of the carbon cycle is tied up with volcanoes. Subduction in the Earth's tectonic plates takes carbon down into the mantle and it is very easy to calculate how much is going down. It is also easy to monitor the amount of carbon coming out via volcanoes. However, there is a vast imbalance between the two, with the carbon emitted from volcanoes being only around 5% of that being subducted. So within a few hundred million years, all of the Earth's surface carbon would disappear and there would be no carbon for life. One very important issue that needs answering is whether carbon diffuses out slowly and steadily through the crust or whether there may be periods when lots of carbon is released more rapidly.

**How will you look for the origins of life?**
Another question we are looking at is the nature of deep hydrocarbons. We know that most petroleum comes from the processing of dead biological matter, but there are suggestions of deep reserves of methane or hydrocarbons that may not be entirely biological in nature but formed by other processes. This idea was first proposed 150 years ago by Dmitri Mendeleev, creator of the first version of the periodic table. It may not be valid, but we need to do experiments to find out whether this is case. That then leads to the origin of life. Where did the first "abiological" molecules come from to form the first living cells? We still do not know the mechanisms that formed these biological molecules.

**Will the DCO have a role in the climate-change debate?**
When you study this subject from a fundamental viewpoint, it has practical implications for bigger questions such as climate change, carbon sequestration and fracking. The kind of discoveries we hope to make will inform some of those questions. We don't want to get directly involved in those debates, but rather provide the ground truth that people can then use to form policy.

**What do you hope to achieve after the 10 years are up?**
We have a number of very ambitious goals. One is to provide real-time tracking of every active volcano on the planet, including its emissions and seismology. We also want a carry out a global census of so-called deep fluids – fluids that lie hundreds of metres below the Earth's surface – as well as a census of deep microbial life to discover the 3D distribution and nature of microbial life within the Earth's crust.

# Settling the fracking question

Energy firms have not convinced sceptics that shale-gas extraction, or "fracking", is safe for the environment. **Jon Cartwright** examines whether physics could help

Hydraulic fracturing, or "fracking", is by any measure controversial. The process – which involves pumping sand and liquid into deep shale deposits to liberate natural gas – has been touted by its proponents as an energy saviour. For them, fracking allows energy companies to tap into reserves that are otherwise difficult, if not impossible, to get gas from. Yet the process has been slammed by opponents as being hugely damaging to the environment.

While fracking has taken off rapidly in the US, it has been banned in France and Bulgaria. Unfortunately, this polarized debate about fracking is not helped by a shortage of facts. No-one is sure to what extent fracking can contaminate groundwater, either with methane or with toxic chemicals. There is also a concern that fracking can trigger moderate earthquakes. While there may be no hard-and-fast answers, it seems that geophysics may be able to prod the debate in a constructive direction.

Without geophysics, of course, fracking would not be possible at all. Shale is a fine, clay-based sedimentary rock that has low permeability, so it will not release its gas into a well easily. To get at the gas, therefore, energy companies have to display their engineering prowess by drilling wells 1500–3000 m deep into a shale deposit and then running a perforated steel pipe horizontally. Millions of litres of water are pumped into the pipe, together with sand and chemicals, at high pressure. The mixture bursts out of the holes in the pipe, creating fractures in the shale around it. Over time, natural gas, which is primarily methane, can then flow from the shale into the pipe and back to the surface, where it can be extracted.

Fracking in this modern form – which can use hundreds of thousands of litres of fluid per well – began in Texas in the mid-1990s, although it only really took off in 2007 when other US states such as Arkansas, Louisiana and Pennsylvania also became sites for drilling. The reason for this strong US interest is that some parts of the country appear to be sitting on massive shale-gas reserves – roughly 2.4 trillion $m^3$, according to the US Geological Survey, which is one of the more modest estimates. Colorado-based business-information company HIS, for example, puts the figure at about 42 trillion $m^3$.

iStockphoto.com/jonmullen

**Heading underground** The International Energy Agency suggests the world might be en route to "a golden age of gas" thanks to the emergence of hydraulic fracturing, or "fracking" – a rig for which is pictured here in Colorado.

The US is not, though, the only nation with large deposits. UK energy firm Cuadrilla Resources estimates around 5.6 trillion $m^3$ of shale-gas reserves in the UK. Hardly surprising, then, that a report last year from the International Energy Agency suggested the world might be en route to "a golden age of gas".

### Halting the gold rush

In his State of the Union address in January, US President Barack Obama embraced shale gas, saying that US reserves could last "nearly 100 years". Obama called for governments to develop a roadmap for responsible shale-gas production and said his administration would move forward with "common sense" new rules to make sure drillers protect the public. "America will develop this resource without putting the health and safety of our citizens at risk," he said.

Environmental campaigners, however, are not letting this route go unobstructed. One problem they highlight is the suspected contamination of groundwater around drilling sites. Last year, ecologist Robert Jackson and colleagues at Duke University in North Carolina published evidence that aquifers in north-east Pennsylvania and upstate New York had been contaminated with methane, which can be explosive in high concentrations (*Proc. Natl Acad. Sci. USA* **108** 8172). That risk had already been highlighted the year before in the documentary film *Gasland*, directed by the US environmental campaigner Josh Fox, which pictured families in Dimock, Pennsylvania, igniting their tap water, allegedly thanks to methane contamination as a result of nearby gas drilling.

A more serious potential problem is contamination with fracking chemicals, which include "surfactants" – short-chain organic molecules that lower the surface tension of a liquid or the interfacial tension between two liquids or a liquid and a solid – as well as chemical compounds that act as friction reducers. Most of these are thought to be relatively benign, but some may be toxic. Indeed, the precise fracking mixture is often kept secret by the energy companies involved.

While it is unlikely that such liquids could seep up from fracture zones to ground level, there is the possibility that they could contaminate water sources via surface spills or poor disposal. There is no peer-reviewed evidence of this, but a 1987 report by the US Environmental Protection Agency, which was brought to light only last year by the *New York Times*, revealed at least one documented instance of fracking-fluid contamination of drinking water. It occurred in 1984 in Jackson County, West Virginia, albeit at a time when there was poorer technology and fewer environmental safeguards.

Anthony Gorody, a consultant at Universal Geoscience Consulting in Houston, Texas, believes such reports of contamination are based on poor science, and that the issues have become less scientific and more political. "In my experience, I have neither found nor seen any evidence to support the contention that hydraulic fracturing is responsible for contaminating shallow groundwater," he says.

But if the issues are mostly political, then both sides might be to blame. "It's a cavalier and frankly idiotic attitude that's causing [energy] companies all these problems," says Steve Cohen, an expert in environmental policy at Columbia University in New York. "They're acting as if it's the gold rush – let's just get out there and start digging. And that sort of attitude breeds mistrust."

**Shaky ground**

Geophysics, and specifically seismology – the study of earthquakes – may be one way to help matters. In fact, seismology has long been used by oil and gas companies as a means to "see" underground. Typically, surface sources of seismic energy, such as dynamite, are used to create minor earthquakes. Then seismologists can measure the subsequent seismic waves to map underground geology and fractures in three dimensions, just as radar is used to map overground terrain.

New techniques in seismology are making this type of mapping both more adaptable and more precise, which may make fracking safer. Rather than using explosions to create earthquakes, seismologists can now monitor the tiny man-made earthquakes, or microseisms, that occur during the fracking process, as rocks fracture and move around. The energy released in these microseisms is relatively small – think of dropping a bag of sugar from a three storey house – but using arrays of "geophones" in adjacent wells, seismologists can just about detect them. This could allow engineers to observe the fracking in real time to see how it is progressing and stop if anything looks suspect. "The industry is getting close to using such data to modify fracture propagation rates in real time," says Gorody. "Quite a feat, but not possible yet."

Another nascent technique in seismology avoids the need for man-made earthquakes altogether. Known as seismic interferometry, it relies merely on the background noise of seismic waves that is ever present in the Earth's crust to map the geology underground. "If you go into a dark room, you need a torch to see something," says Peter Styles, a geophysicist at Keele University in the UK. "But when there's already sunlight, you don't need the torch."

Last year, seismologist Brian Baptie of the British Geological Survey and colleagues showed that seismic interferometry could be used pick out major geological features in the Scottish Highlands, such as sedimentary basins and centres of igneous and metamorphic rock – thereby demonstrating some potential of the technique (*Proc. Geol. Assoc.* **123** 74). Styles believes studies like this show that seismic interferometry and microseismic mapping could help scientists assess where the safest places are to frack in the first place.


**Up in arms**
Environmental campaigners – such as those in the Frack Mob at an industry greenwash conference in London in November 2011 – warn there are many problems with fracking, including the possible contamination of groundwater around drilling sites.

Nanda Nalin/Demotix/Corbis

Earthquakes are one of the greatest concerns about fracking. In April and May last year, for example, two fracking-related quakes of magnitude 2.3 and 1.4 hit Lancashire in the UK. Those magnitudes were not especially high – magnitude-3.1 quakes resulting from coal mining had hit the region in the past – but they were strong enough for protestors to mobilize against the drilling and persuade the energy company performing the fracking, Cuadrilla Resources, to stop operations.

According to Styles, these earthquakes probably occurred because the fracking was done on pre-existing faults. Gaining a more precise knowledge of the underlying geology could reveal these faults beforehand, he says, encouraging energy companies to frack elsewhere. Nonetheless, he stresses that "It's important to realize that without very small earthquakes, we would have no idea what was going on underground when we are carrying out things like fracking."

Without very small earthquakes, we would have no idea what was going on underground when we are fracking

**Climate concerns?**

The potential for any earthquakes caused by fracking may worry some people, but they might find solace in a recent unpublished analysis that shows it could be possible to predict the size of earthquakes caused by fracking (although not the timing or likelihood of their occurring). By studying previous cases of quakes triggered by fluid injection into the ground, geophysicist Arthur McGarr of the University of the Witwatersrand in Johannesburg, South Africa, found that there is a relationship between the magnitude of a quake and the amount of water injected. Double the volume of water, he concludes, and the maximum magnitude quake rises by about 0.4 on the Richter scale.

So could geophysics help scientists better understand the risks of contamination of groundwater by fracking? It may be too soon to tell. However, ecologist Bob Howarth of Cornell University in New York thinks it might be a good time for physicists to begin investigating a related issue: the amount of methane leaked into the atmosphere from fracking sites and gas pipes. Methane is a more potent greenhouse gas than carbon dioxide, so it is important to know exactly how much is lost. "The way to [estimate leaked methane] is using modern atmospheric techniques," Howarth says. "I think you could come up with a pretty good estimate of what the flux might be."

According to Howarth, physicists could both help to design measurement techniques to calculate the flux from the fracking process and use atmospheric techniques such as "eddy correlation", which uses measurements of methane and wind velocity to figure out how much methane finds its way into the upper atmosphere. Indeed, Howarth has reason to think this is an important issue: last month researchers at the US National Oceanic and Atmospheric Administration and the University of Colorado, Boulder, estimated that natural-gas companies in the Denver–Julesburg Basin, which is centred on eastern Colorado, were losing around 4% of their gas to the atmosphere.

Indeed, Howarth's research suggests that, over a 20-year time period, the greenhouse-gas footprint – the total amount of emissions from fracking – of shale gas is worse than that of coal or oil, although other studies have suggested it has a smaller footprint. In any case, he says, the science is unresolved, and depends on how much methane finds its way into the atmosphere. "That sort of [atmospheric physics] approach could give the information that is needed to say, 'We're way too pessimistic and it's nowhere near that big a problem,' or, 'We're too optimistic, and it's worse than we thought.'"

# Comment

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**Subscription information 2012 volume**
The subscription rate for institutions is £330 per annum for the magazine, £625 per annum for the archive. Single issues are £30. Orders to: IOP Circulation Centre, CDS Global, Tower House, Lathkill Street, Sovereign Park, Market Harborough, Leicestershire LE16 9EF, UK (tel: +44 (0)845 4561511; fax: +44 (0)1858 438428; e-mail: iop@subscription.co.uk). *Physics World* is available on an individual basis, worldwide, through membership of the Institute of Physics



**Bibliographic codes ISSN: 0953-8585**
**CODEN: PHWOEW**
Printed in the UK by Warners (Midlands) plc, The Maltings, West Street, Bourne, Lincolnshire PE10 9PH

**IOP** Publishing

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76 Portland Place, London W1B 1NT, UK
Tel: +44 (0)20 7470 4800
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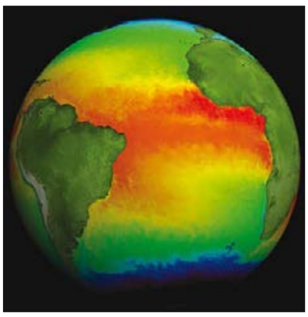
# Our planet in perspective

**This special issue of *Physics World* looks at how physics is helping us to understand the Earth, while our website *physicsworld.com* hosts an accompanying series of video reports**

The devastation unleashed a year ago this month by an earthquake off the east coast of Japan was a reminder, if any were needed, of the deadly power of our planet. The magnitude-9.0 earthquake, which was one of the strongest of the modern age, triggered a huge tsunami that rose to more than 40 m in places and spread up to 10 km inland. Together, the earthquake and tsunami killed more than 15 000 people, with the rising waters doing the most damage, including crippling the Fukushima Daiichi nuclear power plant.

One year on from the Japanese disaster, it is natural that this special issue of *Physics World* on "Physics and the Earth" should include a look at the latest advances in earthquake forecasting. While we are unlikely to ever be able to predict precisely when, where and with what magnitude particular earthquakes will strike, much can be gained from short-term "probabilistic" forecasting, which can give the odds that an earthquake above a certain size will occur within a given area and time (see pp58–63). The virtues of this kind of prediction are also underlined in a series of special video reports that you can watch at *physicsworld.com*.



ESA

Ultimately, the best bet for combating the power of earthquakes is to ensure that buildings are as structurally sound as possible. Indeed, the Fukushima Daiichi plant safely survived last year's earthquake; as Mike Weightman – the UK's chief inspector of nuclear installations – points out (pp19–20), what caused the problems was insufficient flood protection. While the plant's tsunami defences had recently been increased to cope with a 5.7 m high tsunami, the waves that engulfed it were nearly three times that height. Those waves subsequently spread right across the Pacific Ocean, vividly depicted in the opening image of our Earth-visualization feature (pp30–35).

On a calmer note, this special issue also describes how neutrinos generated through the decay of uranium, thorium and potassium deep within the Earth are giving us a new technique for understanding our planet (pp44–48). Detecting such "geoneutrinos" is a fiendish task, but two experiments have already managed to do so, in the process revealing new insights into how much heat is generated from radioactive decay. This heat powers many vital processes on Earth, notably mantle convection and plate tectonics. Interestingly, some researchers even think that the movement of the Earth's plates could be linked to one of the long-standing mysteries in geosciences – why our planet's magnetic field has reversed at a rate that has risen and fallen over the years (pp51–55).

Elsewhere, we look at progress in understanding the physical properties of materials in the Earth's core, which includes the bizarre possibility that it may hide huge crystals of iron some 10 km long (pp37–41). We also tackle the controversy over "fracking" (pp14–15), which involves pumping sand and chemicals into shale deposits to release trapped natural gas, and we speak to the head of a project that seeks to understand what happens to carbon that gets subducted into the Earth's crust (p13). And finally, if you enjoyed the images in this issue, why not share your own pictures in the new *Physics World* "photo challenge" group on *Flickr*, which this month is dedicated to Earth sciences (see p27).

# Lessons from Fukushima

One year on from an earthquake and subsequent tsunami that crippled the Fukushima Daiichi nuclear power plant in Japan, **Mike Weightman** says that the quest to improve nuclear safety must never stop

REUTERS/POOL New

**You can never be too careful** A man is checked for radiation on arrival at a vehicle-decontamination centre at J-Village in November 2011. This site serves as an operations centre for those battling the nuclear incident in Japan's Fukushima prefecture.

At 2.46 p.m. local time on 11 March 2011 the biggest earthquake recorded in Japan occurred off the country's east coast. The magnitude-9 earthquake was one of half a dozen earthquakes greater than magnitude 7 to occur on that day. Within an hour, the first of a series of massive tsunamis hit that caused catastrophic damage and loss of life across Japan. The tsunami also led to a serious nuclear accident at the TEPCO Fukushima Daiichi site, with repercussions felt across the international community.

As time went on, the number of dead from the earthquake and tsunami started to rise: final estimates suggest 20 000 people died or are missing. More than 100 000 homes were damaged or destroyed, with whole villages and towns swept away. The disaster is on a scale that we can only imagine here in the UK. Even for Japan, which experiences high seismic activity, it was unimaginable.

In the UK, the Office for Nuclear Regulation (ONR) responded by setting up the Redgrave Court incident suite to provide expert advice for the UK government on the implications for the 17 000 UK citizens in Japan. We also required all of our licensed nuclear sites to promptly answer questions and justify the ongoing safety of their operations. For more than two weeks we operated our incident suite and provided advice to the Cabinet Office Briefing Room – the UK's crisis response committee – and to John Beddington, the UK government's chief scientific adviser. After this, as requested by the secretary of state for energy and climate change, we set about producing an interim report on the implications for the UK nuclear industry.

### Getting back on track

At about the same time, it was with great honour and no little humility that I accepted an invitation from the International Atomic Energy Agency (IAEA) to lead a team of nuclear experts from around the world on a fact-finding mission to Japan from 24 May to 1 June 2011.

The earthquake and tsunami particularly affected the five nuclear plants along the Japanese east coast. My IAEA team visited three of them: Tokai, Fukushima Daiichi and Fukushima Daini. At all these sites I encountered tales of bravery, leadership and resilience. Workers at the Daini site laid 9 km of heavy power cabling by hand in 16 hours to ensure initial safety systems worked to cool and control the reactors, while those at the stricken Daiichi plant had to resort to novel means, using what they had to hand in attempts to secure cooling of the reactor.

I was particularly impressed by the commitment of the several-hundred-strong workforce at the Daiichi site, who all stayed on for days after the tsunami struck, despite not knowing whether it had affected their villages and put their families at great risk. This type of uncompromising loyalty and determination is commonplace in Japan; it is testament to the country's spirit that its people approached the disaster with characteristic stoicism, discipline and organization. Everyone I encountered was willing to help with total openness and transparency.

All the evidence supports the view that the Daiichi plant safely survived the massive earthquake

Looking back, the visit achieved its aim to identify lessons from which the whole world can learn. Ultimately, it appears that the Japanese authorities underestimated the hazard presented by the tsunami. This was despite adequately estimating the hazard presented by the earthquake.

The magnitude-9 earthquake caused severe ground motions that lasted for several minutes at the Daiichi plant. The measured motions reasonably matched the predictions of the designers of the seismic protection measures. Upon detection of these ground motions, the safety systems at Daiichi shut down the reactors and started the back-up systems. All the evidence I have seen, including the evidence at the other Japanese nuclear power plants that witnessed similar ground motions, supports the view that the Daiichi plant safely survived this massive earthquake.

However, the flood protection measures at the Daiichi plant were originally designed to withstand a 3.1 m high tsunami, whereas the largest wave that crashed into the site in March inundated it to around 15 m. A review in 2002 by the operators of the Daiichi plant did result in increases to the tsunami defences to enable it to better survive a 5.7 m high tsunami. This improvement still proved to be inadequate, especially considering the history of tsunamis along that coast over the past century.

### Lessons learned

The IAEA team presented a summary report to the Japanese Government on 1 June and, later that month, presented its full report to a ministerial meeting in Vienna, at which the world community sought to learn lessons from Fukushima. In response to a request from the secretary of state, I have produced two reports (with massive help from colleagues in the ONR and elsewhere) on lessons for the UK nuclear industry – an interim report in mid-May and a final report in September 2011.

My final report reaffirmed the conclusions and recommendations in my interim report and added to them, resulting in 17 conclusions and 38 recommendations in total. Overall, I remain confident that there are no fundamental weaknesses in the regulation of the UK nuclear industry or indeed in the industry itself. We have a consistent and well-founded approach to safety assessment in the UK , including for extreme natural hazards. Additionally, the affected reactors at the Daiichi plant were all boiling-water reactors, which do not form part of the UK fleet. The UK reactors are either advanced gas-cooled reactors or, in the case of Sizewell B, one of the most modern pressurized-water reactors in the world. The UK is also far from any edge of a tectonic plate and therefore is not at risk from frequent or extreme seismic activity (and their subsequent tsunamis). Although this is reassuring, this is not a time for complacency, hence my 38 recommendations.

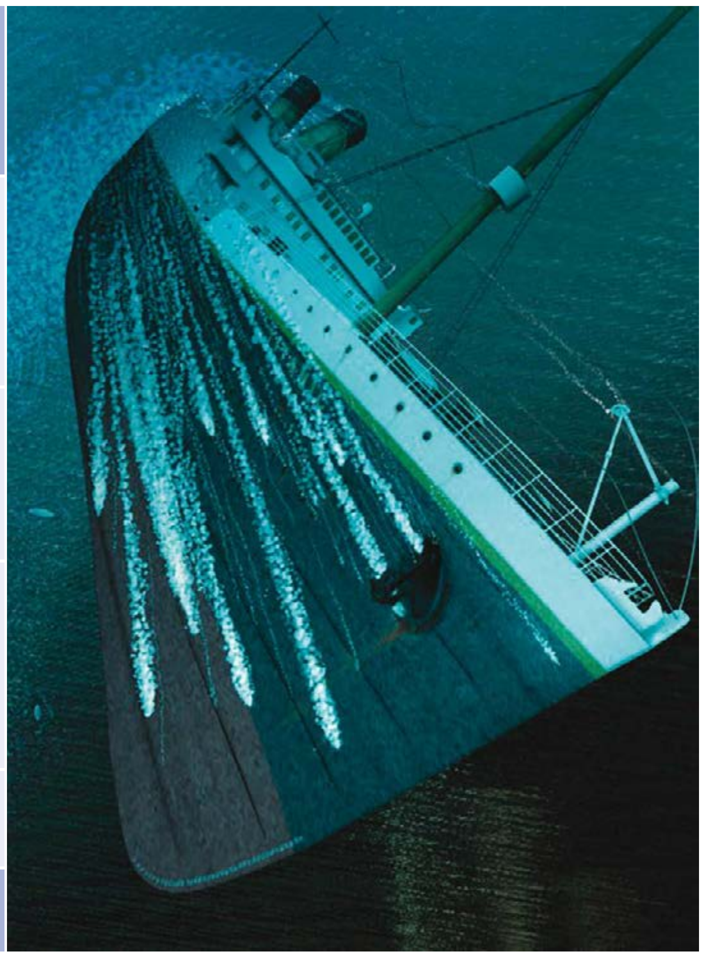
> Safety is founded on the principle of continuous improvement – no matter how high our standards, the quest for improvement must never stop

All nuclear power plants in the UK and across Europe have undertaken a "stress test" to identify whether any improvements can potentially be made. We submitted the UK national report on stress tests in December and it is published on the ONR website. I have also required all non-power-plant licensed nuclear installations in the UK to undertake similar tests of relevant safety margins. The outcome of these stress tests will be added to the outcome of my already published reports. The aim of all these activities will be to transparently and openly ensure that the UK government, nuclear regulator and nuclear industry are doing all that they can to ensure the highest levels of nuclear safety both at home and across the world.

I have always said that safety is founded on the principle of continuous improvement. The ONR already requires protection of nuclear sites against the worst-case scenarios that are predictable for the UK, but no matter how high our standards, the quest for improvement must never stop. We will ensure lessons are learned from Fukushima. In many cases, action has already been taken, but work will continue to learn the lessons.

**Mike Weightman** is Her Majesty's Chief Inspector of Nuclear Installations and executive head of the Office for Nuclear Regulation, UK, e-mail onrenquiries@hse.gsi.gov.uk





National Geographic Society/Corbis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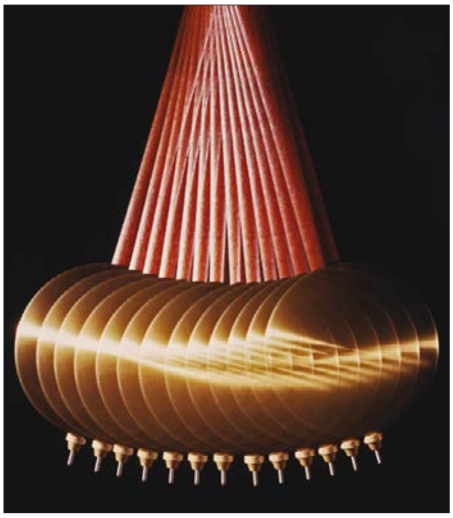
# Critical Point Measuring the Earth

**The precise shape of the Earth is now remarkably well known, but it was first measured by perhaps the oldest and most humble of instruments – the pendulum. Robert P Crease explains**

In his travel book *The Innocents Abroad* (1869), Mark Twain describes his visit to the Baptistery of the Duomo of Pisa, where, according to legend, in 1581 the young Galileo noticed the regularity of the building's swinging chandelier. Using his pulse as a stopwatch, the then 17-year-old medical student observed that the chandelier took the same time to swing back and forth whether traversing a short or a long arc. Twain marvelled at how "insignificant" the chandelier looked, even though we had learned from it that such swinging objects were not mere lamps but pendulums. The awestruck Twain concluded that this was no common pendulum, "but the old original patriarchal Pendulum – the Abraham pendulum of the world".

The principle Galileo noticed – that a pendulum's period, $T$, depends only on its length, $L$ – is strictly true only in a vacuum, applies just for small swings, and ignores friction and other factors. Still, the very simplicity of the principle makes the pendulum useful as an instrument. Indeed, the pendulum is one of the oldest scientific instruments still in service – older, though just barely, than the telescope, the use of which in astronomy dates to 1609. (As a historical aside, it is worth noting that the Duomo's pendulum was actually replaced in 1587, but if Twain saw an offspring of the Abraham pendulum, it stood in the same spot and obeyed the same laws.)

Seeking to study the laws of falling bodies, in 1603–1604 Galileo built his own pendulums from heavy balls and cord. He also used pendulums to measure short time periods, which was their first use as time standards. Others, meanwhile, realized that pendulums could also be used to create length standards. In 1644 the French scientist and philosopher Marin Mersenne (1588–1648) appears to have been the first to accurately measure the length of a "seconds pendulum" – an ordinary pendulum but with the special property that its swing (half-oscillation or $T/2$) is exactly 1 s. Luckily, the length of a seconds pendulum at standard gravity is almost a metre (99.4 cm), making it a convenient length for a standard. This result sparked investigations into factors that disturbed the pendulum's simple motion, including string stiffness, air resistance and suspension.



iStockphoto.com/raw206

**Simply useful** Pendulums proved that the Earth is shaped like a pumpkin.

> The very simplicity of the principle makes the pendulum useful as an instrument

Later, in about 1656, the Dutch scientist Christiaan Huygens (1629–1695) began creating clocks out of pendulums, vastly increasing the accuracy of time measurements and triggering a revolution in navigation. Because the Earth rotates at a known and fixed rate, the longitude of a ship's position can be determined by comparing the time of some astronomical observation as measured on board ship with that at some reference point. However, this only became possible once clocks that could keep accurate time on ships had been developed. Huygens also devised the theory of the compound pendulum, which does not use a string but a solid rod, and the reversible pendulum – a compound pendulum that can be turned upside down and swings on two adjustable knife edges (one for each direction) embedded in the rod.

In 1673, in *Horologium Oscillatorium*, Huygens produced the equation of motion of a simple pendulum: $T = 2\pi\sqrt{(L/g)}$. He also proved that if a reversible pendulum swings with an equal period when turned upside down, the distance between its two knife edges is equal to the length of an ideal or simple pendulum of the same period. Most disturbing factors can then be ignored, allowing pendulums to become valuable scientific instruments, sensitive to factors that disturbed their simple motion.

Much of the pendulum's subsequent history consists of discoveries and corrections for these factors, or of its use to measure these factors. In 1672, for instance, the French astronomer Jean Richer (1630–1696) discovered that the length of a seconds pendulum changes with latitude: if $g$ is smaller, as it is at the equator, a pendulum has to be shortened to keep $T/2$ to 1 s. Richer's work revealed that the Earth is not spherical but flattened slightly at the poles, like a pumpkin. Pendulums therefore proved to be multipurpose instruments that could help determine not only laws of motion, but also the Earth's shape. "[W]ithout the pendulum," wrote Newton's biographer Richard Westfall, "there would be no *Principia*."

In the 18th century pendulums were increasingly used to measure time and speed. In 1784 the English mathematician George Atwood invented a device, the Atwood Machine, incorporating a pendulum to measure the laws of motion with constant acceleration. Numerous scientists – Thomas Jefferson among them – also assumed that a seconds pendulum could be used to define a natural standard of length. In 1851 Jean-Bernard-Léon Foucault (1819–1868) noticed that the plane of oscillation of a long enough pendulum slowly drifted over time because of the Earth's spin about its axis. This demonstrated directly and accessibly the Earth's rotation, and "Foucault pendulums" quickly became popular science demonstrations installed in museums the world over.

By 1867, the year that Twain witnessed the Abraham pendulum, the pendulum had become the principal instrument used to measure the geoid, the shape of the Earth. In 1872 the International Geodetic Association organized a network of gravimetric surveys with reversible pendulums in one of the first large-scale international science collaborations. Later, in the 19th century and into the 20th, a type of pendulum was used in a series of experiments to try to detect a difference between inertial and gravitational masses.

Today, the geoid is measured from space with precise electronic instrumentation able to detect gravity fluctuations (see p33). But this is a recent development. Until the advent of satellites and electronic equipment, the geoid was determined by lowly offspring of the Abraham pendulum, which continue to serve productively in areas including education, engineering, physics and mathematics.

**Robert P Crease** is chairman of the Department of Philosophy, Stony Brook University, and historian at the Brookhaven National Laboratory, US, e-mail rcrease@notes.cc.sunysb.edu

# Feedback

Letters to the Editor can be sent to *Physics World*, Temple Circus, Temple Way, Bristol BS1 6BE, UK, or to **pwld@iop.org**. Please include your address and a telephone number. Letters should be no more than 500 words and may be edited. Comments on articles from *physicsworld.com* can be posted on the website; an edited selection appears here

## Presidential pledges

I read with interest the article by Robert P Crease on pledges to help voters evaluate presidential candidates (January p19). As a physicist working in the UK's National Health Service (NHS) Cancer Screening Programmes, I was particularly drawn to his proposed pledge for candidates opposed to vaccination: "I pledge that I, my descendants and my constituents will shoulder the financial burden of treating and burying unvaccinated cervical cancer and measles victims".

Cervical cancer is caused by exposure to certain strains of the human papillomavirus (HPV). HPV infection causes approximately 2700 cervical cancers a year in the UK alone. The NHS cervical-screening programme is designed to detect precancerous changes in the cervix that can be treated at an early stage. In addition, the NHS has introduced a free cervical-cancer vaccination programme for girls aged 12–13 years that provides complete protection against the two most common forms of HPV. The vaccine has the potential to reduce incidence and mortality from cervical cancer by just under 80%. In addition, a number of other cancers are caused by HPV infection. For example, just over 500 vulva/vaginal cancers and 760 anus cancers in the UK are considered to be due to HPV infection (M J Stanley 2007 *Journal of Clinical Pathology* **60** 691).

The vaccine is given to girls before they are sexually active to maximize the protective effectiveness. Because of this, the introduction of the HPV vaccination programme has been controversial, with the popular press expressing concerns that the vaccine encourages promiscuity in the young. However, I believe that these concerns are far outweighed by the benefits of the vaccine. On a personal level, both my daughters have decided to have the vaccine and I can report that it has not suddenly changed their social activities.


**Keith Faulkner**
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Crease calls for presidential candidates to sign a series of pledges, one of which states that "my decision making (will) be guided by facts rather than political ideology or financial interest". He goes on to aver that candidates "who let ideology trump facts do not act in the national interest". However, I believe that such a pledge would be unworkable and unwise.

For example, there are many possible ways to reduce the threat from climate change, including geoengineering, more nuclear power, regulations on energy use and different tax rates for more or less green activities, to name only a few. Each of these proposals has different side-effects and costs, and our response as citizens to each is affected by our political opinions.

Equally well-informed people will have different ideologies, and think and vote differently on the same issue. The only acceptable way to choose between these differences of opinion is at the ballot box. Of course, politicians should not ignore scientific evidence, and policy-making should be informed by the best available science, but to prioritize scientific "fact" over political ideology is profoundly undemocratic.

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## Steve Rawlings

I appreciate that you did not wish to include speculative or distressing details in your report of the death of the University of Oxford astrophysicist Steve Rawlings (February p8), but your report, which merely stated that Rawlings' colleague Devinder Sivia had been arrested and was bailed in relation to the death, will lead many to conclude that Sivia bears moral responsibility for Rawlings' demise.

I, too, do not wish to go into detail ahead of the inquest, but as a former colleague of both men, I would like to point out that the two were good friends and that Rawlings' wife is on record as saying that she does not blame Sivia for Steve's death. Also, Detective Superintendent Rob Mason of Thames Valley Police has stated that "the death may be a matter for a coroner's inquest rather than a criminal court" and, so far as I am aware, Sivia has not been charged with any crime.

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## Returning from a career break

I read Jan West's article "Careers, interrupted" (February pp50–51) with interest, having taken a career break myself, and I would like to share my positive experience. I graduated from Bristol University in 1989 with a degree in chemical physics and joined a large engineering firm as part of a graduate-training scheme. Having completed the scheme, I worked for the company in both the UK and abroad before taking maternity leave in 1998.

At the end of the maternity leave, I did

## *Physics World* photo challenge

Andrew Davidhazy, Rochester Institute of Technology

Have you enjoyed the amazing images in this issue? Or do you think you could do better? Then why not add your own physics-related photos to our *Flickr* group? Every few weeks we will post a new theme: our first was light in physics and this month's is earth sciences. We look forward to your photos – happy snapping!

**www.flickr.com/groups/physicsworldphotochallenge**

not feel ready to return to work, and I was initially offered a one-year career break, which was then extended to two years. However, by this time my second son had arrived, and I was no closer to being ready to return to the workplace. It was not until he started school that I began to think of returning to work; but after a 7.5-year break, what could I do and in what capacity? As West's article described, my confidence was low; I had lost my individual identity; and the revolution in computing was positively daunting – not to mention the fact that my everyday wardrobe was totally unsuitable!

However, I still had contact with my former colleagues, and a casual query of whether they were recruiting saw me back at work within a month, with hours to suit the school run. On the eve of my return, my nerves were in shreds. What if I couldn't remember what to do? What if I couldn't pick up the latest technology? What if they regretted taking me back? What if I wasn't up to the job anymore? My colleagues tried to put me at my ease by saying "Well, the fundamental laws of physics haven't changed – you'll pick it up again quickly", but I had my doubts.

Now, almost six years on, I can honestly say it was the best move I ever made. The role has given me confidence, stretched me mentally, given me job satisfaction and, most importantly, given me back my own identity and sense of self-worth. I certainly feel I have proved my worth – and yes, I did pick it up again quickly. What I had failed to appreciate at the time I returned to work was that I had years of training and experience to offer, and I was highly skilled; although I felt I was very rusty and out of the loop, this could soon be overcome and I still had potentially another 25-plus years to offer.

Maybe I was lucky that my employer recognized that despite the changes in technology, the fundamentals – my basic skills, knowledge and capabilities – were still relevant, and it valued them. Other employers would do well to follow its example by recognizing the benefits of employing workers who have been out of the workplace for one reason or another but who have the skills, the benefit of experience and the understanding of their specialism to adapt to the ever-changing face of technology.

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# Unoriginal tales

In his article "Other-worldly tales" (December 2011 pp18–19), Robert P Crease describes Hugh Everett's idea of branching universes or "many worlds" as "one of the strangest ideas in the history of thought, and the inspiration for many science-fiction stories". In fact, this overstates its originality, since Everett himself was almost certainly inspired by the science fiction of the 1940s and 1950s, in which this idea was commonplace. These writers may not have expressed it as poetically as Borges in *The Garden of Forking Paths* (1941), which Crease himself cites, but the idea of a branching universe was around much earlier. Crease also mentions its occurrence in H G Wells's *Men Like Gods*, and it is hard to see what he thinks is fundamentally new in Everett's version. As always, what deserves credit is not having the idea, but working it out.

I would also take issue with Crease's statement that "the ground rule of Everett's idea is that each world remains unobserved to, and cannot influence, the others". If this were strictly true, Everett's interpretation would offer no advantages over the Copenhagen interpretation: undefined "measurements" would be replaced by undefined "worlds", and branching would be equivalent to collapse. But, at least in the version endorsed by John Wheeler in his joint paper with Everett, there is no collapse and therefore no barrier between the different worlds. In principle, there are interference terms that can cause the worlds to influence each other; however, there is no possibility of travel between worlds, and certainly none of the kind that you would need to make a science-fiction story.

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## Comments from *physicsworld.com*

**Do you use social-networking sites or blogs to share and discuss research? If the answer is "no", you are far from alone. According to a report by the UK's Research Information Network, most physical scientists view these services as a "distraction", preferring to communicate by publishing in journals (see "Online tools are 'distraction' for science", 25 January). The report also found that members of various sub-disciplines (such as particle physicists and nanoscientists) use online resources such as *Google Scholar* and *arXiv* differently. So are physical scientists a bunch of fuddy-duddies, or just good at avoiding distractions?**

Senior researchers grew up and developed their career pre-Internet. After doing the same thing for 20 years of their lives it's not surprising they wouldn't adopt rapidly changing new technologies. They're going to coast until retirement and let the next generation use these tools. Also, "publish or perish" still rules, and sharing research doesn't help you win grants at the moment.

Hopefully, some researchers will start using these tools to their advantage and not view them as a threat. I operate a biology "citizen science" site, *Wildlife Sightings*, and would be delighted if senior researchers participated and lent their support and wisdom. Experience tells me it will be a few years before they embrace the Internet and citizen science, though. Hopefully then their peers will recognize the value of openly sharing research and reward researchers for using these new tools, rather than discouraging them as the current system does.
**Wildlife Sightings**

There are two sides of research. The first is making a project work, collecting the data and analysing it in a calm manner. This part is a lonely task away from the glare of publicity. Once the results are there, they have to be scrutinized carefully by people who have the capacity to do this. After this, the publishing and the publicity come in to make people understand the significance of the work. If you mix these two sides at once, you risk turning the whole thing into theatrics...when the information gets more and more widespread in an undigested manner, it ends in masses of ignorance and noisy ideological bouts.
**M Ashgar**

Physicists, in general, seem to lead rather cloistered lives, either publishing only in peer-reviewed journals, or submitting their "work" to blogs and fringe websites for public consumption. The latter practice will probably destroy all hope of a "normal" physics career, so it must be an act of insanity or desperation (perhaps both) that leads people down that road. But that is why we have sites for fringe science, where advocates claim "if only the work wasn't suppressed…". The Internet is full of stuff that simply isn't so, as well as stuff that may be so but isn't common knowledge. *Caveat emptor*.

When there is online access to peer-reviewed publications, it usually requires membership in a society or a fee to read the material. That tends to keep the work in the "club", so to speak.

And it isn't just physicists. I am an electrical engineer, but I can't read the IEEE publications for free. It is the same with most other professions: access to online publications is limited to those who can afford the fees. If there are any Renaissance people living today, surely their efforts to learn and to assimilate, to cross-pollinate disparate fields of endeavour, are more than a little stymied by this sad state of online affairs here in the 21st century.

One ray of hope: the current generation isn't afraid to launch new paradigms of investigation and form new associations of professionals. Thus we have not only biologists, geneticists and medical doctors but now also bio-engineers and bio-physicists collaborating and making tools for each other. Perhaps this new generation will also embrace the idea of truly free flow of information. Or not.
**H B Evans**

The reason astrophysicists and high-energy physicists don't bother with Web-wide search-and-navigation tools is not that their field is narrow or that they are set in their ways. It is that with their habit of making all their papers free for all online by "self-archiving" them in *arXiv*, they already have immediate focused access to just about everything they need in the refereed research-journal literature. In this they are more than two decades ahead of other disciplines. And they did it of their own accord, because it made sense and its feasibility and benefits were obvious.

Other disciplines have been far slower in coming to their senses, although what is optimal for physicists is also optimal for them. They have been combing through the roughly 20% of the rest of the literature that is open access in fields other than physics and computer science, using Web tools that do their best to sort the wheat from the chaff.

It has by now become clear that if the rest of the disciplines are to do the optimal and inevitable for themselves before the heat death of the universe, it will require their funders and institutions to extend their existing "publish or perish" mandates to "self-archive to flourish".
**StevanHarnad**

I think that while an amalgamation of research into media such as *Google Scholar* provides fast and easy access to new information for scientists and academics, standards need to be drawn. That is why I, and I think most scientists, will use traditional resource-gathering methods in conjunction with these newer ones. But to call the newer methods a "distraction" is something I wouldn't agree with entirely. It is more of an additional resource that can be called upon depending on the need.
**drpearson**

physicsworld.com

*Read these comments in full and add your own at* physicsworld.com

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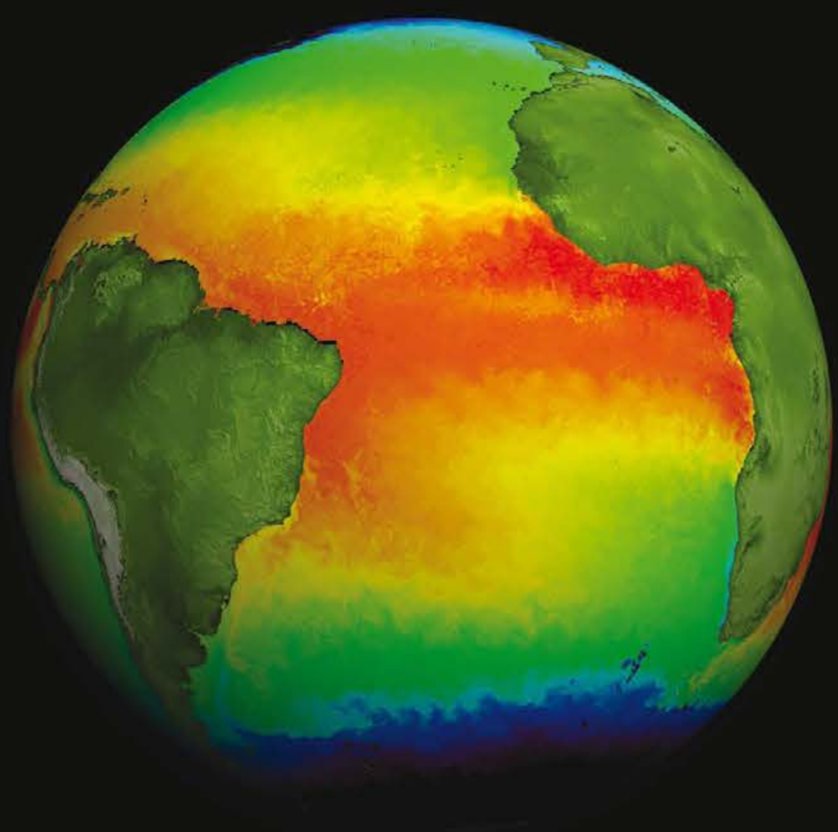
# Physics and the Earth

Welcome to this special issue of *Physics World* devoted to our home, Earth. Over the next 34 pages, we take you on a journey from the crust to the centre of the Earth, encountering earthquake physics, geomagnetic reversal, core conditions and even geoneutrinos. But first we begin with these fabulous visualizations from afar, showing planet-wide phenomena in all their glory

**Wave power** This computer model shows the maximum wave heights in the Pacific Ocean in the aftermath of the 2011 earthquake in Tōhoku, Japan. Colour coding is from shallow (yellow, 20 cm) through to moderate (red, 60 cm) and large (purple, 120 cm, and black, 240 cm+). The worst-hit areas in Japan had surges 3–7 m high. The tsunami did more damage than the magnitude-9.0 earthquake that caused it, with 92.5% of the 13 135 fatalities recorded by 11 April 2011 having died by drowning. As waves spread across the Pacific they decreased in height, before growing again upon reaching coastal areas. This model was produced by the Center for Tsunami Research at the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration.

Mark Garlick/Science Photo Library

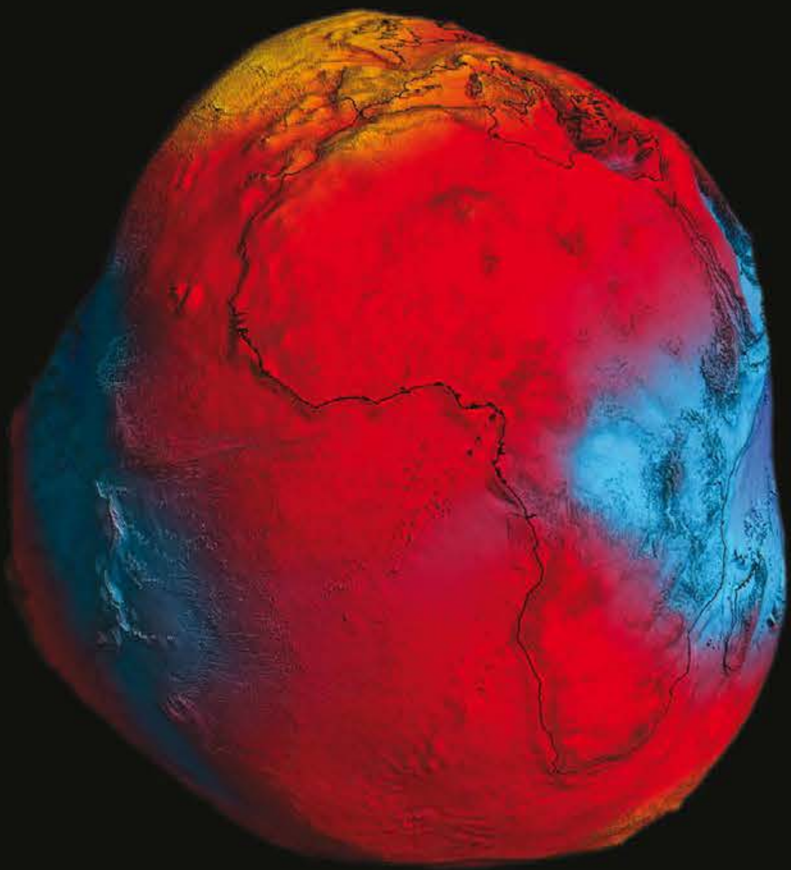
**Time travel** This artwork transports you back about 300 million years to the Palaeozoic Era, when the Earth's land mass formed one giant supercontinent we call Pangaea. About 200 million years ago Pangaea broke up, and its fragments formed the continents as we know them today. Evidence for this past includes fossil records, magnetization of rock minerals and the obvious match in coastal shapes of, for example, the east coast of South America and the west coast of Africa. Pangaea is not the only supercontinent to have formed on Earth, with Columbia here about 2 Gyr ago, followed by Rodinia and then Pannotia.



ESA

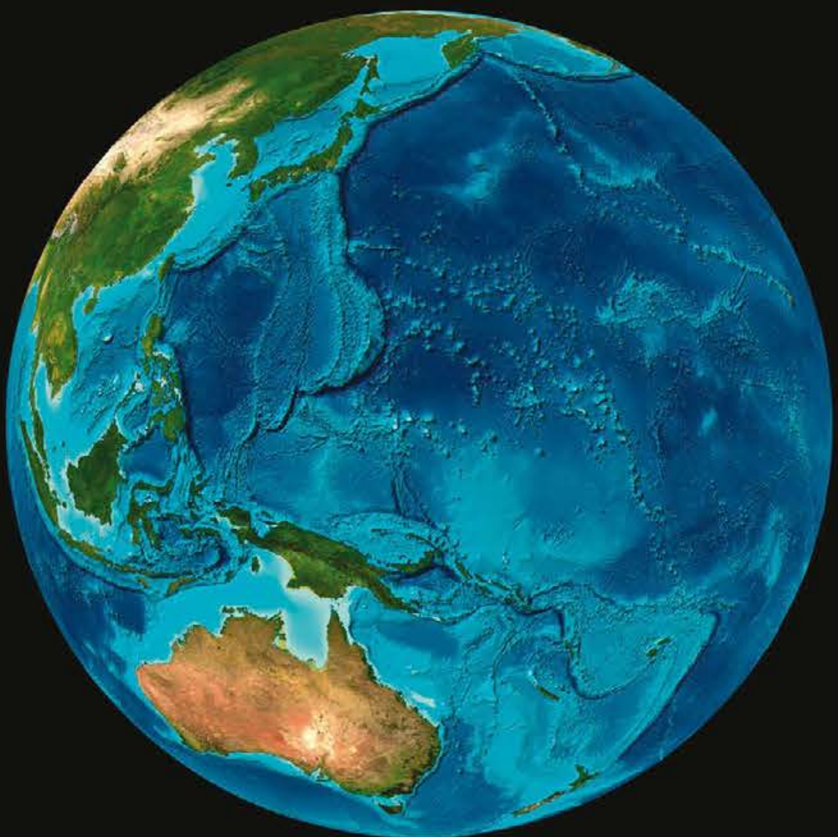
**Hot and cold** This view over the Atlantic shows sea-surface temperature, with blue corresponding to the coldest waters and red to the warmest. The temperature is measured by collecting thermal infrared light using the Advanced Along Track Scanning Radiometer (AATSR) instrument on board the European Space Agency's Envisat satellite. AATSR's primary objective is to continue from its predecessors in creating a near-continuous dataset, which started in 1991, of sea-surface temperature with a precision of 0.3 K or better, which will be a useful resource for climate research.

**On the pull** This peculiar-looking image is the geoid – the Earth's surface of equal gravity potential. The sea surface would be this shape if the oceans were at rest with no tides or currents. Using this as a reference – the most precise geoid yet – changes in mass distribution can be measured using complementary techniques that measure variations of the gravity field with time. Changes in the geoid could be used to detect depleting groundwater supplies, melting of the ice sheets or the flow of the Earth's mantle. The data for this image were collected from March 2009 until March 2011 by the European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE).

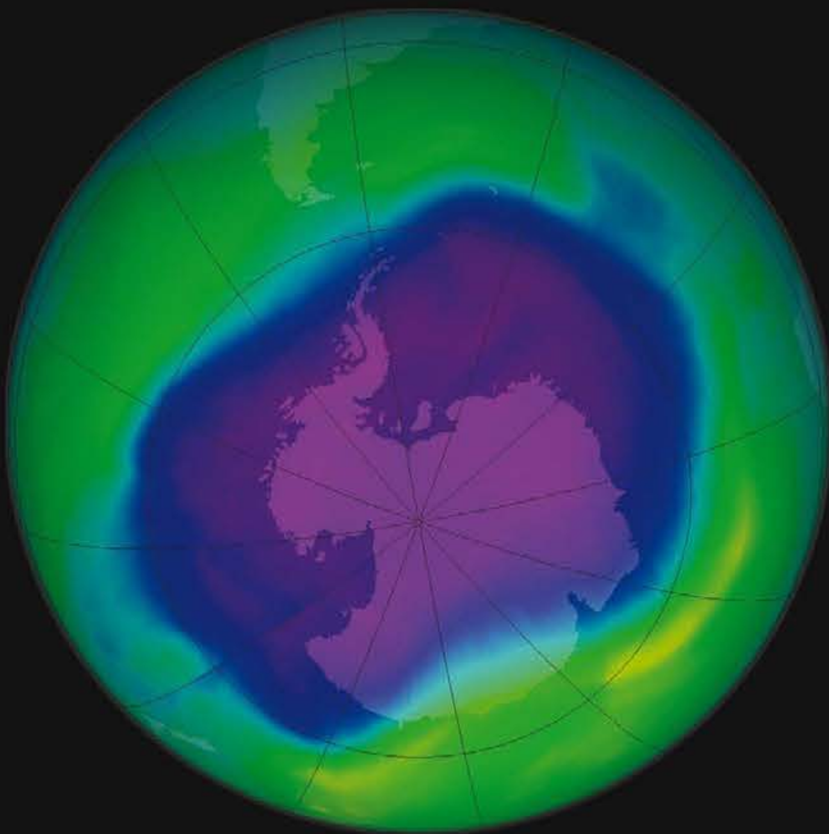


ESA/HPF/DLR

**Under the sea** This map of the Western Pacific Ocean, with Australia bottom left, shows seabed depth from shallow (light blue) on the continental shelves to deep (dark blue) in the ocean basins. The sea floor contains massive mountains as well as trenches, which cause the ocean surface above to bulge outward and inward, respectively, the height of which is measured using satellites to map the ocean floor. The main features seen here are the ridges and subduction zones around the Pacific Ocean's "Ring of Fire", including the Marianas Trench (above and left of centre), which contains the deepest point in the world's oceans at around 11 km.



Martin Jakobsson/Science Photo Library



NASA Ozone Watch

**The hole above** This image from NASA's Aura satellite shows the Antarctic ozone hole in September 2006, when it was at its peak. Green shows a healthy layer of ozone while blue/purple indicate an area of low ozone larger than the size of North America. A previous NASA image from December 1979, when the use of chlorofluorocarbons (CFCs) was only just starting to rise, was uniformly green. The ozone layer is incredibly valuable as it absorbs 97–99% of incident high-frequency ultraviolet light, a high dose of which can be harmful to living things. Although the average hole size is now decreasing, a full recovery of ozone over the Antarctic is not expected until about 2050.

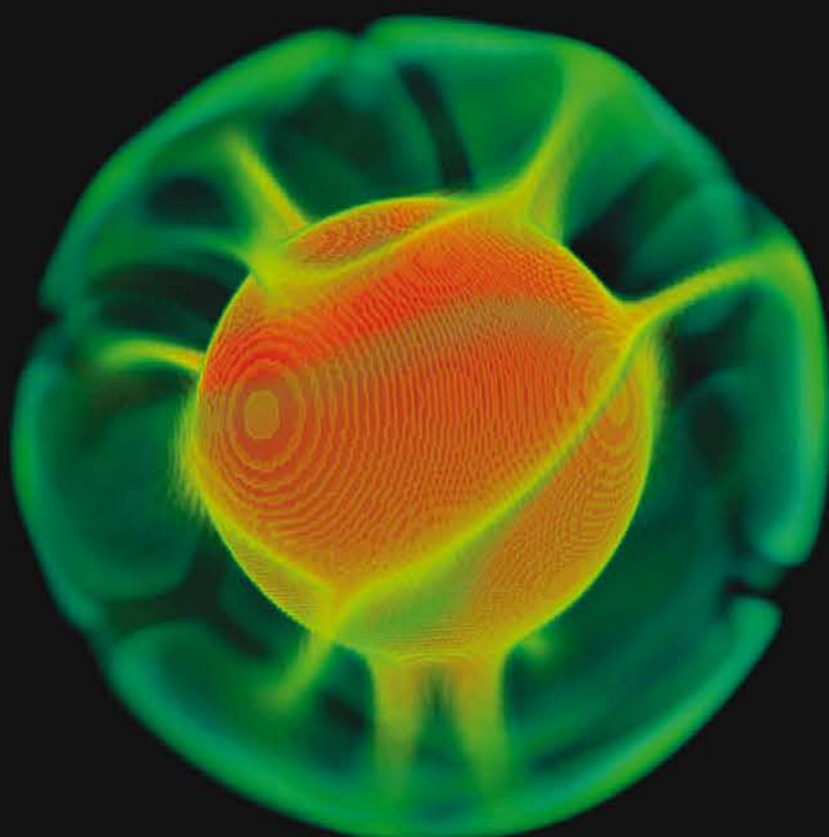
ESA/NOAA/DMU

**Highs and lows** This image shows the first dataset to merge models of the Earth's land elevation and its ocean depths that both use satellite radar altimeter measurements. Both use data from the European Space Agency's European Remote Sensing satellites, although the ocean depths model also uses the US Navy's Geosat satellite along with depth soundings collected from ships.

**Sooty skies** This image from a NASA computer simulation shows the global spread of airborne soot on 26 September 2009. Based on measurements of how much incoming sunlight the particles absorbed, areas thick with soot are shown in white, while lower concentrations are transparent purple. Soot is known to climate scientists as "black carbon" because it absorbs visible light and could contribute significantly to global warming. Its impact is particularly strong in Asia, with emissions from coal, diesel and biomass, used for example in cooking.

NASA

**Fiery flow** This 3D computer model shows hot magma, heated at the Earth's core–mantle boundary, rising as hot plumes (orange) to the upper mantle. Here, the plumes fan out before sinking as cooler magma (green), driven by convective currents. Such mantle plumes are thought to drive plate tectonics as well as some of Earth's volcanoes. However, like much of the science of what is beneath our feet, the exact mechanisms behind mantle plumes are not fully understood. Clues could come from mapping seismic waves, which are predicted to travel slower through hot mantle than through cooler mantle.



Shuxia Zhang/Shuo Wang/Science Photo Library

# FORTHCOMING INSTITUTE CONFERENCES
# MARCH 2012 – JULY 2014

## 2012

**21–22 March**
**Electrospinning, Principles, Possibilities and Practice 2012**
Institute of Physics, London, UK
*Organised by the IOP Dielectrics Group*

**2–4 April**
**IOP Nuclear Physics Group Conference 2012**
University of Brighton, Brighton, UK
*Organised by the IOP Nuclear Physics Group*

**2–5 April**
**Plasma Physics Group Annual Conference**
St Hugh's College, Oxford, UK
*Organised by the IOP Plasma Physics Group*

**14–15 May**
**Quantum interfaces: integrating light, atoms and solid-state devices**
Chicheley Hall, Milton Keynes, UK
*Organised by the IOP Quantum Optics, Quantum Information and Quantum Control Group*

**7–8 June**
**Topical Research Meetings on Physics: Swimming and Complexity at low Reynolds number**
Institute of Physics, London, UK

**2–6 July**
**Ultrasonic Standing Waves – manipulating cells, particles and fluids with sound**
Gregynog Hall, University of Wales, UK
*Organised by the IOP Materials and Characterization Group*

**9–11 July**
**Superconductivity Summer School 2012**
Wolfson College, Oxford, UK
*Organised by the IOP Superconductivity Group*

**20–23 August**
**IEEE NANO 2012 – 12th International Conference on Nanotechnology**
International Convention Centre, Birmingham, UK

**29–31 August**
**Modern Practice in Stress and Vibration Analysis Conference (MPSVA2012)**
University of Glasgow, Glasgow, UK
*Organised by the IOP Applied Mechanics Group*

**3–5 September**
**Physics meets Biology**
University of Oxford, Oxford, UK
*Organised by the IOP Biological Physics Group*

**3–6 September**
**Photon12**
Durham University, Durham, UK
*Organised by the IOP Optics and Photonics Division*

**3–7 September**
**24th General Conference of the Condensed Matter Division of the European Physical Society (CMMP12, ECOSS-29, ECSCD-11)**
Edinburgh International Conference Centre, Edinburgh, UK

**10–11 September**
**Magnetic Tight Binding**
Institute of Physics, London, UK
*Organised by the IOP Computational Physics Group*

**11–13 September**
**Drop Reaction and Microfluidic Analysis (DRAMA)**
Royal Dublin Society, Dublin, Ireland
*Organised by the IOP Instrument, Science and Technology Group*

**20–21 September**
**A Celebration of the 50th Anniversary of the Diode Laser**
University of Warwick, Coventry, UK
*Organised by the IOP Quantum Electronics and Photonics and Semiconductor Physics Groups*

**26–27 November**
**Biomolecular Thermodynamics**
Institute of Physics, London, UK
*Organised by the IOP Biological Physics Group*

**17–18 December**
**Topical Research Meetings on Physics: Quantum technologies: taking concepts through to implementations**
Institute of Physics, London, UK

## 2013

**25–28 March**
**The 40th IOP Annual Conference on Plasma Physics**
University of York, York, UK
*Organised by the IOP Plasma Physics Group*

**25–28 March**
**Interdisciplinary Surface Science Conference (ISSC-19)**
East Midlands Conference Centre, Nottingham, UK
*Organised by the IOP Thin Films and Surfaces Group*

**7–10 April**
**IOP Nuclear Physics Group Conference 2013**
University of York, York, UK
*Organised by the IOP Nuclear Physics Group*

**10–12 April**
**Dielectrics 2013**
University of Reading, Reading, UK
*Organised by the IOP Dielectrics Group*

**8–12 July**
**International Conference on Neutron Scattering (ICNS2013)**
Edinburgh International Conference Centre, Edinburgh, UK

**3–6 September**
**Electron Microscopy and Analysis Group Conference 2013 (EMAG)**
University of York, York, UK
*Organised by the IOP Electron Microscopy and Analysis Group*

**9–11 September**
**Physical Aspects of Polymer Science**
University of Sheffield, Sheffield, UK
*Organised by the IOP Polymer Physics Group*

## 2014

**21–25 July**
**ICSOS'11: International Conference on the Structure of Surfaces**
University of Warwick, Coventry, UK
*Organised by the IOP Thin Films and Surfaces Group*

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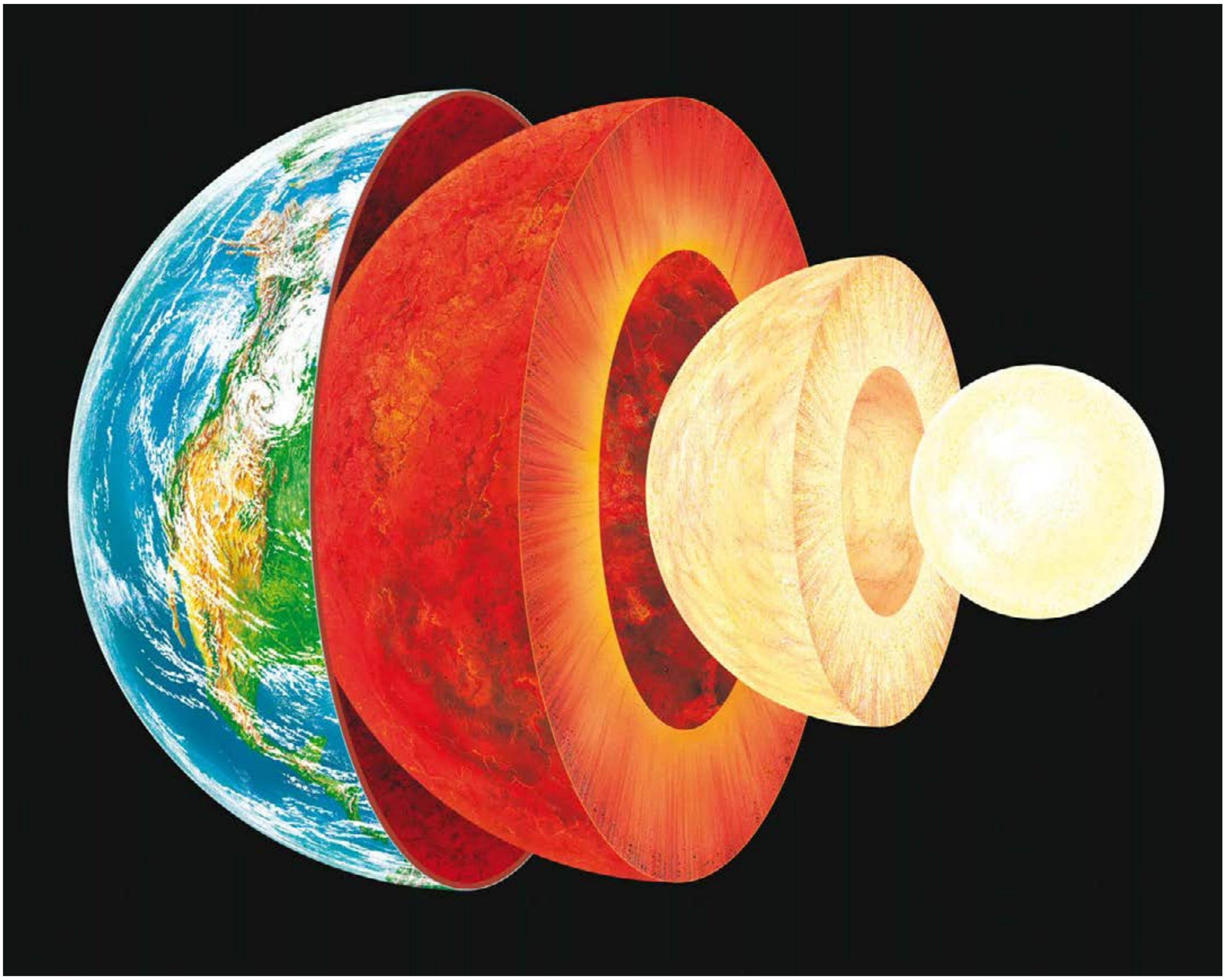


Gary Hincks/Science Photo Library

# A pressing matter

Scorching hot and under immense pressure, the Earth's core is one of the most unusual and extreme places in the entire solar system. **David Appell** looks at progress in understanding the properties of materials there, which includes the possibility that the core may even contain immense crystals of iron up to 10 km long

Directly beneath your feet lies one of the most mysterious places in the solar system – the inside of the Earth. It is a geological concert orchestrated by huge forces and immense transfers of heat, where metals can flow like water and rocks take forms found nowhere else, and if anyone can be said to hold a ticket to this show it is Kei Hirose.

Hirose, a geologist at the Tokyo Institute of Technology, is a pioneer in duplicating the conditions in our planet's innards – pressures of millions of atmospheres and temperatures approaching that of the surface of the Sun. What Hirose does sounds simple, in principle: squeeze materials and heat them. Indeed, he has already solved several enigmas of the Earth's inner structure and hopes to answer even more, especially the most pressing problem in geoscience: what is the chemical composition of the Earth's outer core?

"Kei's combination of talents – pushing the limits of high-pressure experiments and then exploiting this new capability to address important questions – has led to a string of startling discoveries," says Bruce Buffett, a geophysicist at the University of California, Berkeley. That is a bold claim by anyone's standards, so to see if it stacks up, we first need to remind ourselves what lies beneath.

**David Appell** is an independent science journalist based in St Helens, Oregon, US, e-mail david.appell@gmail.com

Kei Hirose

**Inside knowledge** Kei Hirose from the Tokyo Institute of Technology has studied how iron behaves at the conditions in the Earth's core.

No-one, of course, has ever seen the Earth's interior, except for characters in books and Hollywood. A "modest proposal" for sending a probe to its depths was made in 2003 by planetary physicist David Stevenson from the California Institute of Technology, but even though his ideas were published in *Nature* (**423** 239), Stevenson's tongue was somewhere in-between zero and one cheek. The deepest that we have actually managed to penetrate beneath our planet's surface is to the bottom of the Kola Superdeep Borehole – a research facility located on the Kola peninsula in north-western Russia that opened in 1970. Penetrating to 12 262 m below the surface, it was four times deeper than any mine then or now (the site was abandoned in 2008). Yet if the Earth were an orange, the Kola borehole would still only be 2% of the way through the peel.

Nonetheless, geologists know a great deal about the Earth's structure, from rocks that have reached the surface, from its gravitational and magnetic fields, from the scattering of seismic waves created by earthquakes, and from computer models that combine these data with models built with increasing details of the expected physics. They know that it consists of four principal layers: the crust, mantle, outer core and inner core (figure 1). The inner core is smaller than the Moon, and Mars would fit snugly inside the outer core.

The Earth's density changes abruptly at the boundaries between these layers, varying from about 2.5 times that of water near the surface to a value estimated (from seismic-wave data input into models) to be some 13 times that of water near the centre. Temperature and pressure increase quickly in an imaginary descent through the Earth: the bottom of the Kola borehole is already 180 °C, while at the boundary between the mantle and the outer core, the temperature rises to about 4000 K. There, the pressure is calculated to be an immense 140 GPa (1.4 million atmospheres) from the sheer weight of what lies above, rising to 3.5 million atmospheres at the centre. A pleasant little Newtonian calculation finds, assuming a planet of constant density, that the pressure at the very centre is $3g^2/8\pi G$, where $g$ is the acceleration due to gravity at the surface and $G$ is the gravitational constant – the resulting 1.7 million atmospheres is low by a factor of about two, because in reality the density varies with radius.

It is easy to forget just how fresh our knowledge is of the Earth's interior. Plate tectonics came together in the mid-1960s – more than a decade after the CERN particle-physics lab was set up – and scientists had solved the mysteries of the atom long before the Danish seismologist Inge Lehmann realized in 1936 that the Earth's inner core must be solid. (Her paper was wonderfully and simply titled "$P'$".) Lehmann died in 1993, three months shy of 105.

Lehmann was a master in the art of reading and interpreting seismic-wave recordings, and most of our knowledge of the inner Earth has come from what is now known as "seismic tomography". Like a shopper tapping on a melon, waves from large earthquakes fan through the body of the Earth – longitudinal, compressional P-waves and transverse shear S-waves – at speeds of about 10 km s$^{-1}$, reflecting and refracting from the discontinuities and gradients they encounter. The resulting sounds have enabled researchers to glean the density profile of the Earth – an effort that has taken decades – and, from fundamental principles of gravitation and thermodynamics, we can deduce what lies beneath, without needing to drill inside.

Earthquake by earthquake, sublayer by sublayer, geologists puzzled through the Earth's inner structure. The imaginations of its surface dwellers might have shifted from the days of Verne's *A Journey to the Centre of the Earth* to Asimov's robots to Spielberg's *ET*, but the rock hounds kept sifting for clues, crushing rocks and improving models, benefiting from the improvements of technologies and techniques often used to search for petroleum and ores, and trying out their ideas on other planets in the solar system. But puzzles about the interior remained. No-one was at fault – for geologists, however gneiss, take nothing for granite.

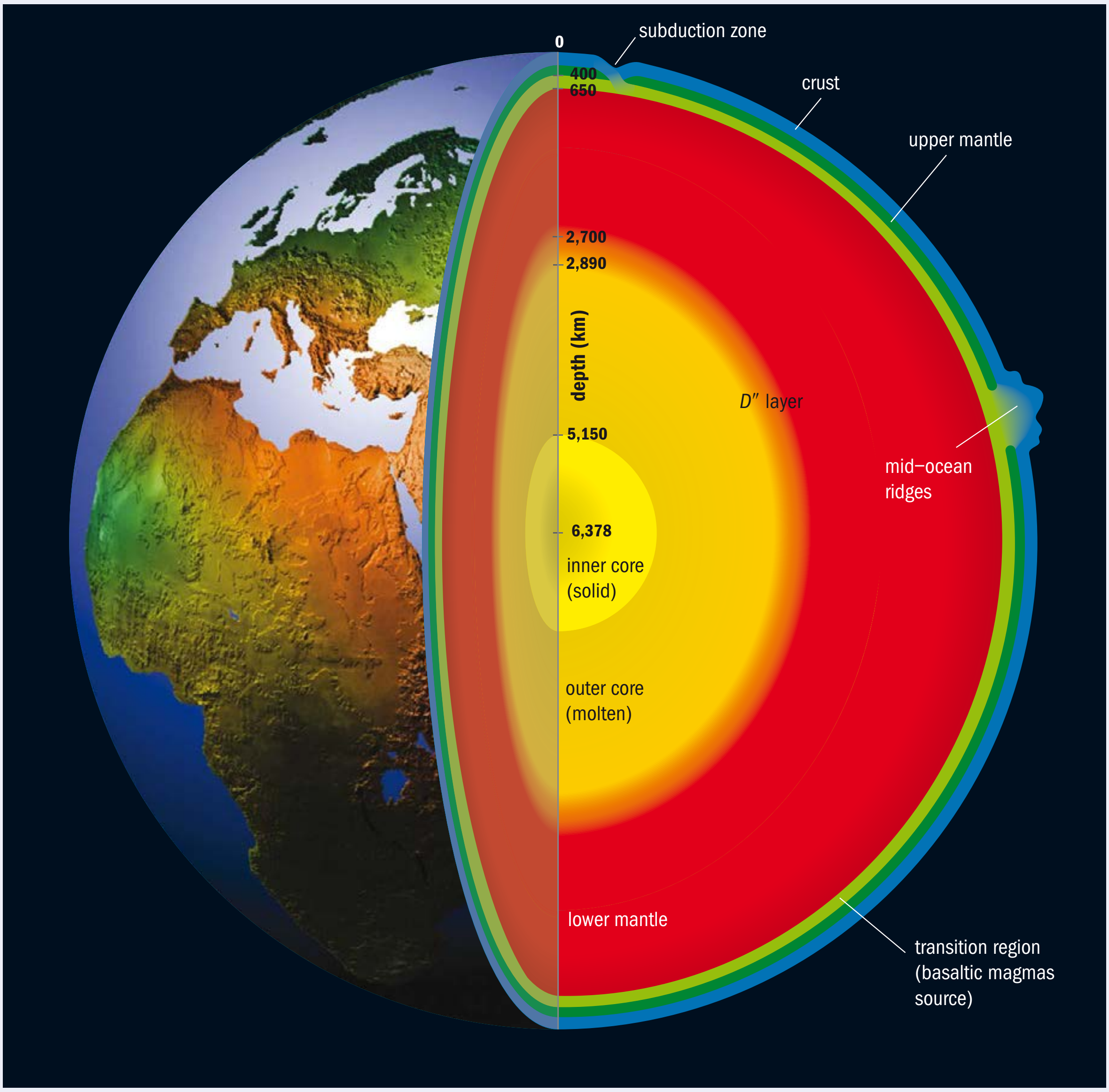
From fundamental principles of gravitation and thermodynamics, we can deduce what lies beneath, without needing to drill inside

### The diamond squeeze

Enter Hirose. In 2004 the Tokyo geologist and his colleagues solved some long-standing problems in earth science when they discovered a new phase of the most common type of material in the Earth's lower mantle. Much of the mantle – from about 650 km down – is composed of the mineral magnesium silicate ($MgSiO_3$) in a crystalline form called "perovskite", named after the Russian mineralogist Lev Perovski. It had been synthesized in the lab as early as 1974 at a pressure of 30 GPa, and geologists originally believed it was the dominant form of rock all the way down to where the mantle meets the top of the outer core, at a depth of 2890 km.

However, in the 1960s seismic-wave data revealed

## 1 The Earth in profile




The core of the Earth is a solid, metallic ball (bright yellow) that further out becomes an ocean of white-hot molten iron–nickel alloy (orange) that is only slightly less viscous than water. Surrounding the core is a 300 km thick boundary ($D''$) region (not shown to scale here) that can be observed by a sudden change in the speed of seismic waves at that depth, while further out still lies the highly viscous lower mantle (red), which moves slowly via convection currents carrying heat outwards from the core. A molten transition region (light green) contains minerals that can melt and flow to the surface as magma through holes in the upper mantle (dark green) to form underwater mountain ranges known as mid-ocean ridges. Topping everything is the crust (blue), which consists of roughly equal proportions of mostly silicon, iron, oxygen and magnesium.

some unexpected anomalies in the lower mantle, which extends to the core–mantle boundary. Things became even stranger in the 1980s when seismic tomographers – who began examining how seismic waves scatter off the Earth's interior with ever better resolution – discovered a discontinuity in the lower mantle, about 300 km above the core–mantle boundary. Dubbed the $D''$ layer, subsequent work seemed to show that the discontinuity was due not to the emergence of a different structure of rock, but to a sudden change in the relative abundance of magnesium silicates and iron alloys. Unfortunately, that conclusion presented a problem, because the convection that keeps the mantle astir should have created uniformity.

The other problem with a discontinuity was that rocks at the high temperature (2500 K) and high pressure (120 GPa) of the $D''$ region had never been studied before, which meant that it was impossible to know whether the conclusion was true. Intrigued, Hirose began to study the problem in the mid-1990s. After a stint at the Geophysical Laboratory at the Carnegie Institute in Washington, DC, he returned to Tokyo and began investigating how to generate the pressures and temperatures necessary to simulate the deepest part of the mantle.

Scientists have been generating high pressures in the lab since the late 1950s, following the invention of the diamond-anvil cell at the US National Bureau of Standards (the forerunner of the National Institute of Standards and Technology). This device consists of

Javier Trueba/MSF/Science Photo Library

**Crystal mystery** Deep inside the Naica mine, 300 m below ground in northern Mexico, lies the Cave of the Crystals, containing these giant selenite structures that are some of the largest known crystals. The biggest found to date in the cave is 11 m long, 4 m in diameter and weighs 55 tonnes. But these could be nothing compared with the 10 km-long crystals that some scientists think might exist inside the inner core. Unlike those in the Naica cave, the hypothesized crystals would have no empty space between them.

opposing, specially cut diamonds that are forced together with a lever arm or tightening screw. The tips of the diamonds, often less than a millimetre wide, are extremely smooth and finely aligned so that they encase the sample with identical and opposing forces. A laser with a fine beam, for which diamond is transparent, is then shone on the sample to heat it. Hirose began working to push pressures above 120 GPa by modifying the shape of the sub-millimetre-sized diamonds, because above 80 GPa even diamond begins to warp. He learned how best to bevel the tips of the gem-quality natural diamonds – breaking many of them in tests.

"Each year I usually buy about 100 diamonds," Hirose says. Each diamond is 0.2 carats (40 mg) and he purchases them to specification from a local company. Tightening the diamond-anvil cells to more than 100 GPa always breaks both diamonds on decompression, he says, but interesting science is obtained first. Hirose and his colleagues were able to reach a pressure of 120 GPa using only a screwdriver to adjust their apparatus.

Hirose's team squeezed magnesium-silicate samples only 25 $\mu$m thick to these ultrahigh pressures, and then heated them with a laser beam at the SPring-8 synchrotron facility in Hyogo. At the same time, the researchers shone a beam of X-rays onto the sample to determine its crystal structure via the resulting diffraction pattern. Hirose's graduate student, Motohiko Murakami (now at Okayama University in Japan), found that the diffraction pattern of magnesium-silicate perovskite changed drastically at the extreme conditions they generated, taking a previously unimagined structure above 120 GPa and 2500 K, with a density about 1% higher.

Hirose and his collaborators spent almost a year trying to fit their diffraction patterns to the tens of thousands available in crystallography catalogues, surely satisfying Jules Verne's notion (from *A Journey to the Centre of the Earth*), that "in the cause of science men are expected to suffer". They found one via a computer simulation, dubbed it "postperovskite", and with this new mineral phase, the solution of the $D''$ puzzle snapped into place (2004 *Science* **304** 855).

### Faster heat, younger core

The enigma facing geophysicists over the $D''$ boundary region centred on the transfer of heat. The lower mantle is only half as dense as the outer core, and little mixing of material occurs at their boundary. Heat must therefore be exchanged across the gap via conduction, which is a very different situation from in the mantle or outer core itself, where convection rules the roost. Although the density of the new postperovskite mineral structure was only about 1% larger than its perovskite form, the Clapeyron equation – which is a way of characterizing a discontinuous transition between two phases of matter – implied a large flow of energy across the boundary that Hirose's team estimated to be $5–10 \times 10^{12}$ W. Numerical simulations by Takashi Nakagawa of the University of Chicago and Paul Tackley of the University of California, Los Angeles then found about a 20% faster heat flow through the mantle – in turn, speeding up the movement of the Earth's continents.

The larger rate across the core–mantle boundary meant that the core must have once been warmer than was assumed (in order to be at the temperature it is today), and so was cooling faster too. That in turn implied that the inner core may have crystallized less than a billion years ago instead of much further back in the past of the 4.6 billion-year-old Earth. That crystallization (the outer core is still molten) made the interior dynamo more stable and Earth's magnetic field stronger. That stronger field in turn diverted harmful cosmic rays and solar winds, which may have allowed animals to crawl out from the protective cover of the oceans to one day discover postperovskite.

Hirose, his collaborators and many other earth scientists went on to explore the properties of postperovskite. In 2008 Kenji Ohta (also of the Tokyo Institute of Technology), Hirose and others made another discovery with important implications – the postperovskite form of magnesium silicate has a much higher electrical conductivity than its perovskite form, by about four orders of magnitude, varying little with temperature (*Science* **320** 89).

This higher conductance meant a much stronger electromagnetic coupling between the core and mantle. This enhanced the exchange of angular momentum from the liquid outer core to the solid mantle, which occurs when the liquid streams in the outer core change their patterns, akin to the shifting jet stream in the atmosphere. Simulations showed that it was enough to account for the Earth's "nutation" – the small, 18.6-year cyclic variation in the angular speed of the 26 000-year precession of the Earth's axis of rotation.

### A new structure of iron

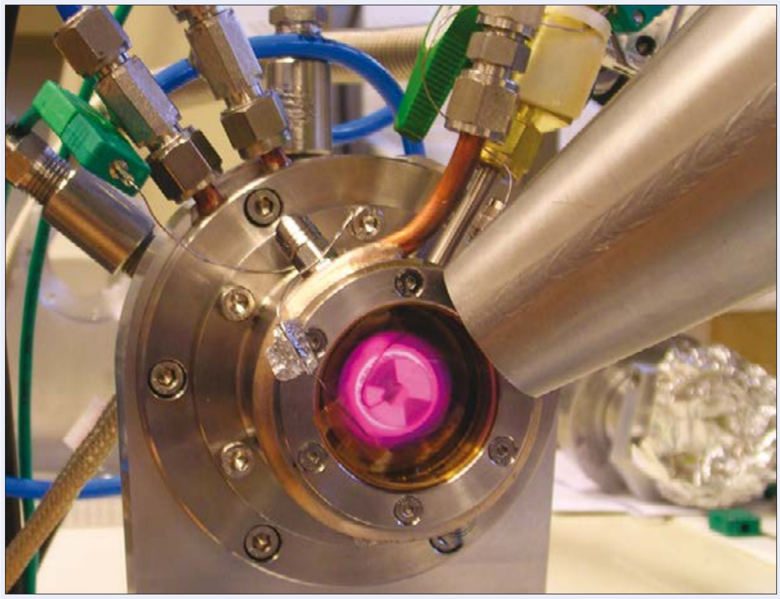
Hirose and his lab continued to push to ever higher pressures and temperatures, striving to reproduce those at the centre of the Earth by studying the properties of iron. Iron has a simple body-centred cubic crystalline structure at ordinary pressures and temperatures, changing to hexagonal close-packed above 15 GPa. There were experimental and theoretical reasons to suspect it might change at high pressure and temperature, but neither approach was able to provide a definitive answer for the structure, which was a key missing ingredient in deciphering the deep inner structure. However, in 2010 Hirose's team succeeded in pressing iron to an incredible 377 GPa and 5700 K in a laser-heated diamond-anvil cell, which was studied using an X-ray beam with a spot only 6 $\mu$m wide (*Science* **330** 359). This temperature was well above that of the boundary between the inner and outer cores, which lies somewhere between 4850 and 5700 K.

Before this work, no-one had succeeded in pressing iron to such conditions except in dynamical shock-wave experiments, which inherently did not allow microsecond-scale measurement of its properties. Hirose and his colleagues were able to solve the mystery of what happens to iron under extreme conditions when they found that the hexagonal close-packed structure remained. Moreover, the length to edge-width ratio of the crystalline unit, which under normal conditions is $\sqrt{(8/3)}$, remained unchanged at high pressure and temperature, meaning that hexagonal close-packed iron is likely to be "elastically anisotropic" – in other words, its strain depends on the crystal's orientation.

But much about the tiny inner core – which makes up just 0.7% of the Earth's volume – remains a mystery. The rate at which waves pass through it depends on their direction of travel – seismic P-waves zip through the inner core about 3% faster in the direction of the Earth's polar axis than in its equatorial plane. The most accepted hypothesis to explain this anomaly is that the inner core has a texture, with the "fast axis" of iron crystals mostly oriented in the north–south direction.

But the inner core also has distinct hemispheres – its seismic properties are different in its eastern and western halves, despite it having grown through crystallization for around the last billion years at a current rate of about 0.5 mm per year. To explain this asymmetry, a group led by Marc Monnereau at the University of Toulouse in France has proposed that the crystal "grains" in the inner core vary in size from west to east (2010 *Science* **328** 1014). A grain is essentially a large number of crystals, either cubic or hexagonal (but not a mixture); the axes of the component crystals all point in the same direction, with the orientation of the axes varying randomly from one grain to another. "From Hirose's work, it seems that crystals as large as 10 km are acceptable from the point of view of mineral physics," says Monnereau. "But whatever their structure, they should be at least 10 times larger on the side facing Indonesia than the one facing Peru." Crystals that huge put even those in Mexico's famous Cave of Crystals to shame.

**2 In a squeeze**

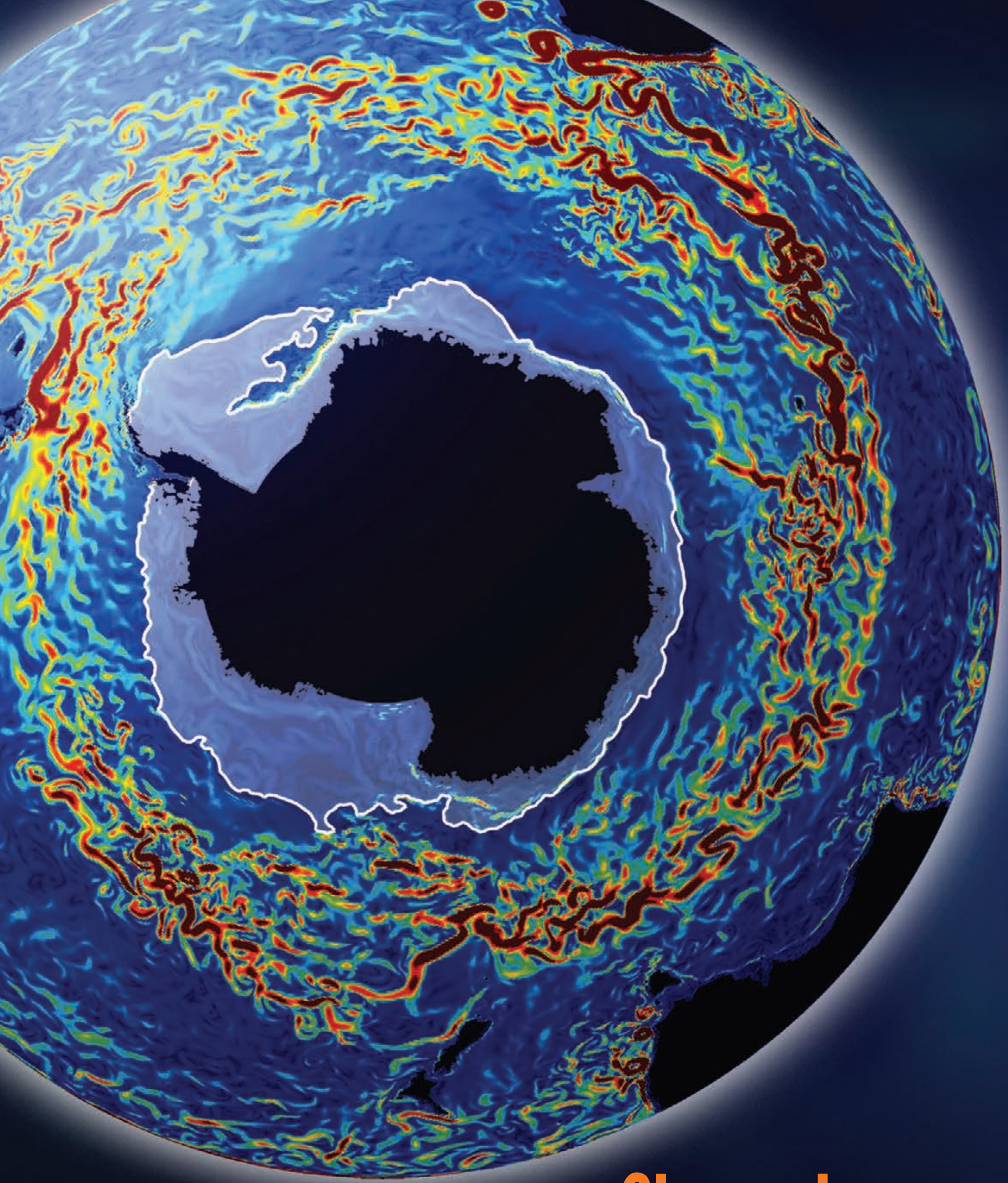

ESRF

The European Synchrotron Radiation Facility in Grenoble, France, has recently opened a beamline that is perfect for studying in real time the behaviour of materials at the extreme temperatures and pressures in the Earth's core. Called ID24, the €180m beamline lets researchers fire X-rays into materials that have been squeezed using diamond-anvil cells before heating the pressurized material with short, intense laser pulses to up to 10 000 K. The beamline can reveal how crystalline samples absorb X-rays in real time with a resolution of the order of microseconds, in turn revealing how their structures change.

### Higher state

Back in Japan, Hirose is now trying to do to liquids what he has done to solids – squeeze and heat them, to simulate the outer core, the precise chemical composition of which is still unknown. Unfortunately, experiments on liquids are much harder than on solids – after all, liquids move, even in minute samples, but solids do not. Under pressure and temperature gradients, liquids normally move away from the high-temperature spot. "So as soon as we melt the sample, the liquid moves away from the heating spot," Hirose points out. The key, he says, is to apply a very homogeneous temperature field.

Hirose's laboratory has now attained conditions of 400 GPa and 6000 K. "I'm very much interested in the liquid of the core, and measuring the sound velocity and density of liquids at high temperature and pressure," he says. Hirose is not alone of course – the European Synchrotron Radiation Facility in Grenoble, France, for example, opened a beamline late last year that is ideal for studying, with microsecond resolution, how materials absorb X-rays at extreme conditions of up to 10 000 K (figure 2). But if Hirose's past accomplishments are any indication, whatever he finds there will bring the picture of the inner Earth into sharper focus still. ■



M Mazloff, MIT/San Diego Supercomputer Center

# Churned up

This map shows the speed of the clockwise Antarctic Circumpolar Current on 12 May 2006, increasing from slow-moving water (blue) to speeds above one mile per hour (dark red). Land masses are black and the Antarctic Polar Front, where cold polar air meets warm tropical air, is shown by a solid white line. The Southern Ocean, with the near-continuous strong winds that churn its surface, is estimated to absorb as much as 40% of the carbon dioxide taken in by the world's oceans, despite only accounting for about 6% of their area.

# Eyeing the Earth with neutrinos

Essential information about the Earth's thermal energy could be obtained by detecting the almost massless neutrinos that flit through the Earth's interior. **Gianpaolo Bellini** and **Livia Ludhova** explain how the study of "geoneutrinos" is opening up an entire new field of interdisciplinary research

The Pulitzer-prize-winning US author John Updike is perhaps best known to physicists for his delightful poem about neutrinos. The first few lines of "Cosmic gall" (1960 *New Yorker*) perfectly capture the elusiveness and trickiness of these almost ghost-like particles:

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass
Like dustmaids down a drafty hall.

Updike was right that neutrinos are tiny and have no electric charge. But we now know that they can interact with matter, albeit rarely, and we also know that neutrinos are not entirely massless either. What is perhaps even more interesting is that, thanks to the recent development of ultrasensitive neutrino detectors, we can now use these particles to obtain new information about the Earth itself. To neutrinos, the Earth may be much more than "a silly ball".

The fact that neutrinos and their antimatter counterparts – antineutrinos – interact so weakly with matter produces some surprising behaviour. Whereas individual photons produced in the Sun, say, can take 100 000 years to escape its core – getting continually absorbed and re-emitted as they travel through solar matter – neutrinos will have escaped the Sun's clutches within a few seconds. Assuming they can be detected, neutrinos are therefore remarkably useful for probing regions that would otherwise be impossible to reach. Indeed, neutrinos (and antineutrinos) can travel through the Sun, the Earth and even the whole universe without being disturbed at all.

Geoneutrinos are a type of antineutrino produced inside the Earth from the radioactive decay of uranium, thorium (and their respective daughter nuclei) and potassium. As the antineutrinos travel to the surface, they bring precious information about the amount and distribution of these radioactive elements from deep within our planet – information that remains undistorted on its passage through the Earth. In addition to the antineutrinos, each radioactive decay produces a known amount of heat – so detecting the geoneutrinos could help us to estimate what fraction of the total heat flux through the Earth is produced in this way.

This heat powers many vital processes on Earth, notably mantle convection and plate tectonics, but the proportion from radioactive decay is far from clear. The problem is that we do not know for sure the abun-

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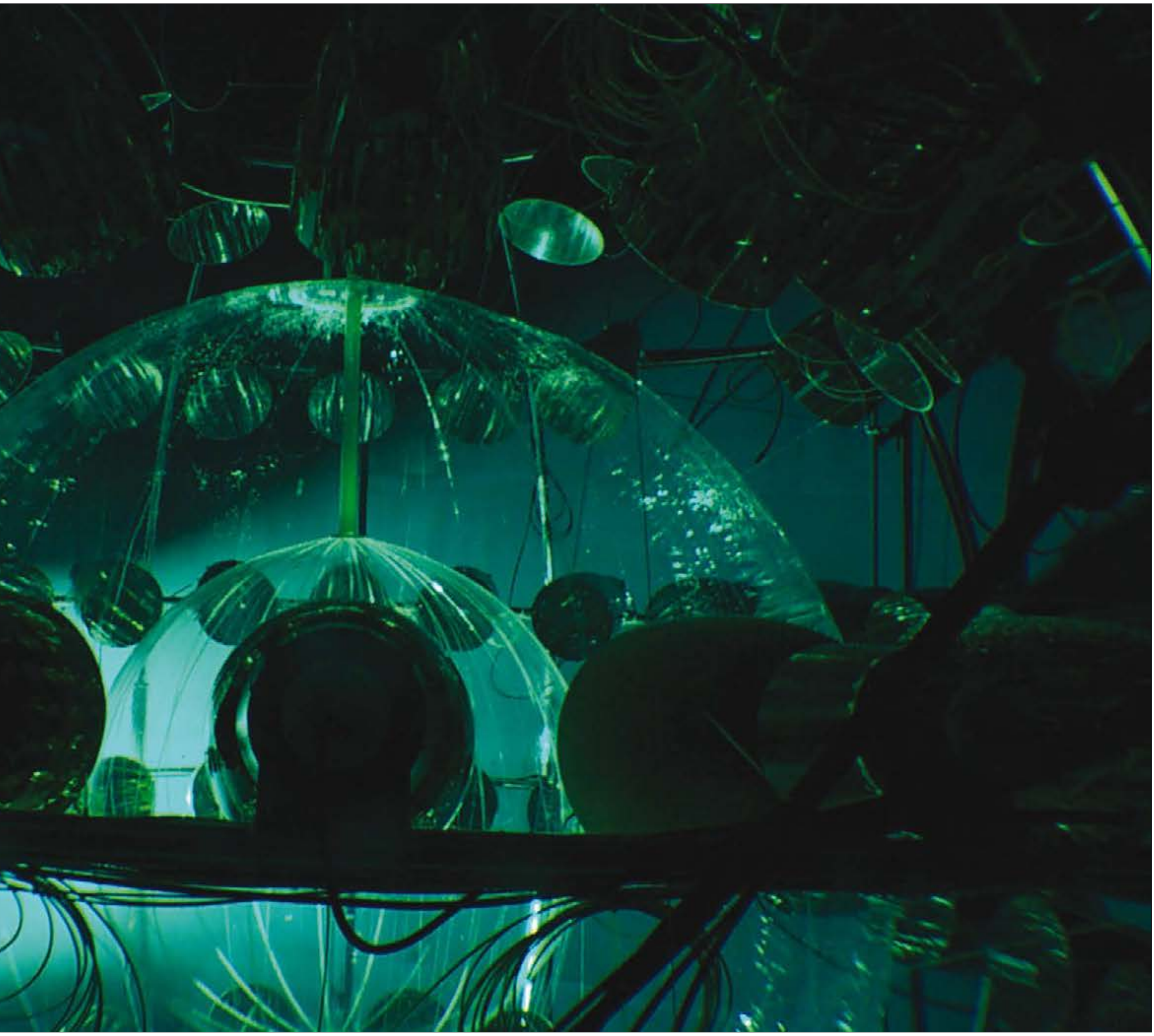


INFN

**Fiendish task** The Counting Test Facility measures the tiny intrinsic radioactivity of the fluid that is used inside the Borexino neutrino detector at the Gran Sasso National Laboratory in Italy.

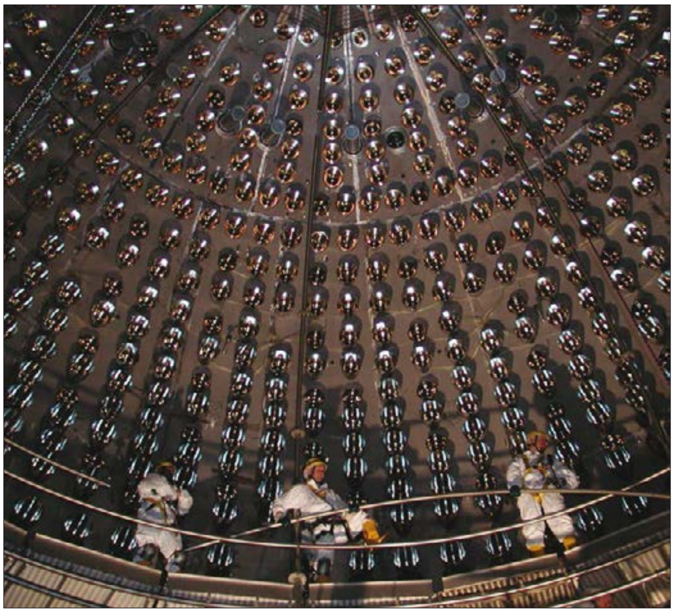
dance of uranium, thorium and potassium, and thus how much heat they produce or whether there are any additional heat sources. Geophysicists have created models of mantle convection that predict that about 70% of the total surface heat flux is from radionuclei, while geochemists think this figure is much less, possibly as little as 25%.

What geoneutrinos could do is give us a way of measuring the amount of this "radiogenic" heat directly. Spotting geoneutrinos is extremely challenging, but researchers have managed to detect them at the KamLAND detector, which is located 1000 m underground at the Kamiokande–Mozumi mine in Japan, and at the Borexino experiment at the Gran Sasso National Laboratory beneath the Apennines in central Italy (of which the present authors are members). Although these experiments were designed to detect interactions from two very different sources – antineutrinos from nuclear reactors in the case of KamLAND and neutrinos from the Sun for Borexino – both their achievements in observing geoneutrinos have opened up an entirely new interdisciplinary endeavour for studying the Earth.

## Unknown Earth

One reason why geophysicists are interested in knowing the total heat flux through the Earth is that this number can help us to understand how our planet formed and evolved, and why it has its current structure. To estimate this value, geophysicists currently turn to measurements of the temperature gradient below the surface obtained mostly by oil-exploration firms that have drilled some 40 000 or so holes to different depths across our planet. These data can then be fed into various models of how our planet has evolved and cooled over the years, each of which makes different

Both images: INFN



**Data source** The photomultiplier tubes on the cupola of the stainless-steel sphere that makes up the Borexino detector. When geoneutrinos strike the fluid in the detector, they can produce photons that are converted by these tubes into electrical signals that can be digitized and analysed.

**Clean through** A technician installs photomultiplier tubes and associated optical fibres on the inner wall of the stainless-steel sphere that makes up the Borexino neutrino detector. The entire sphere is treated as a special clean room to prevent any particulates or dust from clinging to the wall: their radioactivity could swamp the geoneutrino signal.

assumptions about factors such as how young underwater volcanoes behave and how heat is transferred.

Researchers have used these models in recent years to make different estimates of the total heat flux through the Earth's surface – but unfortunately they produce wildly different results. In 2010 Huw Davies from Cardiff University and Rhodri Davies from Imperial College London suggested that the flux is 47 ± 2 TW (*Solid Earth* **1** 5), while an earlier estimate in 2005 by Anne Hofmeister and Robert Criss from Washington University in St Louis put the figure at 31 ± 1 TW (*Tectonophysics* **395** 159). Although the error bars on each number are small, they refer only to the uncertainty in the model and do not take into account the intrinsic uncertainties of the hypotheses used to develop the model.

One way to estimate the radiogenic heat flux is to use models of the silicate shell surrounding our planet's metallic iron–nickel core, which involves calculating the heat released in the decays of the uranium-238 and thorium-232 radioactive families, and potassium-40. Assuming that the relative abundance of these nuclei in our planet is the same as in meteorites that have landed on Earth – which is not unreasonable given that everything in the solar system probably comes from a single primordial body – these models imply that radioactive decay in the Earth's interior accounts for a heat flux of 12–30 TW. As this value is possibly less than the total measured experimentally, it means that other potential heat sources could exist – for example from the original heat remaining from when the Earth was formed, from materials contracting under gravity or from the latent heat generated when, say, two tectonic plates collide. The heat could even come from naturally occurring nuclear reactions arising from critical amounts of uranium-238 at the core–mantle boundary, although this is unlikely.

When estimating the flux, one has to take into account the local geology and the fact that the composition of radioactive elements varies

Detecting geoneutrinos could overcome the discrepancy between the heat fluxes foreseen by the different models because we know how likely it is that a geoneutrino will interact with a detector. So by recording how many geoneutrinos we actually detect in a particular time interval, we can calculate their overall flux. Given that every uranium-238 decay chain emits a total of six antineutrinos, while the thorium-232 decay chain produces four antineutrinos and potassium-40 releases just one, we can therefore use our value of the flux to calculate how many of these nuclei are in the Earth, assuming they exist in the same proportion as in meteorites. And since the number of neutrinos from each decay chain is proportional to the emitted energy, we can calculate how much heat is produced from radiogenic decay.

The thinking is simple – the reality is hard. In particular, when estimating the flux, one has to take into account the local geology and the fact that the composition of radioactive elements within the mantle varies from place to place. Much more challenging still is actually capturing a geoneutrino in the first place, which is why only two experiments – Borexino and KamLAND – have so far managed to detect them.

### A challenging enterprise

Being such elusive particles, capturing a geoneutrino is an exceptionally tricky task. The Borexino detector is basically a big tank containing several thousand litres of an organic solvent (1,2,4-trimethylbenzene) plus a small percentage of another component, known as a fluor. KamLAND is similarly large and has the same two components, but also a lot of mineral oil that makes up 80% of its total volume. Any particle passing through the detector – be it a cosmic ray, an antineutrino from a nuclear reactor or a geoneutrino – can transmit energy to a molecule of the solvent by exciting it. A small portion of this energy migrates to a fluor molecule, which releases a photon when it decays. Photomultiplier tubes capture the photon and transform it into an electronic pulse.

Although such photons can be produced by a variety of incoming particles, we know we have detected an antineutrino because it produces a characteristic signal when it strikes a proton (a hydrogen nucleus) in the detecting material. This collision – known as an "inverse β-decay" – creates a neutron and a positron (anti-electron) that decelerates and annihilates almost immediately on encountering an electron, emitting two gamma rays with an energy of about 0.5 MeV. The energy of the gamma rays plus that lost by the positron make up a unique signature that we call the "prompt" signal. The neutron, however, survives for longer, scattering off matter and losing energy until – after about 250 $\mu$s – it is captured by a proton, releasing a single 2.2 MeV gamma ray called the "delayed" signal. So if we see the prompt signal followed by the delayed signal about 250 $\mu$s later, then we know we have detected an antineutrino. The fact that these interactions are so well "tagged" is essential in allowing us to distinguish antineutrinos from the background signal.

That all sounds fine in principle, but to understand just how challenging it is to detect geoneutrinos, it is worth noting that Borexino observes only one such particle every seven weeks. Even solar neutrinos, which strike the Earth at the much higher rate of some 60 billion per square centimetre per second, are fiendishly hard to detect; Borexino sees only about 45 of these in a single day. With such low statistics, any processes that can mimic geoneutrino interactions have to be either eliminated, or reduced to an extremely low level.

### Low signal, high noise

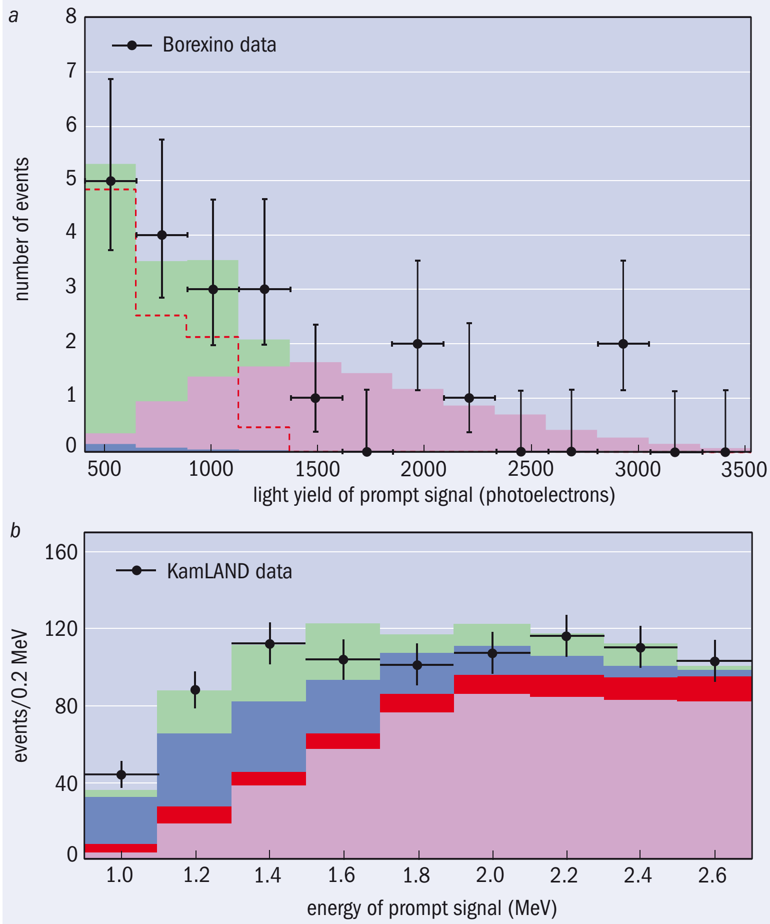
To compensate for the low flux and low rate of detection, any geoneutrino detector has to be installed in a location where almost no cosmic rays from outer space contribute to the signal. In the case of Borexino, this shielding is achieved thanks to the 1400 m or so of rock that lies above the Gran Sasso lab, which absorbs virtually all incoming cosmic rays such that just a few rays reach every square metre of the detector in a single hour. The detector also has to be shielded from "fake" signals arising from the natural radioactivity of everything from the local underground rocks to the materials used for the floor and even the air. In the case of Borexino, the detector is shielded by some 2400 $m^3$ of highly purified water that absorbs gamma rays, neutrons and other electrically charged particles.

But the hardest problem is dealing with the intrinsic radioactivity of the detector and of the scintillator itself. Removing signals from these sources involves building the detector – liquid containers, photomultiplier tubes, pipes, valves, pumps and so on – using materials that have as little natural radioactivity as possible. And, more importantly, the scintillator has to be purified to remove all its radioactive elements. In the case of Borexino, new techniques have been developed with an unprecedented radiopurity that is some 10–11 orders of magnitude lower than most natural materials.

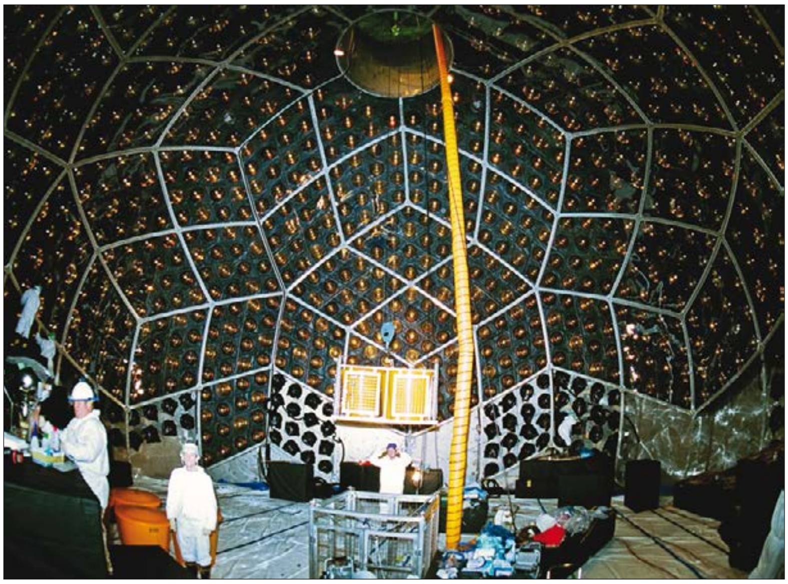
Researchers at KamLAND have also spent much time and effort on fine-tuning their scintillator. However, its radiopurity requirements are not as stringent as those of Borexino because KamLAND is designed to study only antineutrinos. On the other hand, KamLAND has 1000 tonnes of scintillator fluid – more than three times the volume at Borexino – which means that it captures about three times as many geoneutrinos.

But the problems do not end there because we must also deal with antineutrinos from nuclear reactors, which are another source of fake events. This is a particular problem at KamLAND, which has to contend with an antineutrino flux that is about seven times as high as at Borexino as a result of the much higher density and the closer proximity of nuclear reactors in Japan than in Italy. Fortunately, we can in principle disentangle the geoneutrino signal from the reactor-antineutrino signal because each is spread over a different range of energies. Overall, after 18 months of data-taking, Borexino has yielded about 10 geoneutrinos, 11 antineutrinos from reactors and about 0.5 background events, whereas KamLAND has, over a period of 92 months, seen 111 geoneutrinos, 485 reactor antineutrinos and 245 background events (figure 1). The evidence of geoneutrinos achieved by Borexino is the

### 1 Go figure




Energy spectrum of the geoneutrinos detected by (*a*) Borexino and (*b*) KamLAND. the graphs show the distribution of the energy of the "prompt" signal $E_p$ (see main text) expressed as the number of photoelectrons detected by the photomultiplier tubes (Borexino plot) or converted into energy (KamLAND plot). The Borexino plot shows geoneutrinos (green), antineutrinos from nuclear reactors (pink) and the fake events caused by the natural radioactivity (blue) (2010 *Phys. Lett. B* **687** 29). The red line corresponds to the geoneutrinos once the reactor antineutrino signal is subtracted out. In the KamLAND plot geoneutrinos are shown as green, the antineutrinos from reactors as pink, while fake events caused by the natural radioactivity are blue and red (2011 *Nature GeoScience* **4** 647).



KamLAND

**Deep insights** The KamLAND detector in Japan has also spotted geoneutrinos.

same as KamLAND despite the lower volume and the shorter data-taking time, thanks to the almost negligible background caused by natural radioactivity and the lower flux of antineutrinos from reactors.

### Act locally

So how do we connect the number of geoneutrinos detected by an experiment with the overall radioactivity in the crust and mantle? To do so we have to draw on our knowledge of the local geological conditions (at Borexino and KamLAND about half of the signal comes from within a hemispherical volume with a radius of 100–200 km from the detector) and in particular the thickness and local radioactivity of the crust. The thickness is important so that we know the solid angle over which the detector receives the geoneutrinos from the mantle: if the crust beneath one detector were thinner, it would receive more geoneutrinos from the mantle and vice-versa if the crust were thicker. (In fact the crust is about 35 km thick for both Borexino and KamLAND.)

Taking all factors into account, both KamLAND and Borexino now have very robust evidence for the existence of geoneutrinos to a probability of 99.997%. But given that geoscientists were already aware of the presence of radioactive decays in the crust – based on chemical analyses of material in the drill holes – what have these studies told us that we did not know before? The main finding to date is that the total heat flux measured with geoneutrinos is higher than that suggested by existing measurements of radioactive decay in the crust. In other words, we have shown for the first time that radioactive decays must also be taking place in the mantle. In addition, a combined analysis of the KamLAND and Borexino data suggests that the heat from radioactive decay makes up about one half of the total terrestrial heat flux.

But, more importantly, being able to detect geoneutrinos from the Earth's interior gives us a brand new way of investigating the structure of our planet – for the first time we have been able to obtain direct information about the inner regions of the Earth below the crust.

**Being able to detect geoneutrinos gives us a brand new way of investigating the structure of our planet**

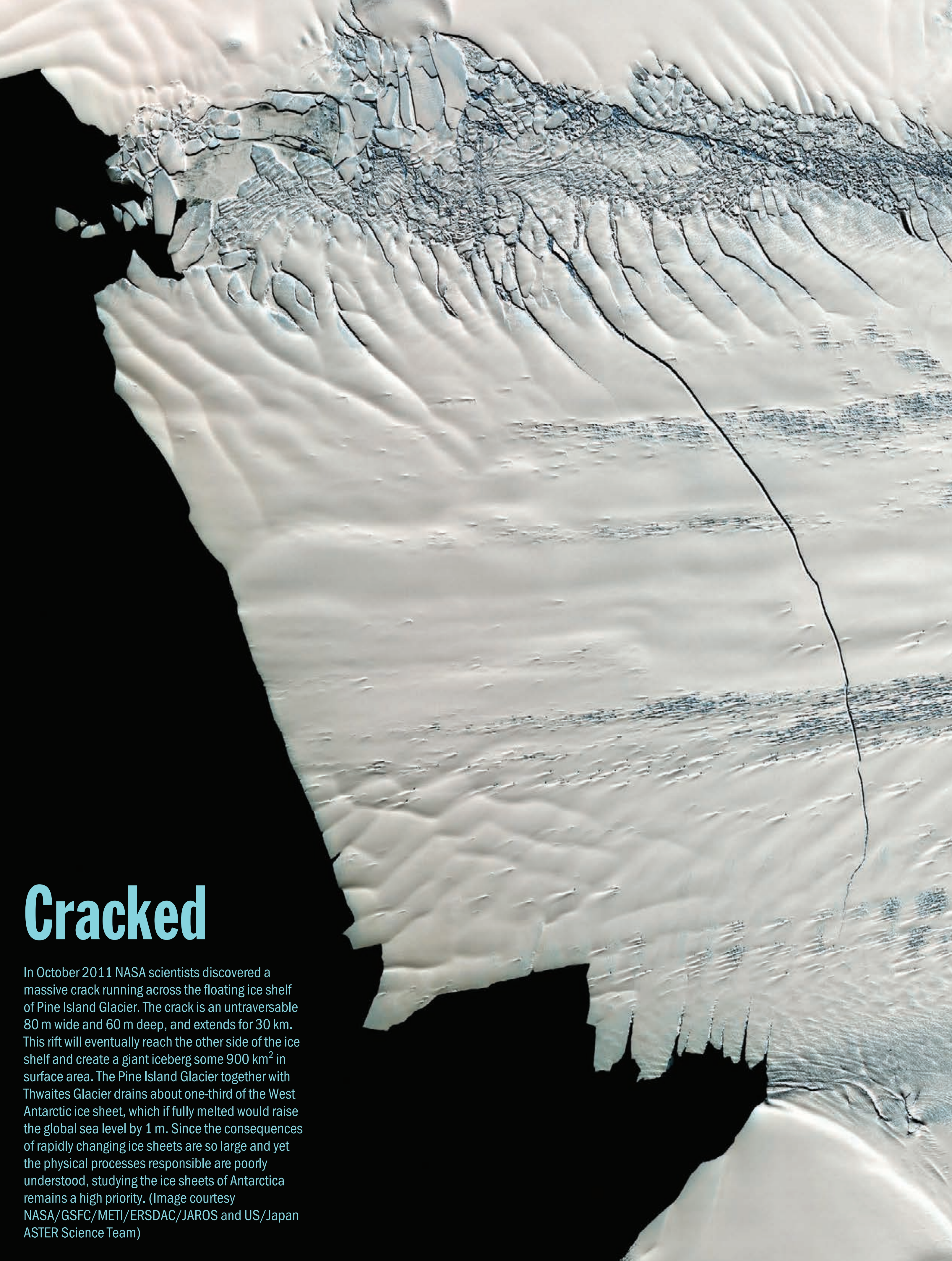
Moreover, the presence of uranium and thorium in the mantle sheds light on its chemical composition because other elements, which have a chemical affinity with them, in principle will have to be present too.

### Fast forward

Although the geoneutrino work at Borexino and KamLAND is a good start, to obtain definitive answers to questions about the radiogenic heat and the abundances of radiogenic elements, more data are needed. The existing experiments will continue to take data over the next three or four years but it would be useful to build bigger detectors to increase the number of captured geoneutrinos and so improve the precision of the flux measurement. What would also be interesting would be to have geoneutrino detectors at different sites around the world, each with a different local geology, to understand if, for example, the composition of the Earth's mantle and the distribution of heat from it are homogenous (or not). If we could estimate the bulk ratio of uranium to thorium in the Earth we could then compare this with the same ratio in meteorites, thereby giving us a better understanding of the Earth's formation and of the distribution of elements in the solar system.

Thankfully, various research groups are designing and even building a new generation of neutrino experiments using liquid scintillators. The SNO+ experiment at the Sudbury mine in Canada, for example, will have a target consisting of 1000 tonnes and is set to come online next year. The mine is located on an old continental crust and the flux from reactor antineutrinos is about twice as much as at Gran Sasso. Europe also has ambitious new plans to build a 50 000 tonne detector, dubbed LENA (Low Energy Neutrino Astronomy). The experiment, which might be located in the Pyhäsalmi mine in Finland or the Fréjus underground lab in France, is designed to detect as many as 1000 geoneutrinos per year. Meanwhile, there are interesting plans for a 5000 tonne underwater experiment, known as HanoHano, in Hawaii that would sit on the ocean crust. As the crust there is particularly thin, most of the geoneutrinos should come from the mantle, which means that the experiment would provide the most direct information to date about the mantle.

Indeed, these future experiments, coupled with those currently under way, could be a starting point for a network of geoneutrino detectors to understand the Earth's heat distribution and the chemical composition of the mantle. By working together, earth scientists and nuclear physicists could allow us to understand otherwise inaccessible aspects of what Updike called "our silly ball".



# Cracked

In October 2011 NASA scientists discovered a massive crack running across the floating ice shelf of Pine Island Glacier. The crack is an untraversable 80 m wide and 60 m deep, and extends for 30 km. This rift will eventually reach the other side of the ice shelf and create a giant iceberg some 900 $km^2$ in surface area. The Pine Island Glacier together with Thwaites Glacier drains about one-third of the West Antarctic ice sheet, which if fully melted would raise the global sea level by 1 m. Since the consequences of rapidly changing ice sheets are so large and yet the physical processes responsible are poorly understood, studying the ice sheets of Antarctica remains a high priority. (Image courtesy NASA/GSFC/METI/ERSDAC/JAROS and US/Japan ASTER Science Team)

# When north heads south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**The polarity of the Earth's magnetic field appears to have flipped randomly throughout history, with visual representations of these changes looking like product barcodes. But François Pétrélis, Jean-Pierre Valet and Jean Besse have a new insight that could explain a pattern in the rate of reversals**

The Earth's magnetic field is becoming weaker. It has deteriorated by 10–15% over the last 150 years at a rate that has recently been speeding up. Doomsday enthusiasts, who believe some earthshattering event will destroy humankind in December this year, cite this weakening field as one of the possible apocalypse scenarios. They think that the poles might reverse, resulting in devastation across the world, possibly from a lack of shielding from cosmic rays.

However, there are many things wrong with this picture. First, a reversal takes several thousand years, not just one. Second, in a reversal the magnetic field does not disappear, because many poles form chaotically and so even though a compass would be useless, a magnetic field still exists. And third, a weakening field is not a sign of an impending reversal anyway – it is normal for the field strength to fluctuate in-between reversals.

But although there is a lot we do know about geomagnetic reversal – we are pretty sure we know how the field is generated and how it is able to change polarity – mystery still surrounds whether reversals are spontaneous or whether they are caused by some external trigger. Another enigma is that the reversal rate changes over time. During one 12-million-year period centred on 15 million years ago, for example, there were a staggering 51 reversals, while one 40-million-year period centred on 100 million years ago saw none.

The exact reason why such periods of reversal activity are so different is still unclear. But we have discovered one possible explanation that could hold the key. To build up a picture of what we speculate and why, we must first start with the basics – how the Earth's magnetic field is generated, and how it reverses.

## Molten-metal magnet

Beneath the Earth's crust, the interior of the planet can be roughly described by three concentric layers (see figure on p39). The mantle, which lies between the crust and 2890 km deep, is pretty solid, but if you wait long enough, it acts as a slowly moving material. The mantle

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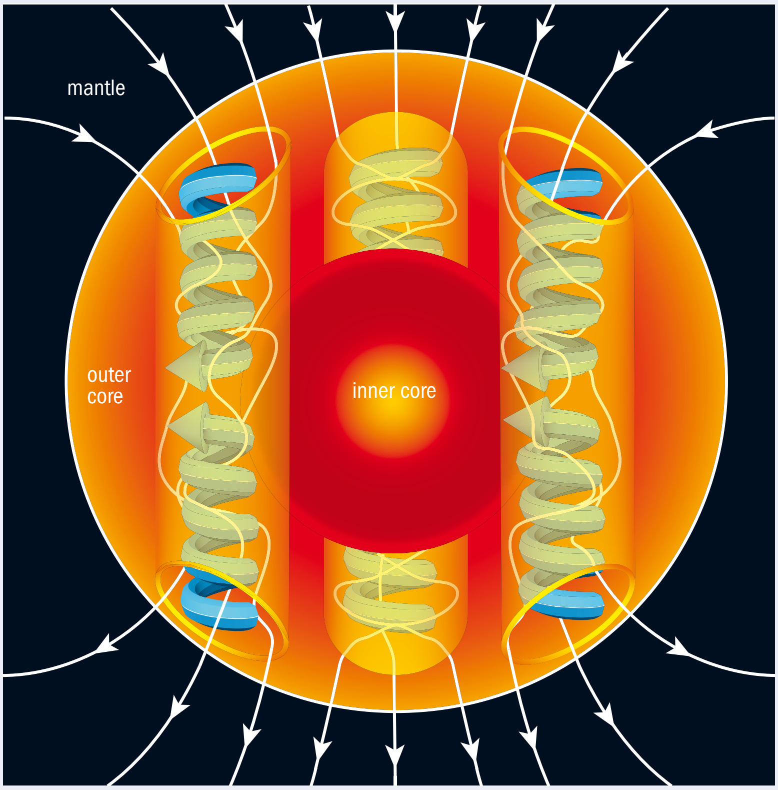
## 1 At the core of the matter




The Earth's magnetic field is produced by the movement of liquid metal in the Earth's outer core. Energy to power this movement comes from heat that is released as material from the outer core slowly freezes onto the solid inner core. This heat powers convection cells in the outer core, which keep liquid metal moving through the magnetic field, thus creating a bigger field in a feedback effect known as the geodynamo. The Earth's spinning motion causes the liquid to form spiralling eddies, the alignment of which allows the magnetic field produced in each to join together to make an even bigger field.

is also an insulator, which is great for allowing us to scrutinize the field pattern at the surface of the next layer down, the outer core. (For insulators, the magnetic field equation is simple, and so knowing the field at the mantle's surface lets you calculate what lies below.) The outer core is mostly molten iron and a few lighter elements, and lies 2890–5150 km below the surface. At these depths, where the temperature reaches 4000 K, this outer-core layer is a fluid and it moves rapidly (about a few kilometres per year). Finally, at the centre of the Earth is a solid-iron sphere, the inner core, which has a radius of 1228 km.

Scientists and engineers have discovered several ways to generate electric current and magnetic field from the mechanical energy of a moving electrically conducting solid. One way to do this is to use the "dynamo effect", in which a seed magnetic field is amplified by an instability to produce a larger field, and it is this phenomenon that also drives the magnetic field of the Earth. The liquid metal that makes up the outer core, which moves in convection cells powered by heat, passes through a small seed magnetic field, which induces an electric current to flow within it. This creates another magnetic field that is stronger than the pre-existing field and reinforces it. In turn, more current flows and the field increases, in a self-sustaining loop called the geodynamo. How the flow in the liquid core is organized is not clearly known but the Coriolis force is also expected to play a part. A common model is that the Earth's rotation causes the liquid metal of the outer core to form spiralling eddies aligned north–south, allowing the magnetic field generated by separate cells to join up (figure 1).

On the Earth's surface, the magnetic field appears very much like the dipole field that would be generated if a huge magnet existed inside the Earth, aligned along its axis of rotation. This is not exactly the case because the axis of the dipole is actually inclined by about 11° with respect to the rotation axis, which is why the poles of the dipole differ from the geographic poles. (When averaged over a few thousand years, however, the dipole axis is aligned along the rotation axis so that the geographic and the magnetic poles are at the same locations.) The reason for this discrepancy is that the magnetic field is not a perfect dipole aligned with the axis of rotation of the Earth, but has extra components that collectively cause the pole to wander. These extra components are responsible for the "secular variation" – changes in the strength and location of the field on a timescale on the order of 100 years that represent 10–20% of the total field.

### Into reverse

The most dramatic and impressive consequences of secular variations are geomagnetic reversals. They were discovered by Bernard Brunhes at the beginning of the 20th century, when he noticed that the magnetization of some lava flows pointed the "wrong" way. This could be explained if the Earth's magnetic field had pointed in the opposite direction when the lava solidified. Since then it has been established that reversals are a permanent and dominant feature of the Earth's magnetic field. Their history has been deciphered using the magnetization of lava flows or from sequences of sediments that contain small magnetized particles that were oriented by the field when the rock was formed. The last magnetic-field reversal occurred about 780 000 years ago, and the detailed reversal timescale is very well known for the past 160 million years (myr) and with rather good confidence for the past 300 myr (see box, and blue curve in figure 3 on p55).

At first glance it seems as if the field has reversed in a random manner. But the "reversal frequency" – the number of reversals per million years – has varied markedly throughout history. Indeed, between 120 and 80 myr ago the average reversal frequency was zero, but since then it has been rising. These long periods without any reversals are called "superchrons" and the existence of several of these suggests that long intervals without reversals may have punctuated a large part of our geomagnetic history. The changing reversal frequency over time gives us reason to wonder whether it is influenced by some external factor that changes on a similar timescale. The timescale on which superchrons repeat therefore suggests that processes associated with geomagnetic-field reversals recur on a 200 myr timescale.

As humans have only ever penetrated a tiny fraction of the way through the crust, and seismic waves can only tell us so much about what lies beneath it, the Earth's insides remain pretty hidden from us. Our under-

## Back and forth throughout history


This graph shows the polarity of Earth's magnetic field as far back as the Jurassic period some 160 million years (myr) ago. Purple denotes periods when the polarity of Earth's magnetic field was the same as it is today, and white denotes periods when the polarity was the opposite. So in purple times (like the present) compasses would have pointed north, but in white times they would have pointed south.

standing of what goes on there has therefore relied partly on laboratory and computer experiments that try to simulate what happens. To gauge whether such models are successful we can measure their behaviour and see whether it matches that of the Earth, such as having a magnetic field that flips over time.

**In the lab**

During the last 30 years, several computer simulations of the dynamo have attempted to recreate the processes involved in the generation of the Earth's magnetic field. But a major difficulty is that computers do not have enough processing power to accurately model an object as large as the Earth. The equations describing the dynamo must therefore be simplified before they can make any predictions. Yet although these models are not perfect representations, it is significant that they do produce fields with similar characteristics to the Earth.

In parallel, much information has been gained during the last 10 years from laboratory fluid-dynamo experiments that attempt to mimic the Earth's liquid outer core. In these experiments, moving parts create flow in a container of liquid metal – usually liquid sodium because of its good electrical conductivity and relatively low density. Properties including the magnetic field are measured and finally in 2001 the dynamo effect was seen in liquid sodium heated above 100 °C in two separate experiments by Robert Stieglitz and Ulrike Müller at the Karlsruhe Institute of Technology, Germany, and by a group led by Agris Gailitis at the University of Latvia. These experiments dealt with liquid flowing in a pipe or in an array of pipes.

A different approach was from an experiment that began in 1999 at the CEA research centre in Cadarache, France, in a collaboration with physicists at CEA Saclay, ENS Lyon and ENS Paris. What is known as the Von Kármán sodium (VKS) experiment involves a turbulent swirling flow of liquid sodium between two counter-rotating discs, aligned along the same axis, within a cylindrical container. A later version of the experiment produced not only the dynamo effect but also spontaneous reversals of the magnetic field. The reversals showed a remarkable degree of repeatability and appeared to be very similar to what is known about reversals of the Earth's magnetic field. Similar behaviour included a random field distribution, dipole collapse, rapid polarity change, and recovery of the dipole intensity. Interestingly, reversals were only observed when one of the discs rotated faster than the other.

A mechanism that explains why the magnetic field reverses in the experiment provides an interesting link to the reversals of the Earth's field (F Pétrélis, S Fauve, E Dormy, J-P Valet 2009 *Phys. Rev. Lett.* **102** 144503). We know that in both cases the dipolar field is not the only field of importance – if it were, the field would be stable – and that there is some non-dipolar contribution. In the VKS experiment a significant role is also played by a second mode, which is quadrupolar – roughly speaking this is like two dipoles facing each other. The coupling between the two modes provides a pathway for the dipole to flip from one polarity to the other: as the dipole field weakens, the quadrupole field grows, and then as the dipole grows in the opposite direction, the quadrupole field shrinks. If this coupling is strong enough, the magnetic field spontaneously oscillates between the two modes and their opposite polarities, yielding periodic field reversals. We believe that a similar process is involved in the case of the solar magnetic field, which oscillates with a period of 22 years.

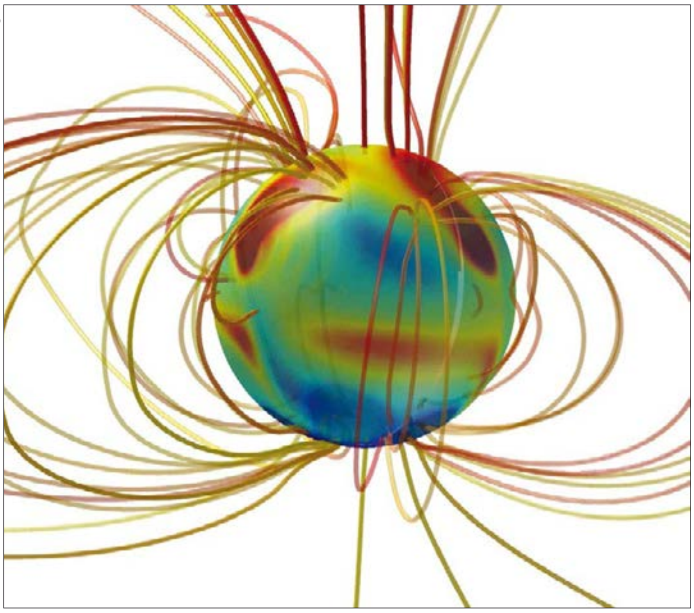
Unlike the Sun, though, the coupling between the dipole and other modes in the Earth is not strong enough to create a regular, periodic oscillation. To trigger a reversal, velocity fluctuations in the liquid core are also needed. For the Earth, a reversal involves two phases: a slow decrease of the dipole amplitude followed by a rapid recovery towards the opposite polarity. At the end of the first phase, the dipole–quadrupole interaction mechanism predicts that the magnetic field can either reverse, or increase back to the initial polarity, accomplishing what is called an excursion: a reversal that begins to take place but is then aborted.

If the dipole does reverse, however, the total field never actually goes to zero: at no point does it "switch off". In contrast, the dipolar field continuously changes shape during a reversal because the amplitude of other modes (including quadrupolar) continuously increases as the dipole decreases. Once the dipolar component has vanished, it is restored with the opposite polarity while the amplitudes of the other modes decrease. Paleomagnetic records of geomagnetic reversals show characteristics that are consistent with these predictions.

Experiments have therefore helped shed light on the

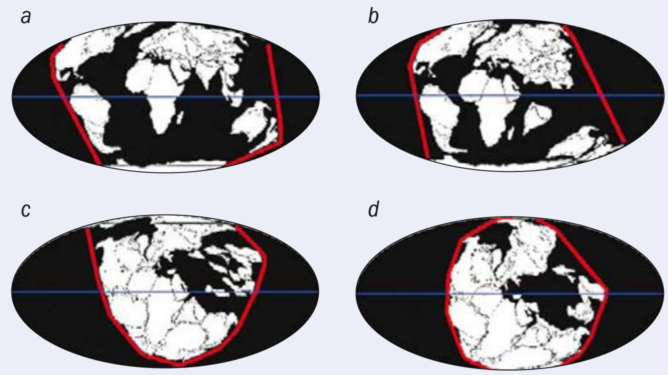
In the laboratory, reversals were only observed when one of the discs rotated faster than the other

C Gissinger



**Pole position** This computer simulation by C Gissinger shows the “dynamo effect” in the Earth’s liquid outer core. This effect generates the Earth’s magnetic field (shown here by looping lines). The radial component of the magnetic field is represented at the surface of the model, which corresponds to the core–mantle boundary.

## 2 Continents enclosed




The authors have found that the geographic distribution of the Earth’s continents throughout history seems to be linked to the frequency at which the Earth’s magnetic field reverses (see figure 3). These diagrams show how they defined the parameter they used to describe where the continents were. The continents were enclosed by their convex envelopes (red) and the distance from the equator of the centre of masses of these was measured. Examples here show the Earth’s continents (*a*) at present, (*b*) 65 myr ago, (*c*) 200 myr ago and (*d*) 260 myr ago. In (*a*) and (*c*) there is a larger continental surface in the north and in (*b*) and (*d*) there is more in the south.

Earth’s inner workings – both the mechanism by which the poles flip, and the intriguing fact that in the VKS experiment reversals were only observed when the discs rotated at different speeds.

### Slow mover

As we have discussed, the Earth’s magnetic field is caused by the dynamo effect in the liquid outer core, so for reversals we have to wonder what it is that perturbs the liquid flow to cause the magnetic-field change. One thing we know for sure is that the overall rate at which the Earth’s magnetic field reverses varies on a timescale of about 200 myr. (Note that the poles themselves flip many times within this timescale: 200 myr is the time it takes for the reversal frequency to vary from zero – a superchron – to a maximum, and back again.)

It is difficult to link the change of reversal rate with turbulent flows within the Earth’s liquid core as these have a characteristic timescale of the order of just a few centuries, which is much less than 200 myr. Conversely, the variations are too short to be accounted for by the extremely long-term growth of the inner core. Changes in the Earth’s rotation are possible candidates, but they occur on timescales four orders of magnitude too short (20 000–100 000 years for Milankovitch cycles).

In the absence of any other mechanisms on this timescale, could mantle dynamics be related to long-term variations in reversal frequency? In other words, does the key lie in what happens at the core–mantle boundary, where the slow-moving solid mantle meets the faster-moving liquid-metal outer core? Indeed, flow velocity of the mantle does not exceed a few centimetres per year and the characteristic time for mantle convection is therefore on the order of 100 myr.

We should expect some link between reversal frequency and plate tectonics

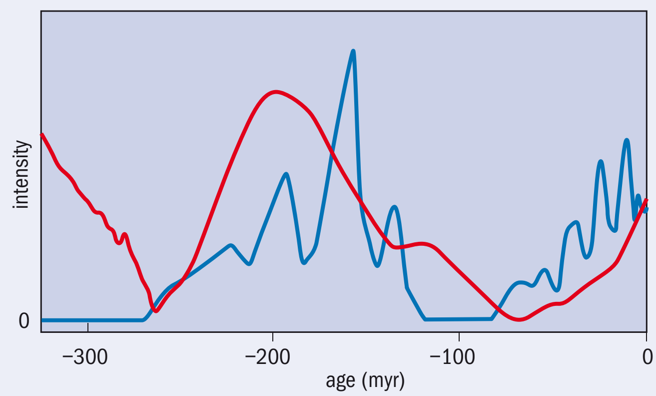
To understand how the mantle has behaved over the last 300 myr, a good tool is the study of plate tectonics. The large plates that make up the globe (currently eight major and many minor plates) have moved dramatically over the years. For example, 330 myr ago the continents as we know them were assembled as one supercontinent, Pangaea, which began to break up 200 myr ago with the opening of the central Atlantic. Tectonic plates can include continental crust or oceanic crust, and many plates contain both. Oceanic crust has a different composition to continental crust and is more dense. As a result of this density stratification, oceanic crust generally lies below sea level, while the continental crust corresponds to continents.

At certain plate boundaries, the oceanic crust can return down into the mantle in a region known as a subduction zone, where the oceanic crust then becomes known as oceanic slab. Seismic tomographic images have shown that many, but not all, slabs descend into the lower mantle. Some may be deflected at around 670 km deep and remain at the boundary between the upper and lower boundary, the lower mantle being of much higher viscosity. However, a large number of slabs do sink into the lower mantle, and can reach the core–mantle boundary in some 80–100 myr as part of huge mantle convection cells. It therefore becomes clear that what happens on the surface of the Earth – specifically the location of plates and subduction zones – could directly relate to the liquid outer core over a long enough timescale.

Thus, assuming that heat-flow conditions at the core–mantle boundary would control reversal frequency and also influence mantle convection, we should expect some link between reversal frequency and plate tectonics. As in the laboratory experiment where reversals only occur when the discs’ velocities are different, we suggest that the reversal frequency of the Earth’s magnetic field is constrained by a similar symmetry-breaking: some unevenness between the mantle flows of the Earth’s northern and southern hemispheres.

We speculate that the long-term evolution in reversal

## 3 Reversal frequency meets its match




This graph shows the temporal evolution of geomagnetic reversal frequency (blue) and a parameter that shows the distance from the equator of the centre of mass of Earth's continents (red). The frequency at which the Earth's magnetic poles have flipped has changed throughout history. At some points in history – at around −300 and −100 myr on this graph, for example – no reversals took place for long periods of time. In-between these times the rate of reversals seems to rise and fall. The authors speculate that this long-term evolution in reversal frequency is linked to the equatorial symmetry of the geographic distribution of the continents. Curves were normalized, and shifted in the vertical direction, for comparison.

frequency is caused by changes at the core–mantle boundary, which are linked to the equatorial symmetry of the geographic distribution of the continents (2011 *Geophys. Res. Lett.* **38** L19303). To measure this, we considered the convex envelope of the continents back through history (figure 2) and measured the distance of its centre of mass from the equator. The centre of mass moved north and south of the equator over time, when the continents were top- or bottom-heavy.

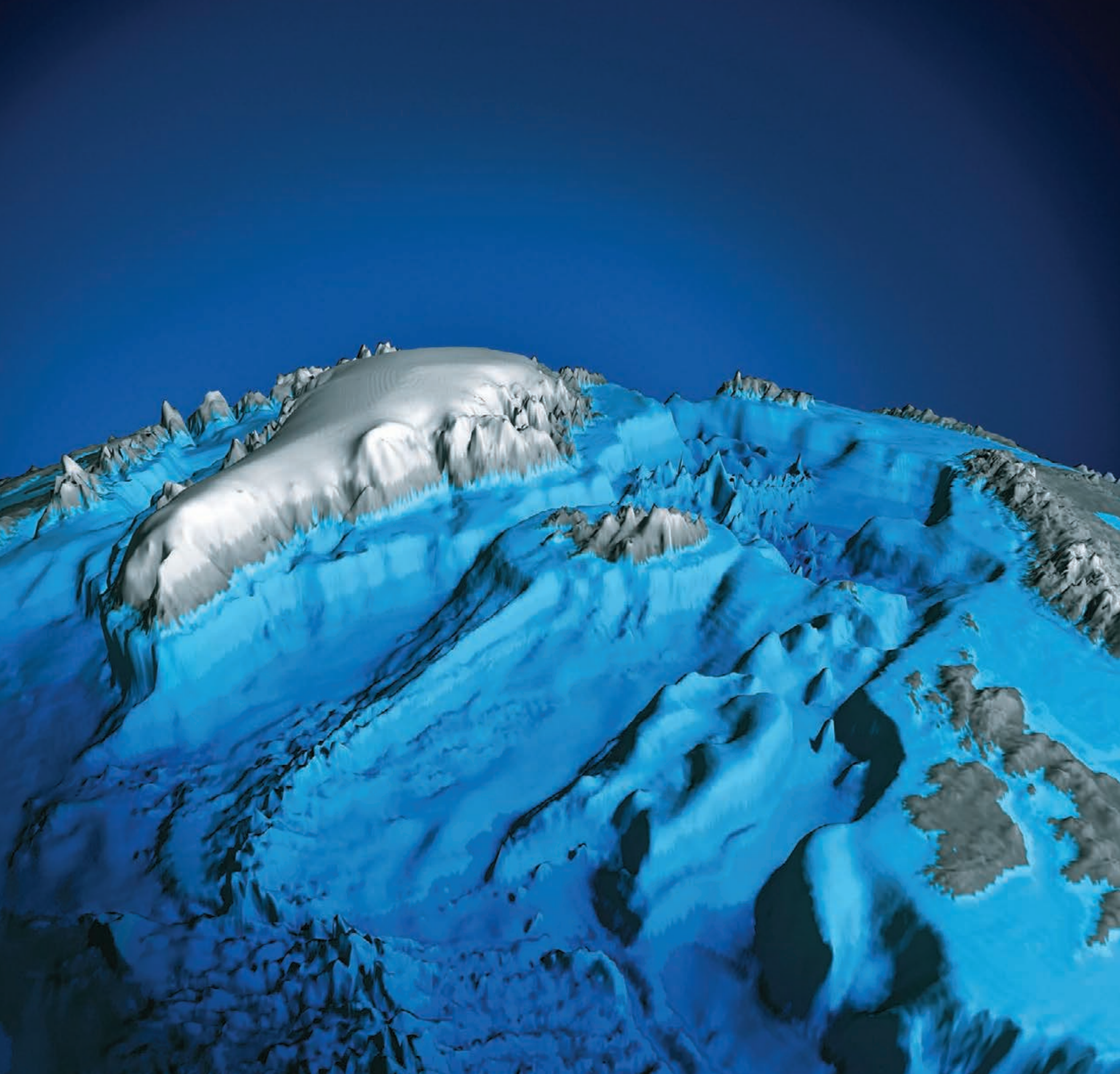
When we compared this parameter with the geomagnetic reversal frequency, we found striking similarities (figure 3). The quantity varies on the same timescale as the reversal frequency and the two are strongly correlated. The similarities between the two curves suggest that a link exists between continental motion and the geodynamo processes that take place deep inside the Earth's liquid core.

A detailed description of this coupling is not currently possible because the evolution of mantle properties back in time is not yet well known. All we can suggest is that plate motions are indicators of motions deep inside the mantle, and that these motions are associated with changes in the boundary conditions at the core–mantle boundary. These changes modify the symmetry of the liquid flow within the outer core and change the reversal frequency. The mechanisms that drive this correlation are yet to be understood.

The current results suggest that plate tectonics – the visible motion of the plates together with the mantle motions that drive them – have exerted a significant control over geomagnetic reversal frequency for at least the past 300 myr. They thus bring additional evidence when assessing the importance of mantle dynamics in the mechanisms driving long-term dynamo processes. The next step is to further constrain the link between plate motions and the mantle, and ultimately to be able to relate this to the physical properties at the core–mantle boundary. ■

# Deep trenches

This 3D satellite and bathymetry model shows the topography of the Earth's crust over the North Atlantic. Iceland (right of centre) sits on the Mid-Atlantic Ridge – a mid-oceanic ridge that is extremely volcanically active. Lava pushing up beneath this ridge creates new oceanic crust, pushing the North American plate (left) and the Eurasian plate (right) apart. Greenland is the pale landmass seen above left, which is mostly covered by the Greenland ice sheet. The British Isles can be seen bottom right, and above right is the mountainous region of western Norway. (Image courtesy German Aerospace Center/DLR/ Science Photo Library)



# How to forecast an earthquake

As seven Italian experts stand trial on manslaughter charges for underplaying the risk of a major earthquake, **Edwin Cartlidge** investigates the latest in earthquake forecasting

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In March 2009 a "swarm" of more than 50 small earthquakes struck within a few kilometres of the southern end of the San Andreas fault in California. Several hours after the largest of these, a magnitude-4.8 tremor that occurred on 24 March, the state's earthquake experts held a teleconference to assess the risk of an even bigger quake striking in the following days, given the extra stress exerted on the fault. They concluded that the chances of this happening had risen sharply, to between 1 and 5%, and therefore issued an alert to the civil authorities. Thankfully, as expected, no major quake actually took place.

What happened a week later in the medieval town of L'Aquila in central Italy was very different. On 31 March a group of seven Italian scientists and engineers met up as full or acting members of the country's National Commission for the Forecast and Prevention of Major Risks to assess the dangers posed by a swarm that had been ongoing for about four months and which had seen a magnitude-4.1 tremor shake the town the day before. The experts considered that the chances of a more powerful quake striking in the coming days or weeks were not significantly increased by the swarm, and following the meeting local politicians reassured townspeople that there were no grounds for alarm. Tragically, in the early hours of 6 April a magnitude-6.3 earthquake struck very close to L'Aquila and left 308 people dead. The seven commission members are now on trial for manslaughter, and the then head of Italy's Civil Protection Department, who set up but was not present at the 31 March meeting, is also being investigated for the same offence.

In the wake of the L'Aquila earthquake, the Civil Protection Department appointed a group of experts known as the International Commission on Earthquake Forecasting (ICEF) to review the potential of the type of forecasting used in California. Known as short-term probabilistic forecasting, it involves calculating the odds that an earthquake above a certain size will occur within a given area and (short) time period. The technique relies on the fact that quakes tend to cluster in space and time – the occurrence of one or more tremors tending to increase the chance that other tremors, including more powerful ones, will take place nearby within the coming days or weeks.

In a report explaining its findings and recommendations, published last August, the ICEF points out that while such forecasting can yield probabilities up to several hundred times background levels, the absolute probabilities very rarely exceed a few per cent. Nevertheless, the commission believes that this short-term forecasting can provide valuable information to civil authorities and urged Italy and all other countries in seismically active regions to use short-term-forecasting models for civil protection.

Scientists have developed many such models, each of which makes slightly different assumptions about the statistical behaviour of earthquake clustering. They are now trying to work out which of these models is the most accurate, and ultimately hope to enhance the predictive power of these models as we gain a better understanding of basic earthquake physics.

"In the past there hasn't been a lot of motivation for governments to take this short-term forecasting seriously," says the ICEF's chairman, Thomas Jordan of the University of Southern California, Los Angeles. "But that is changing, partly because of what happened at L'Aquila." Jordan argues that the tragedy at L'Aquila highlights how vital it is for us to understand what the most reliable types of forecasting are so that we have the best possible information at our fingertips. But he also believes it underlines the need for governments to work out exactly how to respond to such forecasts and in particular under what conditions they should issue alarms.

## Faulty matters

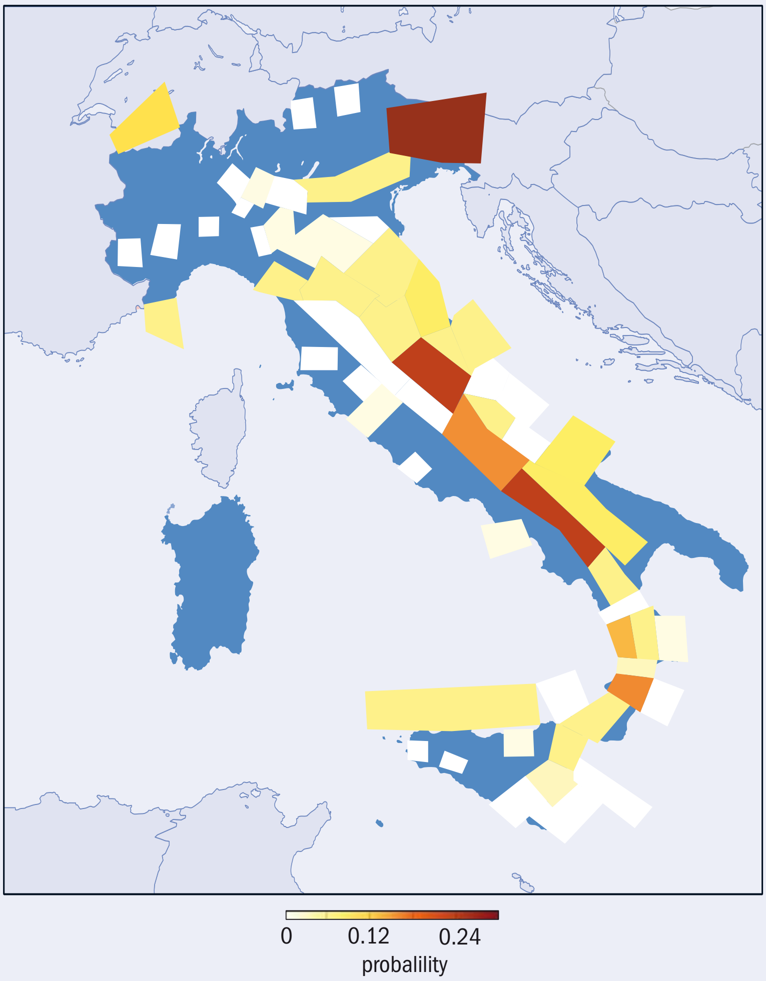
The development of *probabilistic forecasting* marks a change in strategy for earthquake scientists. Previously, seismologists had pursued *deterministic prediction*, which involved trying to work out with near certainty when, where and with what magnitude particular earthquakes would strike. Researchers came to realize, however, just how complex earthquakes are and how difficult it is to predict them.

Most earthquakes occur on faults separating two adjacent pieces of the Earth's crust that move relative to each other. Normally, the faults are locked together by friction, and stresses steadily accumulate over time. But when the faults reach breaking point and two rock faces suddenly slide past each other, a huge amount of energy is released in the form of heat, rock fracture and earthquake-causing seismic waves.

Scarred Earth
The San Andreas Fault in California.

David Parker/Science Photo Library

## 1 Mapping seismic hazard




A key tool used in earthquake forecasting is the seismic-hazard map. This map of Italy, based on one produced by the country's National Institute of Geophysics and Volcanology, shows the probability, as of 1 January 2012, that within the next 10 years an earthquake of magnitude 5.5 or greater will occur. The map is split into zones in which the "stress field" is fairly homogeneous, and so similar probabilities apply. These maps are based on long-term time-independent forecasting models, but we are now seeing a rise in the use of short-term time-dependent models that take into account recent events and give increased probabilities of major quakes. Despite this, seismic-hazard maps remain a useful tool because they allow long-term planning, such as setting building regulations – one of the best defences against loss of life when an event does strike.

Scientists have tried to predict earthquakes on the basis that the slow build-up and then sudden release of stress on any given fault occurs cyclically, with nearly identically powerful tremors spaced equally in time. A number of factors complicate this simple picture, including the fact that a single fault can slip at different stress levels, and also that interactions between neighbouring faults are highly complex.

An alternative route to predicting earthquakes is to try to identify precursors – physical, chemical or biological changes triggered in the build-up to a fault rupture. Perhaps the earliest example, often heard in folklore, is the idea that animals flee an area after somehow sensing an impending quake. Other possible precursors include changes in the rates of strain or conductivity within rocks, fluctuations in groundwater levels, electromagnetic signals near or above the Earth's surface, and characteristic foreshocks (a distinctive pattern of smaller quakes that would precede a larger quake). However, the ICEF reported that it is "not optimistic" that such precursors can be identified in the near future, and is "not convinced" by the claims of Gioacchino Giuliani, a technician at the Gran Sasso National Laboratory near L'Aquila, who hit the headlines after claiming to have predicted the L'Aquila quake using his prediction system based on variations in the local emissions of radon gas. The committee's reasoning is based on Giuliani's treatment of background radon emissions and also the fact that he has yet to publish his results in a peer-reviewed journal.

An alternative to trying to predict earthquakes ahead of time is to send out a warning once a quake has started, giving people a few seconds' notice of impending ground-shaking by exploiting the fact that information can be sent at close to the speed of light while seismic waves travel at the speed of sound. Japan makes use of such warning systems, but unfortunately they cannot provide accurate information on an earthquake's magnitude, and also cannot alert people close to the earthquake's epicentre because the effects there are so immediate.

### Uncertain times

Given the difficulty of earthquake prediction and the limitations of early warnings, forecasting is the main defence against earthquakes. And the key forecasting tool is the seismic-hazard map (figure 1). These are based on long-term *time-independent* models, which reveal how often – but not *when* – a certain-sized earthquake is likely to occur. The models, and therefore the maps, do not tell us how the probabilities of major earthquakes change over time as a result of other quakes taking place but instead reveal the expected spatial distribution of quakes of a certain size happening over a certain time period (usually on the scale of decades). The distribution in space relies on seismographic data and historical records, while the distribution by size uses a statistical relationship known as Gutenberg–Richter scaling, which says that the frequency of earthquakes falls off exponentially with their magnitude.

Seismic-hazard maps allow governments to tune the severity of building regulations according to an area's seismicity (as well as other factors such as the susceptibility of the local terrain to seismic waves) and also enable insurance companies to set premiums. However, the underlying models are only as good as the data used to calibrate them. And unfortunately, seismographic and historical records generally only go back a fraction of the many hundreds of years that typically separate the occurrence of major quakes on most active faults.

This limitation lay behind the complete failure to anticipate the magnitude-9.0 earthquake that struck the Tōhoku region in Japan in March last year, which unleashed a devastating tsunami and caused the meltdown of several reactors at the Fukushima Daiichi nuclear plant. The country's current seismic-hazard maps provide very detailed information about earthquake probabilities across the whole country but, according to ICEF chairman Jordan, they indicated a "very low, if not zero" probability for such a powerful quake because no such quake had occurred in the

Tōhoku region within the past 1000 years. "They had a magnitude cut-off in that region of Japan," Jordan points out. In other words, such a high-magnitude earthquake was never expected to strike there.

Jim Mori, an earthquake scientist at the University of Kyoto, says that Japan's hazard maps are now being re-evaluated to "consider the possibility of magnitude-9 or larger earthquakes". However, he believes that there are unlikely to be "drastic changes" to Japanese earthquake research, adding that the inclusion of a one-in-a-thousand-year event like that in Tōhoku would probably not change the maps a great deal.

### Short-term solutions

To calculate how the probability of a major earthquake changes in time by accounting for the occurrence of other quakes, researchers have developed different kinds of *time-dependent* forecasting models. Some of these models make forecasts for the long term, i.e. over periods of several decades. The simplest form of these models assumes that the time of the next earthquake on a particular fault segment depends only on the time of the most recent quake on that segment, with a repeating cycle of quakes made slightly aperiodic (to try to match the models with observations) by introducing a "coefficient of variation" into the cycle. More sophisticated versions of these models make the time to the next quake also dependent on the past occurrence of major earthquakes nearby.

For a fault segment that has not ruptured for something approaching its mean recurrence time inferred from historical data, these models can yield probabilities roughly twice those obtained with the time-independent models for the occurrence of major quakes. However, such long-term time-dependent models have not fared well when put to the test. In 1984, for example, the US Geological Survey estimated with 95% confidence that a roughly magnitude-6 earthquake would rupture the Parkfield segment of the San Andreas fault in central California before January 1993. This prediction was made on the basis that similar-sized earthquakes had occurred on that segment six times since 1857, the last of which took place in 1966. In the end, however, the next magnitude-6 event did not take place until 2004. Similar failures have occurred when trying to predict earthquakes in Japan and Turkey.

The approach taken with short-term forecasting, which provides probabilities of earthquakes occurring over a matter of days or weeks, is fundamentally different. Once an earthquake has taken place and the stress on that particular fault segment relieved, the chances of another comparable quake taking place on the same fault segment in the short term tends to be lower. But the probability of a quake taking place on a neighbouring fault, thanks to the increased stress brought about by the original tremor, increases.

Short-term models come in a number of different guises. In *single-generation* versions, such as the Short-Term Earthquake Probability (STEP) model used by the US Geological Survey to make forecasts in California, a single mainshock is assumed to trigger all aftershocks. This contrasts with *multiple-generation* models, such as Epidemic-Type Aftershock Sequence (ETAS) models, in which each new daughter earthquake itself spawns aftershocks.

New Zealand Defence Force

**Scene of destruction** An aerial view of Christchurch Cathedral following the earthquake in Christchurch, New Zealand, in February 2011.

When seismic activity is high, short-term time-dependent models can yield probability values that are tens or even hundreds of times higher than those calculated using time-independent models. However, scientists do not yet know which of the many different types of short-term model is the most reliable. Jordan says that even the California Earthquake Prediction Evaluation Council, of which he is a member, does not use properly tested models but instead often relies on "back of the envelope calculations" to generate its forecasts.

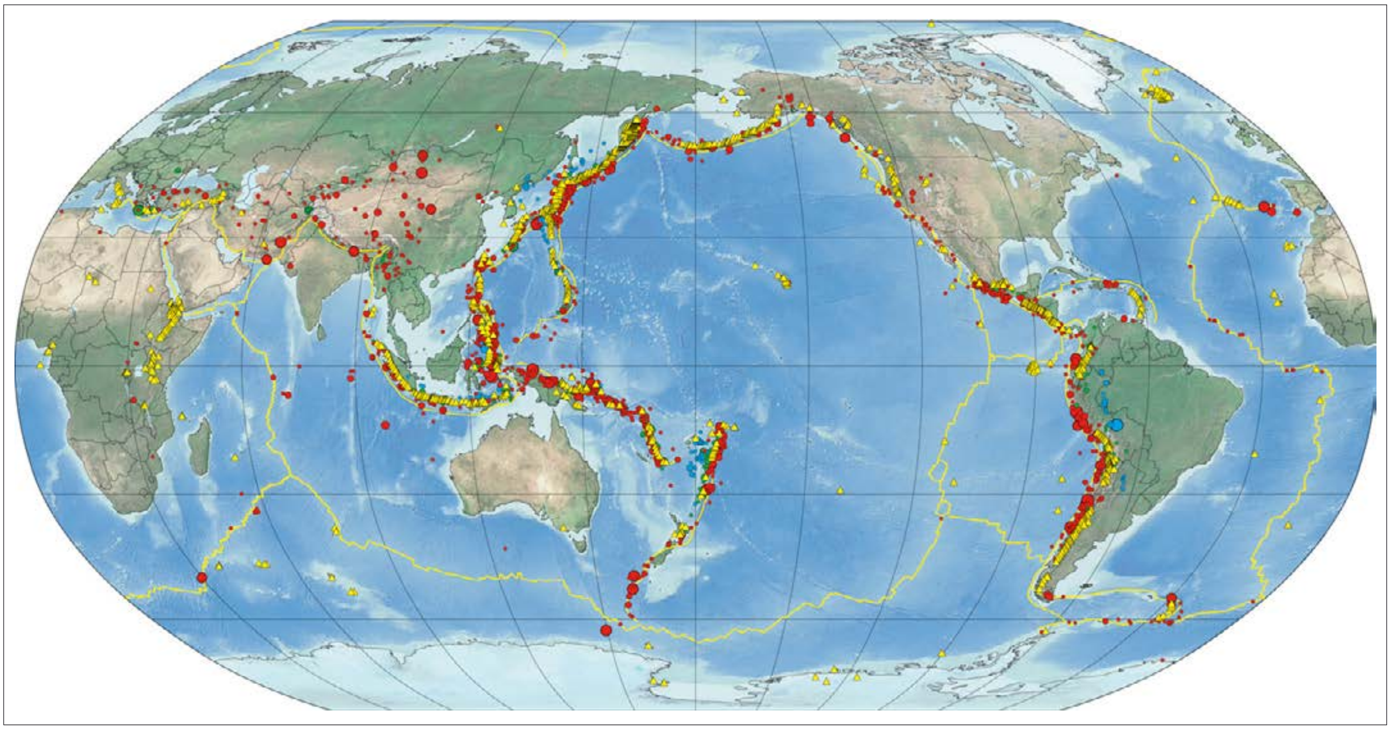
### Testing the data

To improve confidence in the models, in 2007 Jordan set up a programme known as the Collaboratory for the Study of Earthquake Predictability (CSEP). This provides common software and standardized procedures to test models against prospective seismic data, using independent testers, rather than the authors, to put the models through their paces. Starting from a single test centre in California, it now features centres in other parts of the world, including Italy and Japan, where faulting behaviour, and hence models, are different.

In Italy, Warner Marzocchi and Anna Maria Lombardi of the National Institute of Geophysics and Vulcanology tested an ETAS model against real aftershock data following the L'Aquila earthquake in 2009. Using all of the seismic data since, and including the mainshock on 6 April, the researchers updated their model on a daily basis and carried out aftershock forecasts until the end of September 2009. They found that the calculated distributions of aftershocks broadly tallied with those actually observed. Marzocchi has since teamed up with Jiancang Zhuang of the Institute of Statistical Mathematics in Tachikawa, Japan, to see if the model can in principle be used to forecast mainshocks, as well as aftershocks, on the basis that mainshocks are simply aftershocks that are more powerful than their parent tremors, which are then labelled as foreshocks. After comparing real data with the model, Marzocchi concluded "I am reasonably confident that

Short-term forecasting provides probabilities of earthquakes occurring over a matter of days or weeks

USGS



**Danger zones** This map shows seismic activity from 1900 to 2010. Circles represent earthquakes (their size scaling with magnitude), with the depth of the earthquake's focus being 0–69 km (red), 70–299 km (green) or 300–700 km (blue). Yellow triangles are active volcanoes, while the yellow lines are tectonic plate boundaries.

we can use this kind of model to forecast mainshocks."

In fact, a few months after the L'Aquila quake Marzocchi and Lombardi used the same model retrospectively to see what kind of forecast could have been made of the 6 April mainshock. They found that a few hours before the quake the model would have given odds of about 1 in 1000 that a powerful tremor would strike within 10 km of L'Aquila within three days, up from the long-term time-independent probability of 1 in 200 000.

Researchers in New Zealand, meanwhile, have been using probabilistic forecasting to calculate the changing rates of aftershocks in the Canterbury region, following the magnitude-7.1 mainshock near the town of Darfield in September 2010 and the more lethal magnitude-6.2 aftershock that struck close to Christchurch in February last year. Matthew Gerstenberger and colleagues at GNS Science, a geophysics research institute in New Zealand, have used an ensemble of short-, medium- and long-term models to keep the public up to date and to revise building codes in the region. As pointed out by Gerstenberger, who developed the STEP model, time-independent forecasting on its own would be inadequate. "Christchurch was a moderate-to-low hazard region in the national seismic-hazard model prior to these earthquakes," he says. "But the ongoing sequence has increased its estimated hazard."

Scientists do not yet know which of the many different types of short-term model is the most reliable

Dramatic changes to earthquake probabilities have also been calculated in Japan, following the Tōhoku earthquake last year. Shinichi Sakai and colleagues at the University of Tokyo have worked out that the chances of a magnitude-7 or greater earthquake striking the Tokyo region have skyrocketed to 70% over the next four years. This contrasts with the Japanese government's estimate of a 70% chance over the next 30 years. The researchers have stated that they obtain a much higher probability because they take into account the effects of a fivefold increase in tremors in Tokyo since the March 2011 event.

### The limits of modelling

While ETAS- and STEP-like models can improve on the information available from time-independent forecasts, they are no panacea. In particular, they oversimplify the spatial properties of triggering, by representing earthquakes as point, rather than finite-length, sources, while also ignoring earthquakes' proximities to major active faults. According to ICEF member Ian Main of the University of Edinburgh, incorporating fault-based information into these models might provide additional probability gain compared with time-independent calculations, given adequate fault and seismicity data. But significant improvements will only be made by gaining a better understanding of the physics of fault interactions. One particular challenge is to understand the extent to which one earthquake triggers another through the bulk movement of the Earth's crust and how much it does so via the seismic waves it generates. "We know roughly how the statistics of earthquakes scale, and that is why we use statistical models," says Main. "But the precise physical mechanism that leads to this scaling is underdetermined."

Even if models can be significantly improved, they will, for the foreseeable future at least, only ever provide quite low probabilities of impending major quakes. That leaves the civil authorities responsible for mitigation actions in a difficult position. The ICEF recommends that governments try to establish a series of predefined responses, based on cost–benefit analyses, that local or national authorities could automatically enact once certain probability thresholds have been exceeded, from placing emergency services on higher


Shutterstock/Franco Volpato

**Devastated** Building damage in the village of Onna, days after the L'Aquila earthquake struck Italy in April 2009.

alert to mass evacuation. But Marzocchi points out this will not be easy. "I can say from a scientific point of view that such and such is the probability of a certain earthquake occurring," he says. "But acting on these low probabilities would very likely mean creating false alarms. This raises the problem of crying wolf."

Some scientists continue to believe, on the other hand, that precursors will be found. Friedemann Freund, a physicist at NASA's Ames Research Center near San Francisco, is investigating a number of potential precursors, including electromagnetic ones, and he maintains that the combination of such precursors, even if individually they are "fraught with uncertainty", will lead "in the not-too-distant future to a robust earthquake forecasting system" (see January 2009 pp22–25). He contends that seismologists are "too proud to admit that other scientific disciplines could help them out".

Danijel Schorlemmer of the University of Southern California, who is joint leader of the CSEP model-testing project with Jordan, disagrees. He insists that deterministic earthquake prediction will not be possible "in my lifetime" and adds that, even though he hopes precursors will be identified, "the search has been unsuccessful so far".

For Jordan, as for many other seismologists, ensuring that buildings are made as resistant as possible remains the most important strategy for combating the destructive power of earthquakes. But he believes that short-term probabilistic forecasting, if carried out properly, has an important role to play. "This approach is tricky," he concedes, "because no-one can quite agree on which are the best models. So we have uncertainty on uncertainty. But can we ignore the information that they give us? The earthquakes in L'Aquila and New Zealand taught us we don't have that luxury." ■

# Reviews

**Dan Falk**

## The time of our lives

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**In good time**
The astronomical clock on the Old Town Hall in Prague.

**About Time: From Sun Dials to Quantum Clocks, How the Cosmos Shapes Our Lives**
*Adam Frank*
2012 Oneworld Publications, £12.99pb 432pp

There is something about time that seems to perplex us. Time is everywhere, and nowhere; it is easy to measure, but hard to define; the past seems different from the future, but our equations do not tell us why. No wonder books about the nature of time have appeared almost as regularly as, well, clockwork, from Stephen Hawking's *A Brief History of Time* (1988) to Paul Davies' *About Time* (1995), Sean Carroll's *From Eternity to Here* (2010) and Roger Penrose's *Cycles of Time* (2010). In fact, I am guilty of adding to the heap myself, with *In Search of Time* (2008).

The latest contribution is another book called *About Time*, this one written by Adam Frank, an astrophysicist at the University of Rochester in upstate New York. With all the good titles having been taken, Frank can perhaps be forgiven for re-using Davies' from 17 years ago. More importantly, he has found a largely untapped branch of the temporal landscape to explore. Time, it seems, is the dimension that keeps on giving.

In this ambitious and sprawling work, Frank attempts to weave together the cosmological and the cultural – to show that our theories about space and time, and how we *live* in time, are deeply intertwined. One example of what Frank calls the "braiding" of cosmology and culture concerns the mechanical clock, which in his view is "without a doubt, the most important invention of the last thousand years". Clocks became widespread in Europe in the 14th century, bringing a more structured workday and, arguably, a more rushed way of life. But the ubiquitous clock also changed the way we imagine the cosmos itself, as the metaphor of the "clockwork universe" began to take hold. The medieval philosopher Nicole Oresme, Frank tells us, described the world as "a regular clockwork that was neither fast nor slow, never stopped, and worked in summer and winter". As for the planets circling above, Oresme found them "similar to when a person has made a *horologe* [a clock] and sets it in motion, and then it moves by itself". To drive the point home, Frank adds that "People had refashioned their daily, intimate worlds to the beat of the clock, so it was only natural that their conception of the surrounding universe should follow."

At this point we are about one-quarter of the way into the book. Next comes Newton and his postulate of absolute space and time, which formed the foundation for his laws of mechanics and his law of universal gravitation. Often described as the climax of the scientific revolution, this is an oft-told tale, but Frank gives it new life by telling, in parallel, the story of Ambrose Crowley. An English industrialist and contemporary of Newton, Crowley built an ironworks near Newcastle that was, in its own way, as revolutionary as Newton's physics. This ironworks operation was the forerunner of the modern factory, and Frank argues that it succeeded because of Crowley's "genius for organizing human activity across space and time".

Frank finds these "braids" everywhere. After the scientific revolution came the industrial one, accompanied by the huffing and puffing machines that nurtured the study of thermodynamics. And it was the laws of thermodynamics that gave rise to our conception of the "heat death" of the universe, a far-off but terrifying (and seemingly inescapable) catastrophe. Then, a few decades later, radio broadcasting gave us, for the first time, a "national now", just as Einstein's theory of relativity was showing just how fragile the notion of "now" really is.

Frank includes quite a lot of material here, from the birth of agriculture and the social effect of washing machines to the pros and cons of multiple universes. Considering the scope of the text, it is a remarkably tight narrative. And he is very much up to speed on the latest speculations on what may have preceded the Big Bang, from the "colliding branes" imagined by Paul Steinhardt and Neil Turok in an offshoot of string theory to the "eternal inflation" model championed by Sean Carroll and others. But there are a few bumps along the way. He loves the phrase "material engagement" a little too much; in one spot it appears four times in about a page. In discussing 21st-century time pressures, a surprisingly large chunk of text is devoted to the effects of Microsoft Outlook; I found myself wondering whether life would really be any less rushed under iCalendar or Windows Live Mail. The Gregorian reform of the calendar, meanwhile, gets barely a mention, while some digressions, such as a discussion of the "Sokal hoax" of 1996, come out of the blue.

I found myself wondering whether life would really be any less rushed under iCalendar or Windows Live Mail

Then there is the feel-good ending. Aficionados of popular-physics writing will remember Steven Weinberg's claim in *The First Three Minutes* (1977) that "[The] more the universe seems comprehensible, the more it seems pointless." Frank, however, is untroubled by such Weinbergian pessimism. Because of the braiding of the cultural and the cosmological, he argues, we are "participants" in the universe; we are its "co-creators"; the universe contains "a vital place for us". For Frank, there is meaning to be found in this vast, dark cosmos, and "If we can recognize the enigmatic entanglement between cultural time and cosmic time, we might stop looking for God in the form of 'final theories' and find our rightful – and rightfully central – place in the narratives of creation." Our universe, Frank argues, is "suffused with meaning and potential".

Some readers will no doubt warm to this message. A sceptic, however, might counter that such a reader is like a carpenter who builds their house with a window, peers out at the world outside – and then takes comfort in the fact that they happen to have built the window that frames their view of the universe. Sure, being human requires that we experience the universe in a particular way, but does that really make us cosmic "participants"? I will also say that, in a book of this length, the second-to-last page is a bit late in the game to suddenly declare that Buddhism may hold the answer. (The author observes that "Buddhist philosophy emphasizes a doctrine called dependent arising [in which] everything in the universe…depends on everything else. Nothing ever exists entirely alone.")

For those who have been sampling the recent "time" books, there is much that will be familiar here. Even so, the book contains enough that is original to keep even seasoned "time buffs" engaged, and its author is a first-rate storyteller. Reading *About Time* would be time well spent.

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## Web life: *Earth Exploration Toolbook*


**URL:** http://serc.carleton.edu/eet/index.html

### So what is the site about?

The *Earth Exploration Toolbook* (EET) website is home to a series of projects, or "chapters", that are designed to teach older children and young adults about geoscience. At the time of writing there were 43 different chapters to choose from, on subjects ranging from climate and atmospheric science to plate tectonics and astronomy. Each chapter gives students a bit of background on the subject, points them towards online sources of real earth-science data, and then shows them how to analyse these data for themselves. According to the site, such "data-rich learning experiences" will help students learn to solve real-world problems in the future, and will also teach them how to design and conduct scientific investigations. In September 2011 the site received one of *Science* magazine's SPORE awards, which recognize excellence in online science education.

### What sorts of earth-science data are we talking about here?

Oh, the usual suspects. Earthquake locations and magnitudes. Air-quality information recorded by NASA satellites. Ocean temperatures measured during and after El Niño cycles. Sediment cores. Weather patterns. A few different climate models. In fact, pretty much anything you can think of that relates to earth science crops up at least once on EET; one project even requires students to analyse images of other planets in our solar system. The common thread here is real data, packaged in a user-friendly way.

### Who is behind it?

Most members of the EET team – including its lead scientist/educator, Tamara Ledley – are part of a US non-profit organization called TERC, which promotes science and mathematics education. A few team members hold posts at other earth-science institutions, such as the US National Oceanic and Atmospheric Administration, while others are affiliated to the Science Education Research Center at Minnesota's Carleton College. Ledley and her colleagues also work with geoscientists around the world to develop new chapters and revise existing ones.

### Can you give me an example of a project?

One of the more visually appealing projects involves the IRIS Seismic Monitor, a continually updated, zoomable online map that displays the location of every earthquake our planet has experienced in the past five years. The most recent quakes are marked with circles (the size of the circle depicts the earthquake's magnitude), while the older ones show up as tiny pink dots that line the edges of tectonic plates. The "Ring of Fire" around the Pacific Ocean never looked so good, but pretty pictures are not the goal here: the IRIS map is really just a way of introducing students to the nascent science of earthquake prediction (see pp58–63). The main aim of the project is to get students to prepare and analyse their own Geographic Information Systems (GIS) data using some basic software packages – a great "trial run" for more advanced work.

### Why should I visit?

That depends on who you are. EET is clearly designed for high-school students, first-year undergraduates and their teachers, and these three groups will undoubtedly benefit most from the site's intensive, data-rich element. A lot of the chapters would make great class activities or science-fair projects. However, visitors who do not wish to go data-digging will still enjoy browsing through the site's wealth of background information and ready-made visuals, which include the above-mentioned earthquake map and a QuickTime movie depicting the extent of Arctic sea ice between 1976 and 2006. So if the earth-science articles in this special issue have piqued your curiosity, and you want to learn more, this site is a good place to start.

Brian Clegg

# Physics for students, not poets

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**Break it down**
*Quantum Physics for Poets* attempts to make this complex subject accessible to arts students.

**Quantum Physics for Poets**
*Leon Lederman and Christopher Hill*
2011 Prometheus Books £24.95/ $28.00hb 338pp

My immediate response to the title of *Quantum Physics for Poets* is "I am not worthy." Although I have written a couple of limericks and a particularly dire sonnet, I am hardly a poet. Luckily, the book's target audience is not actually so limited. Instead, the authors' stated aim is to introduce quantum physics in a way that enables arts students – and presumably poets are regarded as the ultimate of that ilk – to get their heads around this truly mind-bending subject.

With this principle in mind, I was a little disappointed with the verbose introduction, in which drawn-out parallels are made with revolutions in the arts and politics – as if to prove that quantum physics is particularly suited to the intellectual rebel and make it more palatable to arty types. This seems rather condescending. The introduction also reflects a problem that reoccurs throughout the book. Although their intent is to present information in a non-technical way, authors Leon Lederman and Christopher Hill struggle to detach themselves from their jargon. Theoretical physicist Hill and Nobel-prize-winning particle physicist Lederman have had a long involvement in the public understanding of science, but demonstrate here how difficult it is for science professionals to understand the worldview of the non-scientist.

As an example, I find it difficult to believe that anyone with a non-scientific background would be comfortable with this sentence from the introduction: "Since the location of June can be deduced without measuring the electron Molly, whose properties are correlated by the initial quantum state of the radioactive parent particle, the properties of the particle arriving at Alpha Centauri must seemingly have an objective reality." I can imagine an awful lot of poets (and other people) going "Huh?".

After the introduction, we are eased into the quantum world with a brief historical exploration of classical physics. Galileo and Newton feature heavily here, providing a good mix of historical context and basic science. Occasionally, though, the history is something of a caricature; for example, we are told that Galileo dropped balls off the leaning tower of Pisa, an event that most historians of science consider unlikely. The exploration then moves on to cover light, which introduces the reader to the "ultraviolet crisis" – the prediction from 19th-century electromagnetic theory that all atoms should emit vast quantities of high-energy light – and the origins of quantum physics.

As the book's scientific side comes to the fore, the historical context is downplayed, though we do get occasional snippets. I found it particularly delightful to discover that Max Born was Olivia Newton-John's grandfather. But again, there is something of a tendency to tiptoe around historical accuracy. So, for example, we hear that in 1685 the Danish astronomer Ole Rømer's calculations "yielded the first precise measurement of the speed of light, a whopping 300 000 000 $\mathrm{m\,s^{-1}}$". In reality, Rømer's value was closer to 220 000 000 $\mathrm{m\,s^{-1}}$. Suggesting otherwise condenses history a little too much.

Once we enter the 20th century, the science is given considerably more opportunity to develop, so the reader is taken with some care through Planck's idea that radiation should be split up into "bunches, or quanta". An interesting revelation in this section is that Planck did not really see this as an observation about light itself, but rather a description of the action of the atoms in a black body that is radiating light. Soon, Einstein enters the picture, and from this point on, a key part of the book's message is the "shock of the new". Looking back, it is hard to imagine just how much of a departure from classical thinking was required to begin to grasp quantum theory, and Lederman and Hill make sure that we really understand that the culture shock among physicists was immense. Indeed, some – Einstein and Schrödinger being two obvious examples – were never comfortable with its implications.

To get this far has taken only around one-third of the book. Now we plunge into the structure of the atom, matrix mechanics, the uncertainty principle and the Schrödinger equation. A whole chapter is dedicated to quantum entanglement and its implications, with an unusually detailed exploration of Bell's theorem – a topic that is often considered too confusing for the general reader, as the authors demonstrate here. After exploring Dirac's relativistic expansion of the Schrödinger equation and a quick tour of Feynman's sum-over-paths approach, the book concludes with a rapid crescendo of supersymmetry, holographic universes, quantum gravity and string theory, climaxing with a brief introduction to some of the new quantum technologies of quantum cryptography and quantum computing.

Throughout the book, I get the impression that it is essentially a collection of physics lectures for arts students, generated by simplifying standard introductory physics lectures. This is acceptable for an actual course, for students who are prepared to sit through it to get their credits, but it does not work as well as a science book for the general reader. Such "science-for-the-arts" courses are quite common at US universities, but even if this were the target audience of this book, the authors could take lessons in how to go about it from Richard Muller's superb *Physics for*

*Future Presidents*, while a more general audience would benefit much more from the approach of a title such as Marcus Chown's *Quantum Theory Cannot Hurt You*. Unfortunately, poets have not been well served here.

This is, nonetheless, a good book. Lederman and Hill provide the reader with plenty of introductory meat on the development of quantum physics and they really bring out the startling surprises at the heart of it. But the approach they take is not for poets. It would be much better targeted at high-school physics students to help prepare them for university physics. Rather than quantum physics for poets, this is quantum physics 101 lite. That is a useful book, and in that role I would heartily recommend it. But it doesn't do what it says on the tin.

**Brian Clegg** is a science writer based in Wiltshire, UK, e-mail brian@brianclegg.net

# Between the lines

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**Categorized**
In *The Wavewatcher's Companion*, nine types of wave are investigated.

### The ways of the wave

From ocean waves and sound waves, to the "muscular waves" of human heartbeats and Mexican waves that sweep across a stadium, it is easy to see how this ubiquitous phenomenon grabbed the attention of author Gavin Pretor-Pinney. He decided to write *The Wavewatcher's Companion* after spending an afternoon at the Cornish seaside with his daughter – although the prospect of a "research trip" to Hawaii may have helped, too, Pretor-Pinney admits. One of the most interesting wave narratives concerns the German scientist Hans Berger, who conducted the first ever electroencephalograph (EEG) test, apparently on his 15-year-old son, Klaus. Berger carried out further experiments on his daughter as she completed her homework, on toddlers and even on a dying dog; the last of these experiments allowed him to see the EEG trace flatline. As Pretor-Pinney wryly observes, Berger "was clearly unable to restrain himself from hooking up anyone he came across". Other sections of the book deal with sonar, "nasty waves" such as shock waves and even "sexy waves" such as mating calls and husky human voices. Yet despite these attempts at organization – there are nine "wave types" in total, plus an introduction – the book's individual sections lack distinct structure. The author's attention seems to ebb and flow between largely unrelated phenomena, and while his prose is charming in places, a few of his attempts at humour seem tone-deaf. There is one particularly grating reference to "the type of broad who drinks, smokes, doesn't hold back and is up for anything and everything" in the "sexy waves" chapter. Overall, *The Wavewatcher's Companion* reads like the first draft of what could have been a really good book, and it is difficult to understand why it won the 2011 Royal Society Winton Prize for Science Books. While some readers might – like the Winton Prize judges – be inclined to "go with the flow", it is certainly not for everyone.

● 2011 Bloomsbury £8.99pb 336pp

### A real puzzler

Can you prove that there are at least two people in the city of Tokyo with the same number of hairs on their heads? What about demonstrating that if you take at least one aspirin a day (and 45 aspirin in total) during the month of April, there must be a stretch of consecutive days over which you take precisely 14 aspirin? Or maybe you would prefer to show that if you select 16 integers between 1 and 30, at least two of those integers must differ by exactly 3? All three puzzles are examples of the so-called pigeonhole principle in action, and if they appeal to you, then *The Puzzler's Dilemma* will be your ticket to a pleasantly diverting afternoon. In this slim volume, mathematician and *New York Times* crossword setter Derrick Niederman leads readers through 11 classes of conundrum, offering sample problems and sketching out some of the general principles for solving them. The pigeonhole principle, for example, is discussed in a chapter on turning complex conundrums into simpler ones; other chapters explore such topics as probability theory, induction errors and puzzles that seem easy but are actually impossible. There is even a chapter devoted to "kangaroo puzzles", where the statement of the puzzle contains a clue to the solution, like a joey in a mother kangaroo's pouch. Kangaroos notwithstanding, Niederman's prose certainly hops along nicely, making the book a fairly effortless read – unless, of course, you stop to solve the puzzles before he reveals their solutions.

● 2012 Duckworth Overlook £14.99hb 216pp

### Analogy failure

Analogies are tricky things. A good one will only take you so far, and a bad one can be worse than useless. This lesson was brought home to your reviewer several years ago when, as an undergraduate, a classmate asked a mathematics lecturer to give the class a physically intuitive explanation of curl, $\nabla \times \mathrm{F}$. "That's a tough one," the lecturer replied. "Can you imagine an infinitely small paddle wheel spinning in the middle of a river?" Unfortunately, the class could not, and the lecturer never tried again. Authors Brian Cox and Jeff Forshaw are made of sterner stuff, however, and in their new book *The Quantum Universe: Everything That Can Happen Does Happen* they work much harder to bridge the gap between analogy and physics. After a promising start, though, they are soon off into infinitesimal paddle-wheel territory. In their analogy, quantum fields are replaced by an infinite array of clocks, in which the length (squared, of course) of the individual clock hands represents the probability that a particle will be found in a particular spot, and particles deposit additional clocks as they move from place to place. Sometimes, the clocks have to shrink in size for the maths to work out. This is scarcely simpler than the actual physics, and will confuse experts more than it reassures novices. Setting aside the clock analogy for a moment, though, the amount of mathematical detail is fairly high for a popularly oriented book, which should please those who felt that Cox's *Wonders* series for BBC television lacked rigour. The authors are not afraid of the occasional equation, and the overall level is similar to that of Feynman's *QED: the Strange Theory of Light and Matter* (a fact that Cox and Forshaw acknowledge in the "further reading" section at the end of the book). If you can get past the tortuous clock analogy, you will find the book a real treat. If not, well, there is always the option of watching Cox's television documentaries instead.

● 2011 Allen Lane £20.00hb 256pp

# GraduateCareers

## March 2012

# Be a front-runner

Finding your first job
in a tough market

In association with **brightrecruits.com**

# Finding jobs in hard times

With graduation looming, it is time to think about what comes next. **Simon Perks** examines how physicists can make themselves stand out in a competitive graduate job market


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If you have read a newspaper, listened to the radio or browsed the Internet in the last 12 months, you could be forgiven for thinking that the outlook for new graduates is bleak. Graduate numbers are up, employment figures are down and business confidence is teetering on the edge. But are things really that desperate? For this special graduate section, *Physics World* set out to discover who is hiring physics graduates – and how you can get your application to the top of the pile.

The good news is that the job market for new graduates is looking up. "Things have never been as bad as the headlines might suggest," says Don Murray, a careers adviser at the University of Edinburgh. "From a low point in 2008, we've seen a steady rise in vacancies year on year." Brian Staines, head of guidance at the University of Bristol careers service, agrees. "The situation for graduates is improving gently," he explains. "Things have definitely picked up."

The message from employers is similarly positive. Data from High Fliers Research, the specialist graduate-recruitment market-research company, show that the UK's leading employers expect to increase their graduate intakes by an average of 6.4% in 2012 compared with 2011. In some sectors, the picture is even more encouraging. Vacancies in engineering and industrial companies are up by 22%; in banking and finance, they are up by 16%. This will be promising news for many physics graduates, says Murray, noting that the top three destinations for Edinburgh's physicists are engineering, finance and information technology. Data from other universities tell a similar story (see box on p73).

For graduates who want to pursue their interest in science, a range of opportunities are available in energy companies, engineering firms and the research divisions of larger manufacturers. And despite planned cutbacks in government spending, physics graduates should not necessarily overlook the public sector. Recruiters such as the Met Office and the Defence Science and Technology Laboratory are keen to attract high-quality science graduates.

Despite a post-credit-crunch dip in the numbers of graduates entering banking and finance, businesses in this sector remain eager to draw on the numerical skills and problem-solving ability that science graduates can bring. "We are proactively trying to attract people from outside finance and economics, as well as those with financial backgrounds," says Sarah Harper, head of recruiting for Europe, Middle East and Africa at the investment bank Goldman Sachs. She adds that the firm recently held a careers event aimed specifically at students of STEM (science, technology, engineering and maths) subjects.

The not-so-good news, according to High Fliers Research, is that graduate recruitment is still 6% down on its high point in 2007, and with 50 000 more graduates taking the first step onto the career ladder than five years ago, competition for jobs is fierce. Last year, recruiters from the large, high-profile firms covered by High Fliers Research received an average of 48 applications for each graduate place, and that figure is likely to be even higher in 2012. In such a crowded market, even graduates in the sought-after discipline of physics are going to have to really stand out if they are to find – and secure – their dream job.

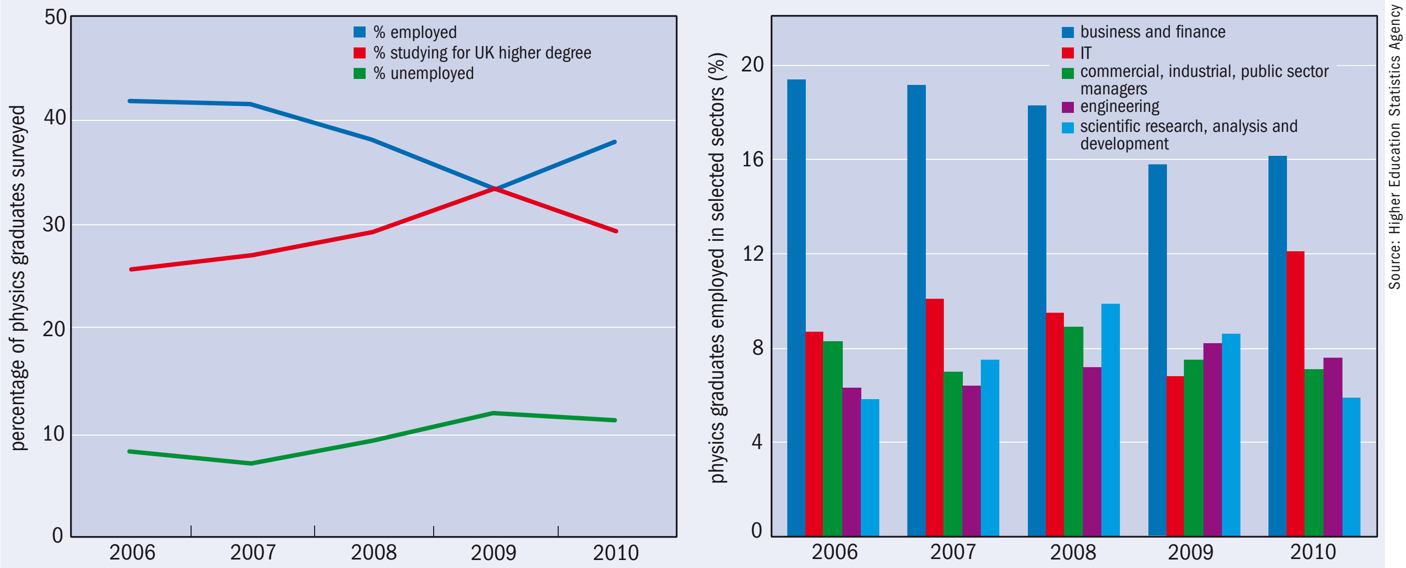
In such a crowded market, even graduates in the sought-after discipline of physics are going to have to really stand out if they are to find their dream job

### Quality, not quantity

Graduates who are trying to boost their applications from "good" to "great" will be pleased to know that many of them will already be more than halfway there, thanks to their educational experience. "We recognize that applicants have already been tested numerous times in their journey through the education system," says Robin Harbach, head of human resources at the Met Office, adding that those who have an upper second from a good university are "already 70% of the way through the selection process". The key to the remaining 30%, he explains, is more about an applicant's attitude than their aptitude. In other words, they need to convince potential employers that they are the right person for that organization, and for that specific role.

The first step to accomplishing this is to learn everything you can about the company and the role that you are applying for. Look at the organization's website and read the job description carefully. Visit your university's careers service to find out what information they have. If the company is holding a recruitment event, go along and hear what it has to say. "We expect applicants to know about our company, who we are and how we are structured," says Vicki Potter, resourcing manager at Oxford Instruments, which recruits physics graduates to a range of roles. Kate Waterstreet, a graduate recruitment adviser at Atkins, an engineering and design consultancy, agrees. "You can tell when someone

**What physics graduates do: 2006–2010**




Employment prospects for UK physics graduates have recovered somewhat since the "credit crunch" of 2008–2009. Left: data from annual surveys conducted six months after graduation show that the fraction of physics graduates in employment fell during the crunch, while the fraction studying for a higher degree rose. Right: among physics graduates in employment, the business and financial sector remained a popular destination throughout the survey period.

has really researched what we do," she says.

This level of research can take a while, however, and it absolutely should not be left until the train journey to your interview. "It is obvious when someone has only started to read the *Financial Times* over the last week," observes Harper, of Goldman Sachs. To help students budget their time, careers officers counsel restraint. "Resist the temptation to bash out 25 mediocre applications," advises Bristol's Staines. "Focus on quality, not quantity. Target each application at the specific organization and vacancy." Recruiters, adds Harper, need to understand why you want to work in their company and what excites you about that role. "We are looking for a personal story about why someone is interested in working at our firm, such as particular deals we have been involved in that have caught their attention or discussions with Goldman Sachs professionals who they have met at recruiting events," she says. Above all, says the Met Office's Harbach, applicants should show that they really, really want the job. "If you're not passionate about what you want to do," he asks, "how will anyone else get passionate about hiring you?"

Being passionate, though, is no excuse for being sloppy. When preparing your cover letter, CV or application form, you must make sure you proof-read it before you send it off. This really should not need saying, but recruiters can provide story after story of poor spelling and grammar, missing attachments and obvious copy-and-paste errors. A genuine, deep interest in a particular role and a perfect cover letter will get you nowhere if you name-check the wrong company in the opening paragraph. "Get the basics right," urges Edinburgh's Murray. "A good, clear application will stand out."

### The importance of soft skills

In addition to spell-checking their applications, physics graduates should also remember that, although physics is a very attractive degree from a technical point of view, employers are looking beyond technical competence. "What you know is half the battle," says Harbach. "How you do it is the other half. We need to know how well you can relate to people."

This is where skills such as communication, teamwork and leadership can play a vital role. However, it is not sufficient just to say that you have these skills – you need to prove it. This means providing concrete examples of how you have used these skills and what you have achieved. So if you have been the president of your university's debating society, worked weekends in a shop or volunteered for a local charity, now would be a good time to mention it. And the more relevant these examples are to the job you are applying for, the better. "Target what the employer wants," says Murray. "Link your own experience and skills to that vacancy. Show why you would be a good employee."

Work experience, in particular, can make the crucial difference between a good application and a great one. According to High Fliers Research, recruiters estimate that one-third of this year's entry-level positions will be filled by graduates who have already worked for their organizations, whether through industrial placements, vacation work or undergraduate sponsorship. For investment banks, this figure rises to three-quarters, and recruiters warn that graduates with no previous work experience are unlikely to be successful. "In a highly competitive graduate job market, new graduates who have not had any work experience at all during their time at university have little hope of landing a well-paid job with a leading employer," says Martin Birchall, managing director of High Fliers Research. This is true, he adds, "irrespective of the academic results they achieve or the university they have attended".

"Work experience is a key way of being able to differentiate yourself," agrees Harper at Goldman Sachs. "[For us], something in an investment bank would be best, even if it is just for a week. But anything where you are challenging yourself is good – something where you are able to demonstrate that you can add value."

On the upside, many leading employers offer paid work-experience programmes for students and recent graduates. Two-thirds provide industrial placements for six to 12 months and more than half have paid vacation internships for three weeks or longer. And if your employment history so far has been somewhat lower key, then don't worry. "Any form of work experience is important," says Waterstreet, of Atkins. Potter, at Oxford Instruments, makes a similar point. "We want people who have experience of dealing with customers," she explains, "even if that

## Vital statistics for UK graduates

**19%** The increase in the number of graduate applications received by employers compared with this time last year

**1/3** The proportion of applications for current graduate positions that come from people who graduated in 2011 or before

**6.4%** The increase in graduate recruitment vacancies since last year among the UK's top recruiters

**£29 000** The median starting salary for a graduate recruit at the UK's leading graduate employers

**48** The number of applicants for each graduate vacancy in 2011

**52%** Proportion of leading recruiters who warn that graduates with no work experience would be unlikely to secure a job offer

**50%** The increase on last year in the number of graduate vacancies at engineering and design consultancy Atkins

**£45 000** Average graduate starting salary in the UK's leading investment banks

**1:1** Ratio of work experience placements to graduate vacancies in the UK's leading investment banks

**1/3** The proportion of this year's graduate position that will be filled by people who already have work experience with that employer

**50 000** The increase in the number of new graduates this year compared with 2007

**5%** Proportion of the UK's leading employers who do not offer any form of work experience placements

**22.4%** The increase in graduate recruitment vacancies since last year among the UK's top engineering and industrial companies

**45%** The increase in graduate vacancies in the IT and telecoms sector since 2007

Source: High Fliers Research, Higher Education Statistics Agency, individual recruiters

is from working in a shop."

If all goes well, the next stage is an interview or assessment. Here, as in the application, the key to success is preparation. Most recruiters explain on their website what form the interview or assessment will take and what you can expect on the day. Your careers service can also help you to prepare, by coaching you on interview skills, helping you to anticipate questions and directing you to online tests for a bit of practice. For example, Staines notes that nearly all interviews are "competency based", which means that the interviewer wants to find out whether you have the specific skills the employer needs. Because of this, he says, a well-prepared student should be able to anticipate 70–80% of the questions, especially "the obvious ones" that ask you to give examples of occasions when you have planned your time effectively, worked in a team or overcome difficulties in completing a task.

Still, you will also need to demonstrate your enthusiasm for the industry, the company and the role. "Just answering the questions well will not get you the job these days," says Harbach at the Met Office, adding that graduates need to show that they are "keen and driven". Potter says that she is always impressed when an applicant comes armed with questions about the company's products and markets; this shows that they are interested and that they have done their research.

As with many things in life, the key to success here is hard work. Put in the time, do the research and find out what the employer is looking for. Then show how your skills, qualifications and experience make you the ideal candidate. It is not easy, but this methodical approach pays dividends. If you make "a real effort" with your application, advises Potter, this will "automatically" put you in the top 10%.

### When the right job isn't there

Sometimes, though, things do not go according to plan. Perhaps you cannot decide what you want to do. Maybe you know what you want but the right vacancy is proving elusive. Or perhaps you have been applying for job after job with no success. The key here is not to panic. You do not have to get into your dream career straight away. Sometimes it takes time to find and secure the job that you want.

One suggestion from Bristol's Staines is to look beyond well-advertised jobs, and submit speculative applications for hands-on work experience in your chosen sector. Small and medium-sized businesses may have vacancies, he says, but many do not advertise heavily with universities. Staines also counsels approaching potential employers just for advice, rather than with a cover letter and CV. "Don't start by asking 'Have you got a job going?', as they can shut the conversation down with a simple 'no'," he says. Instead, just explain your situation and ask for advice.

## Numbers game

Vacancies in 2012 at key employers

| Employer | Number of UK vacancies |
|---|---|
| Arup | 140 |
| Atkins | 240 |
| BP | 175 |
| Deloitte | 1200 |
| DSTL | 70 |
| EDF Energy | 100 |
| Ernst & Young | 900 |
| Goldman Sachs | 300 |
| HSBC | 150 |
| J P Morgan | 300 |
| KPMG | 1000 |
| PricewaterhouseCoopers | 1250 |
| RBS Group | 700 |
| Shell | 100 |
| UBS | 300 |

Source: High Fliers Research, individual recruiters

"Most will be more than happy to help – and if they do have any vacancies coming up, they're likely to let you know, too." It is also worth remembering that many employers recruit graduates year round, not just immediately after graduation.

For those who need more help, university careers services are a good port of call (see *Physics World* March 2011 pp54–56). Many services maintain networks of alumni, for example, who may be able to advise you on your application or your career choice. Even if you have already graduated, it is still worth visiting, since most careers services continue to support graduates for two or three years after they have left. If you have moved away, and a visit to your own university is not practical, you may find that your local university is able to step in; nearly all careers services are part of a "mutual aid" network and will be able to advise you as if you were one of their own graduates.

If you find that you need to boost your skills, then it might be worth thinking about postgraduate study. Edinburgh careers adviser Murray urges caution, though. "Postgraduate study is not for everyone," he explains. "To do it solely as a stop-gap measure is not a good idea. Think carefully about where the course will lead you." Staines agrees, adding that you should only enter into further research or study "if it is what you want or if it will help you with your job prospects". "Look at the destinations of people who have completed that course and see what they are doing now," he adds.

The main thing, says Potter at Oxford Instruments, is to do something with your time while you find the right job. "Find a temporary job," she suggests. "Show that you are willing to work hard. Travel is fine, too. But demonstrate that you are learning something from it. Do anything. Just don't do nothing."

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# Graduate Recruitment



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# Teaching is increasingly a career for the most able graduates

**Make teaching your first choice career – there's never been a better time to join the profession.**

The Training and Development Agency for Schools (TDA) is committed to recruiting the very best graduates into teaching, so that standards can continue to rise in schools across the country. Last year's teacher training entrants had the highest proportion of 2:1 degree classifications and above on record: 62 per cent of entrants to university-based training had a 2:1 or better. Not only that, more physics trainees than ever before began training in 2011 – up 30 per cent on 2010.

However, there still remains a shortage of physics teachers in schools. The Institute of Physics (IOP) believe that around 1,000 new specialist physics teachers in England are needed every year for the next 15 years to plug the gap, so that the subject is taught by specialist teachers.

### Ideal route into teaching

Physics trainees no longer need to train to teach all of the science subjects. Previously, there were a small number of physics with mathematics postgraduate certificate in education (PGCE) routes offered by providers. These courses have been in great demand, so the TDA is making the physics with mathematics PGCE more widely available by increasing the number of providers that offer it. This is the ideal route into teaching if you are passionate about both physics and mathematics.

Rather than the traditional combination of physics, biology and chemistry; physics with mathematics trainees will focus on the two subjects which are currently undergoing a renaissance in schools. Trainees will gain work experience in schools, including some of the new teaching schools judged as outstanding at training and developing their staff. This will give trainees the best opportunity for employment when they qualify.

The new PGCE courses will start in September 2012 and will be delivered by mainstream PGCE providers. Applications can be made to providers via the Graduate Teacher Training Registry (GTTR) website **www.gttr.ac.uk**.

If you think you would enjoy teaching younger children but would like to stay close to the subject you are passionate about, brand new training courses from September 2012 are available to become a science subject specialist in primary schools too.

Teacher training is currently offering big tax-free bursaries to high quality graduates, especially in shortage subjects. If you have at least a 2:2 degree, you may be eligible for up to £20,000, if you intend to start a training course in2012/13. The amount of bursary you are entitled to, depends on your degree class and the subject you choose to teach. Physics with mathematics attracts the same bursary as a standard physics course.

### Special scholarships

There are special scholarships available for physics trainees from the IOP, offering a package of benefits, including a £20,000 award. Around 100 scholarships will be available for graduates with a 2:1 or first class degree who are intending to do a PGCE course in physics, or physics with mathematics.

The IOP will work with experts in teaching practice to award scholarships. They will hand-pick candidates demonstrating exceptional subject knowledge, enthusiasm for the study of physics, and outstanding potential to teach. The IOP's relationship with the scholars will continue into their teaching careers. This will develop a group of outstanding physics teachers, all part of a community of physicists across schools, universities and industry.

There are special scholarships available for physics trainees from the IOP. Around 100 scholarships worth £20,000 each will be available for graduates with a 2:1 or first class degree who are intending to do a mainstream physics, or physics with mathematics, Initial Teacher Training (ITT) course.

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Starting salaries in teaching are high compared to average graduate starting salaries, making the profession one of the most financially secure and rewarding career options available. The average starting salary that newly qualified teachers can now expect to receive is £22,800, compared to a range of £17,720–£23,335 for other graduate jobs. What's more, on average, teachers are seeing their salaries rise by approximately 30 per cent during their first three years in the job.

### New experiences

New experiences and performance can see newly qualified teachers achieve rapid career progression. Teachers are twice as likely to be in management positions compared to many of their fellow graduates three and a half years in, with 19 per cent of having management responsibilities, compared to less than 10 per cent of science professionals (6 per cent), legal professionals (6 per cent) and accountants (9 per cent). As an Advanced Skills Teacher you can earn up to £56,000 and head teachers earn upwards of £100,000.

Teachers are very enthusiastic about their careers, enjoying the autonomy, variety and impact. Significantly more trained teachers stay in their chosen profession compared to other popular graduate careers. Research shows that teachers are twice as likely to remain in their chosen profession, with nearly half (44 per cent) of graduates in a range of popular non-teaching roles switching career within their first three and a half years, compared to just 21 per cent of those who choose teaching first time round. Non-teaching graduates suggest a lack of autonomy, limited opportunities for career progression and the routine nature of the work as the main reason for making the switch.

Training places are filling up much more quickly than last year. Apply quickly to ensure that you can start your career in the classroom in 2012/13.

For more information about how rewarding and challenging teaching has become call the Teaching Information Line on **0800 389 2500** or visit **www.tda.gov.uk**.

## Getting into the teaching profession...

Applicants for initial teacher training must demonstrate a standard equivalent to a GCSE grade C or above in English and maths, and in a science subject for those wishing to teach in primary. If you don't reach this minimum academic standard there are access courses available.

TDA offers a School Experience Programme (SEP), to graduates considering teaching maths, physics, chemistry or a modern foreign language (MFL) at secondary level who hold a 1st, 2:1 or 2:2 degree in a related subject. The programme offers classroom experience in a secondary school for 1 to 10 days, which is agreed between the individual and their host school.

### Teacher requirements

Along with a degree, all teachers are required to have qualified teacher status (QTS) to teach in primary and secondary maintained schools and non-maintained special schools. This is attained via either undergraduate or postgraduate courses. An undergraduate route into teaching will offer either a BEd, BA, or BSc, combining degree studies with QTS. You are required to have two A-levels or equivalent in order to enrol on an undergraduate course. Some ITT providers do offer part-time courses; these can be found on the TDA website **http://www.tda.gov.uk/Recruit/thetrainingprocess/typesofcourse.aspx**.

The postgraduate course will award you with a Postgraduate Certificate in Education (PGCE). A PGCE course mainly focuses on developing your teaching skills, and not on the subject you intend to teach. For this reason, you are expected to have a good understanding of your chosen subject – usually to degree level – before you start training. Entry to most postgraduate courses is through the Graduate Teacher Training Registry, although some training providers accept applications directly.

# Recruitment

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Nuclear Specialist Inspector annual salary will be in the range of £72,517 to £87,371

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**Closing date: 23 March 2012.**

**Interviews will take place during w/c 16 April and 23 April 2012.**

HSE is committed to equality of opportunity for all staff and applications from individuals are encouraged regardless of disability, gender, marital status, race, colour, ethnic or national origin, sexual orientation, age, working pattern, religion and/or belief.

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## INSTRUMENT PROJECT ENGINEER

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PHYSICS DEPARTMENT

## Lectureship in Experimental Condensed Matter Physics

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Applications are invited for a full-time lectureship (equivalent to a tenure track assistant professorship) in experimental condensed matter physics. The Lancaster Physics Department is expanding its research activity in this area, building on its outstanding success in the last two Research Assessment Exercises (5*A in 2001 and 1st by quality profile in 2008), recent appointments and substantial investment in new clean room facilities, as part of a newly formed Quantum Technology Centre http://www.physics.lancs.ac.uk/qtc/
The QTC is being equipped with state-of-the-art fabrication and measurement facilities including an electron-beam writer, evaporation, sputtering and etching machines and a helium-free dilution refrigerator, and a new research group is being created under the leadership of Professor Yuri Pashkin.

The research of the new group is focused on, but not limited to, quantum nanoelectronics, quantum metrology and nanoelectromechanics. Applications will be considered in the first instance from candidates in any area of quantum nano-electronics, including superconducting circuits, single-electron tunneling or qubits. Experience in low-noise measurements at cryogenic temperatures, measurement automation, nanofabrication including electron-beam lithography, dry etching and metal deposition will be regarded as an advantage.

**Closing date: 26 March 2012.**

**To apply, access further information or register for email job alerts please visit our website.**

www.hr-jobs.lancs.ac.uk

## EUROMAGNET CALL FOR PROPOSALS FOR MAGNET TIME

EuroMagNET II

The next deadline for applications for magnet time at the **LABORATOIRE NATIONAL DES CHAMPS MAGNETIQUES INTENSES** (www.lncmi.cnrs.fr)
the **HIGH FIELD MAGNET LABORATORY** (www.ru.nl/hfml/)
and the **HOCHFELD LABOR DRESDEN** (www.hzdr.de/hld)
is May 15th, 2012.

Applications can be done through an on-line application form on the website: http://www.euromagnet.org from April 15th, 2012.

Scientists of EU countries and Associates States* are entitled to apply under FP7 for financial support according to the rules defined by the EC.
*listed on ftp://ftp.cordis.europa.eu/pub/fp7/docs/third_country_agreements_en.pdf

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***Guardian, one of the world's largest manufacturers of float glass and fabricated glass products, supplying the automotive and building products industries, is recruiting a team of Thin Film Coating Engineers to assist in the set up of a brand new thin film coating facility in Goole, UK.***

***Guardian is looking for mature self-starters, who are good communicators, with a strong entrepreneurial spirit.***

**Thin Film Coating Process Engineer**, working within a team of engineers providing technical support to the magnetron sputtering line within a continuous 24/7 process driven manufacturing environment.

**Essential requirements:**

- Experience of working within a fast paced manufacturing environment
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- Previous experience in Research & Development
- Ability to take charge and lead with confidence, control events, clearly present and communicate ideas, concepts and plans across multiple levels
- Strong analytical skills, experienced in using effective trouble shooting and problem solving techniques, as well as formulating and implementing corrective actions
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Further information about Guardian can be found at brightrecruits.com/employer/798634/guardian-industries-uk-ltd

Full job specification can be found at: http://brightrecruits.com/job/2929/thin-film-coating-process-engineer

Applicants should address their covering letter and CV to Shirley Wordsworth, swordsworth@guardian.com, HR

Alternatively, please write to **Shirley Wordsworth, Guardian Industries UK Ltd., Rawcliffe Road, Goole, East Riding of Yorkshire, DN14 8GA.**

## Academic position in Experimental Physics: Functional and Biophysical Properties of Soft Matter

A full-time academic position is available at the Department of Physics and Astronomy of the University of Leuven, Belgium starting October 1, 2012 in the field of experimental soft matter physics.

More information can be found on the web:

http://www.kuleuven.be/personeel/jobsite/vacatures/science.html

Closing date: March 15, 2012

The full-time position can be offered in one of the academic levels, depending on the qualifications of the candidate.

The K.U.Leuven is an equal opportunity employer. Non-Dutch speaking candidates should be able to teach in Dutch within three years.

KATHOLIEKE UNIVERSITEIT LEUVEN

**Department of Physics and Astronomy**
**K.U.Leuven, Belgium**
**http://fys.kuleuven.be/english**

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In addition to research activity, the appointed candidate will be expected to contribute fully to all aspects of School activity, in particular the Physics Bachelors and Masters teaching programmes. In suitable circumstances, there may be the opportunity for linked academic appointments.

Download an application pack from our website **www.hw.ac.uk/jobs** or contact the **Human Resources Office, Heriot-Watt University Edinburgh EH14 4AS** tel **0131-451-3022** (24 hours) email **hr@hw.ac.uk** quoting Ref: 09/12/PW.

Closing date: **23 March 2012.**

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APS physics

## Senior Editor, Physical Review E

The American Physical Society is conducting an international search for a successor to the current Editor of Physical Review E (PRE). The position is that of the senior Editor of the journal, responsible for editorial standards, policies and direction of the journal, and leadership of the staff of about 15 editors. Physical Review E is a large multidisciplinary journal specializing in statistical, nonlinear, and soft matter physics.

The ideal candidate should possess many of the following qualifications: stature in a field of research within the scope of PRE; stature in the PRE author community; experience with scholarly journals; management and interpersonal skills to deal effectively with an international array of authors, referees, and editors and with the APS; advocacy, integrity, and wisdom to lead the journal in responding to important matters and issues.

The Editor may maintain his/her present appointment and location and devote at least 20% of his/her time to the position. A higher level of commitment would be desirable in the initial year of service; several possible levels of long-term commitment, from 20% to 50%, are possible.

The initial appointment is for three years with renewal possible after review. Salary is negotiable and dependent on time commitment. The desired starting date is 1 July 2012. The APS is an equal employment opportunity employer and especially encourages applications from or nominations of women and minorities. The search is not limited to residents of the United States. Inquiries, nominations, and applications should be sent by **1 May 2012** to: **Jerry Gollub, PRE Search Committee Chair, edsearch@aps.org**.

# Baking, speed limits and circuits

What is it that characterizes physicists and distinguishes us from other scientists? After a brief pause for everyone to reply that we are sexier, more sophisticated and socially better-adjusted, we might consider the answer given by Ernest Rutherford, who believed it had something to do with our objectives. Other scientists, he said, collect observations, classify them and identify patterns. Physicists seek to explain those patterns.

This view fits in neatly with Rutherford's famous aphorism that "all science is either physics or stamp collecting" (was that before or after he won the Nobel prize for chemistry?), but I suggest that we also possess a trait that relates to our style of doing science, which is our facility with numbers – specifically, with orders of magnitude and approximations. It is characteristic of physicists that we can look at an equation and instinctively know when to round every quantity to the nearest power of 10 (or when to say that $4\pi = 10$), and when to retain the umpteenth decimal place. This skill surely stems from our comfort at swapping between mathematical descriptions of the world and the physical reality – or rather, our recognition that the two are at some level the same, just expressed differently, so when we are manipulating our equation, we are still mentally connected to the system it describes.

This in-built, instinctive sensitivity analysis does, however, become more interesting when applied outside our own discipline. The biochemical complexity of the liquid paracetamol my wife and I force our children to drink when they are ill is beyond my comprehension. But when the stated dose is 10 ml, my physicist's instincts tell me that a quantity expressed in such round numbers cannot be that precise, and I need not worry about the odd millilitre that trickles down said children's necks rather than into their mouths. But I have learned that my wife – who is equally well qualified and trained, but in medicine rather than physics – takes a less relaxed view.

The strain between our respective opinions on significant figures becomes even more pronounced in the kitchen. To a physicist, a recipe where every quantity is a round number of cups or tablespoons cannot be critically dependent on these quantities – yet domestic harmony requires that I put exactly 600 g of flour in the bread machine, not slop in 550 or 650 g. As a physicist, I would prefer to write $6 \times 10^2$ g, conveying a different meaning from $6.00 \times 10^2$ g. But I don't think I would sell many recipe books.

In real life, quantities cannot be much more precise than the increment between successive available values. The available values for UK speed limits are 30, 40, 50 mph etc, so my physicist's instinct tells me that 1 mph over the limit probably does not matter, whereas 5 mph – half the increment – probably does. Perhaps all those people who seem to think 30 mph really means 40 mph are aspiring physicists who haven't quite mastered the skill yet!

In my own professional area, the exposure limit to magnetic fields produced by electric power systems is an induced current in the body of 10 mA/m$^2$. Like you, I instinctively understand that this means that 2 or 5 mA/m$^2$ would be unnecessarily low and 20 or 50 unacceptably high, so 10 is the ballpark to aim for. After all, if we were still using imperial units, I do not believe the limit would be exactly 6.45 $\mu$A/square inch; it would probably be a nice round 10 again. But the law sadly lacks the wisdom of physicists, and it requires us to say that 9.9 is okay but at 10.1 you have to rebuild your power line.

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To a physicist, a recipe where every quantity is a round number of cups or tablespoons cannot be critically dependent on these quantities

So are round-number quantities always approximate and multiple significant figures always precise? Not necessarily. The 568 ml carton of cream that is ubiquitous in British supermarkets should, of course, be understood as a pint (one significant figure) and not as 568 ml (three). Similarly, the maximum floor area in a home that UK wiring regulations allow to be served by a single standard power circuit is 100 m$^2$ – a classic case, you might think, of choosing the nearest order of magnitude. But actually, when the regulation was established back in 1943, the available copper cables could carry 6.9 kW before overheating unacceptably. Power demand in homes was assessed as 1 W per cubic foot of living space, meaning a single circuit could supply 6900 ft$^3$, which with a 9 ft ceiling and allowance for halls and staircases came out as 1000 ft$^2$ of floor area. This value was subsequently rounded again to 100 m$^2$ (7% larger). So the physicist's instinct is only partly correct: the 100 m$^2$ does indeed represent the nearest order of magnitude – but in the lost-in-the-mists-of-time 1 W/ft$^3$ figure, not in the quantity presented.

I am now nearing the 1000 word limit for this article – except, of course, the limit is not a round 1000 words (which might tempt me to think I could get away with 1100 or 1200). Rather, as befits a physics magazine, it is unambiguously expressed as "900–950 words long". Always trust a physicist's instinct for the true value to be attached to numbers! After all, we are people who comfortably deal with quantities that can range over 30 or more orders of magnitude, such as resistivity or density, yet we can also make measurements of hyperfine transition frequencies (for example) that are accurate to better than one part in $10^{-14}$. But my wife is still better than me at following a recipe.

**John Swanson** is a physicist at the UK National Grid, e-mail john.swanson@physics.org

● Readers are invited to submit their own Lateral Thoughts. Articles should be 900–950 words long, and can be e-mailed to pwld@iop.org