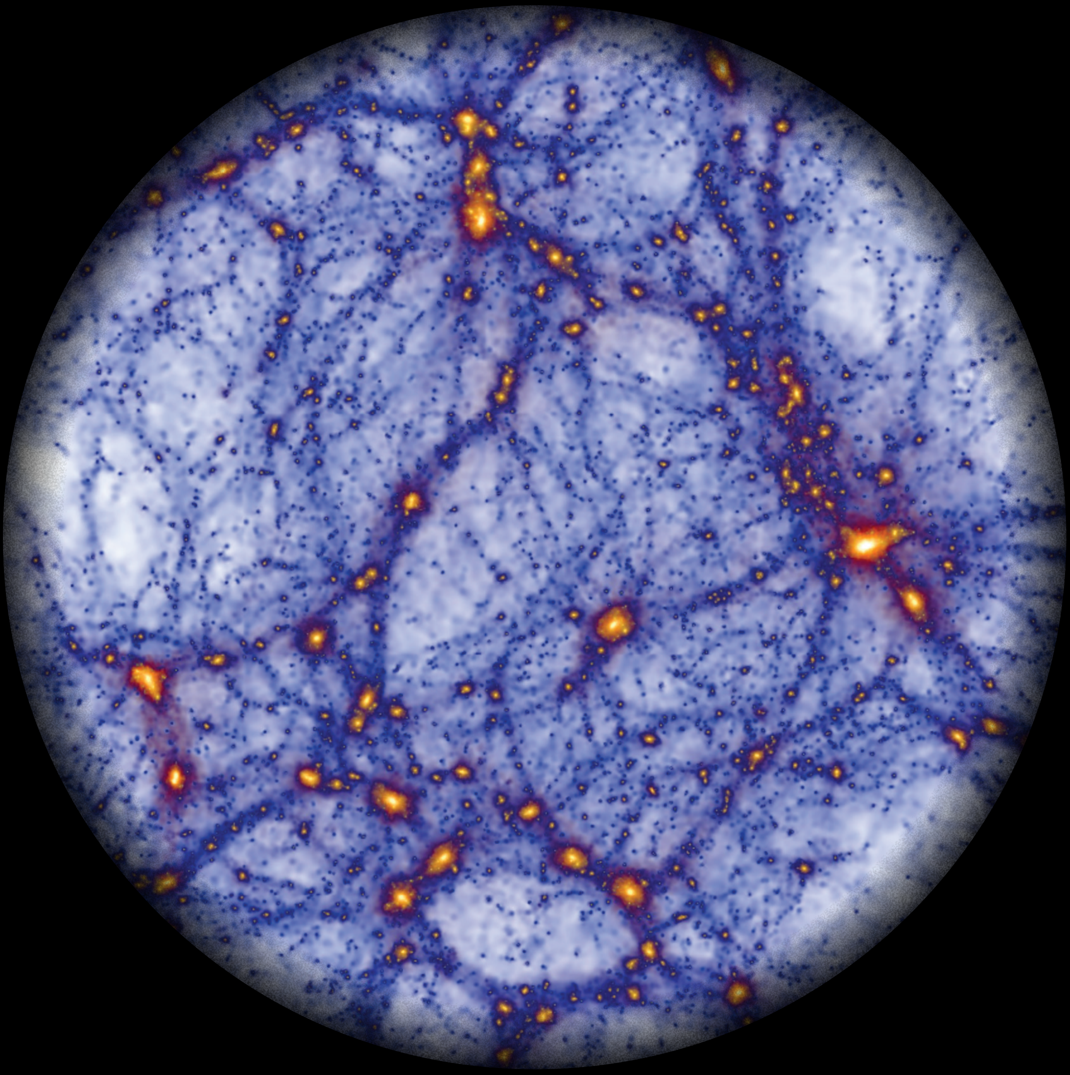
Australian Physics

VOLUME 57, NUMBER 5, OCT-DEC 2020



ACCELERATING OSCILLATORS

THE YOUNG PHYSICIST AND MORE NAMES

IN CONVERSATION WITH RACHEL WEBSTER

NOBEL PRIZE FOR BLACK HOLE RESEARCHERS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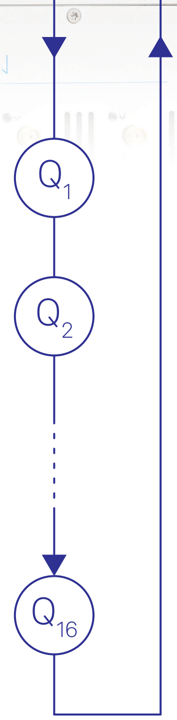
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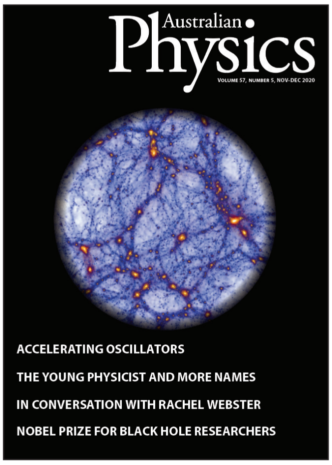

Section of the Millennium-XXL Simulation output showing non-linear growth of dark matter structures in a region of space a few hundred million lightyears across. The original simulated volume is a cube 13.4 x 10^9 lightyears in size, thus spanning the whole observable universe. Each 'particle' in the simulation represents more than 8 x 10^9 solar masses which provides sufficient mass resolution to visualise dark matter halos hosting galaxies that are about 100 times smaller than our own Milky Way (which sports 1.5 x 10^{12} solar masses).

[Max-Planck Institute for Astrophysics and Virgo Consortium; http://galformod.mpa-garching.mpg.de/mxxlbrowser/]

Australian Institute of Physics

Promoting the role of physics in research, education, industry and the community

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Australian Physics

A Publication of the Australian Institute of Physics

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ADVERTISING
Enquiries should be sent to the Editors.

Published six times a year.

Print Post approved PP 224960 / 00008
ISSN 1837-5375

PRODUCTION & PRINTING
Pinnacle Print Group
1/87 Newlands Road, Reservoir VIC 3073
www.pinnacleprintgroup.com.au
Ph: 8480 3333 Fax: 8480 3344

EDITORIAL

Concepts and associations

Physics is full of concepts. With short phrases, we can capture the complexities of phenomena in our surroundings and synthesise simplied truths into models. We explore some of this in our section for young physicists. Interestingly, the compression ratio of concepts can be very high. When you use the word *Photon*, you have packaged a lot of physics into that one word. Of course, there comes the point where compression is not lossless anymore (dare we say “42”…).

With concepts come associations. What does our cover image show? One could think it is an image of something microscopic. The round crop of the image strengthens that association, and of course we have made it deliberately misleading. The image spans a few hundred lightyears of simulated space and dark matter distribution coming out of the Millenium-XXL Simulation. So, context is obviously important, but the [slightly modified] saying that *“A concept saves 1000 words”* is probably still valid. You might have some thoughts to add – please write us: aip_editor@aip.org.au.

Connected to the galactic scale, we bring to you a short piece on this year’s Nobel Prize in Physics, awarded to Roger Penrose, Reinhard Genzel and Andrea Ghez for their work on black holes. Continuing to think large, we also have an article asking what we can learn about dark energy by considering the Hamiltonians arising from different models of an expanding spacetime metric.

Closer to home, we share a conversation with Professor Rachel Webster AO, exploring her journey through a career in physics, including several detours which may be surprising and/or inspiring to our readers. The thread continues in #PhysicsGotMeHere which showcases Phil Dooley’s journjey to connecting science with people. The connection theme continues with a review and preview of the Wagga Condensed Matter conferences.

We’d like to remind you that from next year onwards *Australian Physics* comes in quarterly issues. This last issue for 2020 arrives at the same time as the Festive Season. It is both a concept and a concrete reality for each of us with associations, perhaps of sunshine, beach and BBQ, or snow, fireplace and marzipan. No matter what your concept of this season, after the extraordinary year of 2020, we hope it brings you both reflection and rejuvenation.

Peter Kappen and David Hoxley

PRESIDENT'S COLUMN

Australian physics – some numbers to know

As AIP president I am often asked if we collect data on Physics in Australia such as How many physicist are working in Australia? Sadly the AIP doesn't have the resources to collect and analyse such data. Unlike our equivalent organisations in the UK or USA we do not own income generating journals and hence rely heavily on volunteers to conduct most of the business of the AIP. However, whilst the AIP does not generate our own data we are very keen to know and highlight data on Physics in Australia when it appears in various government reports. In this column I would like to provide you with some useful facts and statistics about Physics in Australia.

One report that I have found very useful to support the significant of Physics in Australia is 'The importance of advanced physical and mathematical sciences to the Australian economy", published by the Australian Academy of Science. In this report, physics, chemistry, the earth sciences and the mathematical sciences are taken collectively to be the 'physical and mathematical sciences' and 'advanced' refers to science first applied within the past 20 years. Some key numbers in this 2015 report to know (and love!) are:

- 11% of Australian economic activity relies directly on the advanced physical and mathematical science
- 7% of total Australian employment is directly related to the advanced physical and mathematical sciences.

The next report with data pertinent to Physics to was published in July this year by the office of the Chief Scientist – "Australia's STEM Workforce Science, Technology, Engineering and Mathematics". Using Australian Bureau of Statistics Census data it contains a whole chapter on Pathways in physics and astronomy.

Some of the key numbers to know here are:

- 9,502 university qualified Physics and Astronomy graduates employed in Australia.
- 75% of employed people with a Physics and Astronomy bachelor degree worked in the private sector.
- And we still have ways to go with gender equity as only 20% of Physics and Astronomy graduates in the labour force are female.

The final report with some some interesting facts to know about your discipline is 'Why Australia: Benchmark Report 2020' published by the Department of Trade, Tourism and Investment. There is a chapter on Innovation & Skills and states that "Australia's 10 strongest categories of published research are: space sciences, physics, computer science, clinical medicine, multidisciplinary, engineering, molecular biology / genetics, materials science, environment/ecology, and plant & animal science." The take home message here is that Space science and Physics top the list. The raw number here is perhaps less impactful but let me include it for completeness. The relative impact of publications in Physics in Australia is 1.76 (with the global average being 1).

I hope you found these numbers interesting. They are good to have on hand should you ever bump into your local MP at the shops (perhaps that is just a Canberra thing!) or are fighting to defend Physics a very valuable sector of our economy. And if you know of other good data sources or reports please reach out and let me know.

Finally, I have to take a moment to wholeheartedly congratulate Dr Cathy Foley on her appointment as the next Chief Scientist of Australia. This is wonderful news and very well deserved. Cathy has always been a strong advocate for physics in this country and was of course AIP President in 2007-08. We all wish her the very best of luck in this new role.

Jodie Bradby

In conversation with Rachel Webster

Rachel Webster is a Redmond Barry Distinguished Professor in the School of Physics at the University of Melbourne. She was made an Officer of the Order of Australia in the 2020 Australia Day Honours list. Rachel has a distinguished research record including, but not limited to, significant work on gravitational lensing and quasars. She recently sat down with one of the editors of Australian Physics for a chat about her path into science and her career, about being a student and becoming inspired, and about learning and building skills .

How would you describe yourself professionally?

I usually say I'm an astronomer, but even more often, an astrophysicist. Partly to emphasise that aspect of what I do. I guess that's where I would sit in the research space, if that makes sense. But I don't think I've ever really thought of myself as only somebody who does research. I have always thought of myself in a much broader context. For example, I spent probably too many years doing various chores around the University. I was initially in the School of Graduate Studies and, was a deputy dean there in the end. I sat on and chaired postgraduate scholarship committees and a whole bunch of those sort of things for many, many years, and wrote and evolved a lot of the policy.

I thought that sort of thing was really very important. Getting it right and trying to put it on a rational footing so that parts of the community weren't excluded. I spent many years doing that. And then I was asked to become part of the executive of the Academic Board at Melbourne Uni. With all the pushes and pulls that a vice chancellor has these days, it's very easy to lose sight of what a university is really there for. It's obviously a dialogue, a balancing act. But it's important that [the academic] voice is independent and strong.

How would you describe your research to a second-year undergraduate physics student?

There are two aspects to it. One is the inspirational aspect and this, I think, is what brings many students to physics, and explicitly to astronomy as well. You get to think about the biggest questions that you can possibly ask: the beginning and the future of the universe and all that’s in it. That's very exciting. And you get paid to do it. I don't think there are many of us who don't enjoy doing that. When the going gets tough, that's where the excitement is.

The flip side is that Astro uses almost every branch of physics and indeed nearly every branch of mathematics as well. We don't do optics, but we use a lot of physics around optics. We don't do quantum physics, but the hydrogen atom is at the core of much of what we do. We're not researching big data, but our big data is bigger than anybody else's. What that means is that you come out of doing Astro or cosmology with a broad range of skills and an integrated problem-solving arsenal, which I think is extraordinary. There have been groups of senior people, for example at CSIRO, who broadly recognise that if you take an astronomer, they can basically do anything. Yes, you might have to teach them a few new explicit skills in the area that you want them to work in. But they come with a broad range of skills that they can apply to any problem. When I first start talking to a new student, one of my questions is always: “What sort of science do you want to do?” Because we can take you anywhere. Really.

Why did you decide to pursue a career in your field?

I was pretty good at maths and physics at school, so I was already interested in those areas. And then, when I was in year twelve, I had an American second cousin who was selected as one of 10 Americans to [a] Science school on Space for secondary students that was held in Sydney in that year [1]. I looked at it and I was already very interested in astronomy at school, but of course we didn't study it at all. I thought, that's really interesting. I'd like to go to that. So I wrote to Harry Messel (this is me at 17) and I said I'd like to come, please. And he wrote back and said, get your physics teacher to write and say you're frightfully clever and you can come. So off I went. And that school was about inner and outer space. There were five kids from Japan, 4 from the U.K. and 10 from the US. And those were the guys I hang out with. There were two really memorable things out of that conference. The first was that Alan Shepard, the astronaut, came and talked about going into space. You know, it was 1968… it was a pretty interesting time. The ABC came and filmed him giving a talk, and they had us in the audience. We were told to suggest questions that we might ask him for the filming. And so I asked him, why are there no women in the space program? I was already thinking correctly at 17.

The other impact was that one of the lecturers gave a series of lectures on cosmology. And that just absolutely blew my mind. It lodged there: if I was ever get the chance to do anything I could choose, it would be to do cosmology. His name was Robert May. He subsequently went into biophysics, went to Princeton and then on to the UK and was Lord Robert May, chief scientist and all the rest of it. But he gave an extraordinary set of lectures. And so that was what lodged in the back of my brain. I didn't actually go on and do that for many years …[but] that was the inspiration. And I will say to this day that one talk can do that [1].

There was no Astro in Melbourne at that time. I started out in physics thinking I was going to do physics. I think I was the second top student going into science at Monash that year. [Then] I dropped out of uni, much to my mother's consternation. She said many years later. “Yes, dear. I know it was okay. But why did you have to be the first person we ever knew to leave university?” I quit for a couple of years. I taught secondary school maths, without a degree because I was in a private school. I worked for the Methodist Church for a year. I did this and that and then I thought, actually, you know, I'm a bit bored. And so I went back and got a degree in pure mathematics. But my heart wasn't in it in the same way. I really wanted to think about something much more tangible; more physical problems than pure maths would let me. So I left again. And this time was it was quite interesting.

I ended up working in real estate in the Victorian Public Service, buying and selling real estate for the Victorian Government and fitting out the office space. I was there for quite a while. The job was extremely interesting. I was fitting out major developments in the city. Absolutely fascinating.

After that, I thought where am I going to go from here? And I realised I didn't want to keep going up the public service ladder. One of my aunts on my 21st sent me a quote I think from Goethe that went something like “Beware of what you want to do at 21, because at 40 you achieve it.” I thought, do I actually want to be a head of a public service department at 40? No, that's not for me. Then I went off to do astronomy. That was not so trivial either because I'd been out of university for quite a long time.

I think that you have to realise that sometimes you have to step back. It's not just about keeping on going forward. Sometimes you have to go back a few steps and start again. I'd forgotten how to integrate. I hadn’t done an integral while I've been doing real estate. In my experience, the hardest thing for people is that when they leave study, they end up earning a lot of money. And then it's very hard to go back to not earning very much money while you re-organise yourself. But on the other hand, there's nothing to stop you doing something new and different if you're prepared to take the risk, and if it's important enough to you.

A very good friend knew that I really wanted to do astronomy. She won a Commonwealth Scholarship and had gone off to Oxford. At some stage, she had been visiting Cambridge. She went and photographed the Institute of Astronomy, sent it to me and said, ‘OK, apply. You know you really want to do this - do it’. So I did. I wrote an application to the Institute of Astronomy. I had decided I wanted to go work for Martin Rees, who was Director of the Institute,. As soon as I put the envelope in the mail, I thought, there's no way on earth he’s going to accept me, because I've been out in the work force. And in fact, he wrote right back to me and said, look, we don't quite know about you. You've got a bit of a chequered history. Why don't you go and do a master's degree at Sussex in astronomy? And if you do well enough, then I will take you at Cambridge. I applied to Sussex to do the master's degree. Of course, I had a good job in the public service, so I had enough money to pay for that year. That was quite a hard year for me. It was basically a coursework masters, but a very good coursework Master's, I have to say, even in retrospect. I still have the notes. They're still good. At the end of that year, I got accepted to Cambridge, so obviously I'd impressed them enough to do that. And I got a number of scholarships. So that was how I funded my way through Cambridge.

How useful are the skills you learnt outside academia?

There's absolutely no question that those other skills [are useful]. You understand how to get things done. You understand that when working in a group, it's not just about deciding things from on high. It's about communication. It's about collaboration. One of the essential things that I learned in that job was what I call 'shoe leather', which is that if you actually want to know something or understand something, you walk to that place and you talk to the people. You don't ask somebody else to go. You go yourself. And you find out whatever it is that you need to know. Obviously, I learned that doing real estate. But it's exactly the same in academia. You can send an email if you like, but you won't learn very much. You pick yourself up and go and have a coffee with somebody. And you learn a lot. So, those sort of skills [are] invaluable. You also learn about information. You know how to keep records. In academia, often just passing information onto other people is quite poor. Ensuring that people are not disenfranchised [and] they understand what's going on and why decisions are being made is important. They may not be perfect decisions, but everyone then has the information to understand the process. So those are things that I think that you learn working in the public service or anywhere else outside the university. You learn to be respectful, and to be open with information.

Is there a teaching-research nexus?

I totally subscribe to that. I learn an enormous amount from my students. They ask me questions I can't answer. The most recent one was an email from one of my third year students [who] had a question about quantum entanglement across black holes. So I asked Andrew Melatos, [who] gave a very lovely answer, which basically said, we don't know. You can try to apply classical stuff or semi-classical stuff into this space, but it is probably fraught. But he put it very well. I just sent his answer back to the student who was delighted. So students can and will ask questions that, in their naivete, push us to the limits of what we know.

I do enjoy teaching. I realise I actually love it and would miss it if I stopped, even though it drives me crazy at times. People often try to compartmentalise and structure teaching in a way that says: this is what I'm teaching you and this is the answer. And by doing that, I think we lose so much of what is exciting and interesting and the questions that kids actually really want to think about. If you teach black holes, we're inclined to write down a set of equations and say "this is what a black hole is. Yes, that problem exists. This is the evidence." That's a pretty standard way of teaching black holes. But just a second. You told me that we compressed matter down like this. We got to atomic or quantum densities, and then you're telling me that something happened, and we went further than that. But we have no physics to understand what that is. What's going on? And for some reason, we just gloss over that absolutely extraordinary step that pushes us into completely unknown territory. And we pretend that, yes, a black hole is something we know and understand and it's real. Well, yes, it may be real. But do we know and understand it? Absolutely not. It makes no sense whatsoever in terms of anything that we teach them. And we forget to say that. I think we forget to do that too often. And make it look like we kind of know everything that's going on, which is not true.

What's your recipe for success?

I have to say, I think luck is an element. Quite often things present themselves and often you're not able to take an opportunity that comes up. But if you are, sometimes that can take you places that you don't expect. I've always considered a hierarchy of opportunities, if that makes sense. I've been ruthless about putting probabilities on each of them. And I was always very clear about what I wouldn't accept. Would I accept a job in the US? I decided fairly early on, no, I would not. Even though I was encouraged to apply for quite a few. I was happy in Canada. In fact, I had residency there and could easily have stayed there. But when the opportunity presented itself [for a job in Melbourne], I took it.

You know, a job comes up in Tasmania and I hear young people say, "Who wants to go to Tasmania?" There are some wonderful things about Tasmania! They do good science. Fantastic place to live. You need to think about what your hierarchy of opportunity is and whether you actually want to do science enough. To take a job that may not be Melbourne and make the most of that opportunity or not. You might not get your first [choice]. It may have a low probability. But if you're very clear about that waterfall of opportunity, then it's okay. You find your place and you're also open to those random things that can come along. So, if you're overseas, if you really want to come back, then you won't necessarily come back to a job as a physicist. But those are the priorities you have to set up and decide on.

I talk to [some] postdocs to say that it is unlikely that they will get a faculty position. They're useful scientists but academic jobs are few. The role of a postdoc is to train and to learn and to develop a fantastic skill base. That's a discussion I have very early on. Usually after about year one, we start to talk about where do you think you want to go? And what's realistic? People are crying out to hire our graduates. You know, these are valuable people. You may know I've spent a lot of time working on climate change stuff as well. If one of my guys ends up working in the Met bureau or CSIRO climate, it's a win. And, if I had my time again, would I have ended up in cosmology or would I have ended in the science of climate change? I don't know. I really don't know.

What is the role of sport in your life?

After I left school, I took up rowing. And my most recent time on the water was only a couple of years ago. I've gone back and back and back to it. At Cambridge, they decided I was too old to row in the blue boat, so I coached it instead. Two of the women I coached ended up going to the Olympics that year. I did their early training for the Olympics, which was great. When I came back to Melbourne, I rowed in all sorts of places. There was a boat called the Rachel Webster that I think Monash University still has. But rowing is a fantastic sport.

What's Next?

One of the parts of climate change that I am involved with [is] trying to get a geothermal industry going in Victoria. It's about developing the geothermal resources in the Latrobe Valley. Latrobe Valley has half a kilometre or so depth of brown coal, which is the best insulating material on the surface of the Earth. It is very hot under the brown coal and there are huge hot aquifers. So you can go down less than a kilometre and be at 60 or 70 degrees quite easily. Our long-term goal is to generate electricity, but our short term goal is just to take the hot water and create industries in the Latrobe Valley that use the heat from that water.

Reference

[1] Trevor Danos, The Pursuit of excellence: A history of the Harry Messel International Science School. UWA publishing (2012).

Nobel Prize for 2020 to black hole researchers

Three Laureates share this year's Nobel Prize for Physics for their research into the physics of black holes. One half of the prize goes to Roger Penrose for "the discovery that black hole formation is a robust prediction of the general theory of relativity". The other half is shared by Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our Galaxy". Ghez becomes just the fourth woman to be awarded the physics prize.

The idea that there might be 'dark stars' that are so massive that not even light can escape their gravity goes back to the eighteenth century. In 1939 Robert Oppenheimer and Hartland Snyder used Einstein's general theory of relativity to describe the spherically symmetric case where an astronomical body contracts to form a singularity of infinite density. However, it was far from clear that this could happen in the real world and whether spherical symmetry was a prerequisite for gravitational collapse.

Nobel Prize for Physics in 2020 (from left): Roger Penrose (University of Oxford), Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics), and Andrea Ghez (University of California, Los Angeles) (© Nobel Media. Ill. Niklas Elmehed).

Penrose set out to analyse the situation without the assumption of spherical symmetry, assuming only that the collapsing matter had a positive energy density. To do this, he had to invent new mathematical methods and make use of topology. The key concept that Penrose introduced was that of a trapped surface – a closed two-dimensional surface with the property that all light rays orthogonal to the surface converge when traced toward the future.

Penrose was able to prove that trapped surfaces are independent of any assumptions about symmetry and that once a trapped surface had formed it is impossible, within general relativity, to prevent the collapse towards a singularity. Penrose published his ideas in 1965, a paper which is still regarded as the most important contribution to general relativity since Einstein.

Two observational teams, one led by Reinhard Genzel and the other by Andrea Ghez, have been monitoring the motions of stars orbiting the Galactic centre for nearly three decades. Genzel's group used telescopes in Chile operated by the European Southern Observatory, while Ghez and her colleagues used the Keck Observatory in Hawaii. Both groups observed at near infrared wavelengths, because only a miniscule fraction of visible light can penetrate the interstellar dust surrounding the centre.

One of the stars observed has been shown to have an orbiting period around the Galactic centre of 16 years (in comparison, the Sun in the outer suburbs has a period of over 200 million years). This star has a highly elliptical orbit and comes within a mere 17 light-hours of the centre. The work of both groups has established that the Galactic centre consists of 4 million solar masses packed into a volume no larger than our Solar System. This is the most compelling evidence to date that the centre is indeed a supermassive black hole.

It is interesting to note that three of the past four Nobel Prizes have been in Astrophysics. Originally, from the first Nobel Prizes in 1901, discoveries in astrophysics were considered ineligible for the Physics prize. The Nobel Foundation changed its policy in 1974 when the discovery of pulsars received the first Astrophysics award. In the 46 years since then, there have been ten prizes in Astrophysics, second only to Particle Physics with 13 prizes.

Peter Robertson

Oscillators and repellers in an expanding accelerating universe

Professor Philip Broadbridge
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Introduction

The domain of quantum phenomena has long been recognised to be at the atomic scale. For more than 50 years after the invention of *quantenmechanik* in the 1920s [1], it was preposterous to consider quantum field effects at cosmological scales. However by the wave-particle duality that was first encountered theoretically in de Broglie's matter waves, and experimentally in the photoelectric effect and the Compton scattering, particle 4-momentum is directly related to frequency and wave number of the matter wave even though the unambiguous oscillatory nature of a field requires an observer to be in an inertial reference frame that is, according to Mach's principle, defined by the overall structure of the universe at large. Two discoveries of the 1970s meant that an in-tandem study of large-scale gravitation and quantum effects could not be avoided. The first was the Hawking effect of black hole evaporation [2]. The second, the Unruh effect, came from studying the Hawking effect at a fundamental level: a vacuum state in an inertial frame contains particles in an accelerating reference frame, with a thermal black-body distribution of particle energies [3] at a Boltzmann temperature $k_B T = \frac{\hbar a}{2\pi c}$. The Hawking spectrum is the special case when acceleration a is the gravitational acceleration at a Schwarzschild surface. This gives a beautifully simple relationship involving the speed of light, Planck's constant, Boltzmann's constant and the universal gravitational constant. Now there are several monographs on quantum fields in curved space, the earliest [4] having an Australian connection.

With current technology, the curvature of a universal cross section at constant proper time, is not experimentally distinguishable from zero, which requires the mass density to be close to the critical value separating open universes from closed universes. In the late 1990's clear experimental evidence was published to show that the expansion of the universe was accelerating [5], even exponentially. This brings new demands to quantum field theory and it calls into question some of the basic assumptions that are routinely made in predicting and analysing outcomes of physical dynamical systems. These issues are best expressed in ways that relate them to systems that we already understand well. Classical mechanics involves systems of finite degrees of freedom evolving as systems of ordinary differential equations for real-valued configuration variables $q_n(t)$ (position variables x_j in the more restrictive Newtonian formulation) and conjugate momentum variables $p_n(t)$. After first quantisation, these variables become non-commuting operators, with unbounded real spectra, acting on a space of wave functions $\psi(x,t)$ and satisfying canonical commutation relations $qp - pq = i\hbar I$. For many purposes in atomic physics it is adequate to have $\psi(x,t)$ evolving under the non-relativistic Schrödinger wave equation. The state variables already have infinite degrees of freedom since ψ belongs to some infinite dimensional function space, most conveniently a complex separable Hilbert space with inner product $\langle\phi|\psi\rangle$. Within the Copenhagen interpretation, to some extent we can still think classically, as $|\psi(x)|^2$ is regarded as a probability density of measurement of the particle location at classical location x.

When the velocities of particles or waves can be a considerable fraction of the speed of light c, a relativistic wave equation is needed, most commonly the Klein-Gordon equation for spin-0 scalar fields, the Dirac equation for spin-$\frac{1}{2}$ spinor fields, the Maxwell system for massless spin-1 vector fields and the Einstein system for spin-2 tensor fields. However in those cases, attempts to interpret the wave function as a probability amplitude were not successful. Interpretability was restored in quantum field theory through second quantisation in which the complex valued wave functions $\psi(x,t)$ and their conjugate momentum fields $\pi(x,t)$ were themselves extended to operators $\Psi(\psi)$ and $\Pi(\psi)$ satisfying equal-time commutation relations $\Psi(\phi)\Pi(\psi) - \Pi(\psi)\Psi(\phi) = i\hbar\langle\phi|\psi\rangle$. The inner product on the right hand side usually appears in the simpler form $\delta(x-y)$ which follows when ϕ and ψ are eigenstates of position in the first quantisation. It is much easier to analyse quantum fields when ψ is thought of as a wave function of the single particle, after which one takes tensor products to get n-particle states that are built up from a vacuum state by creation operators. This Fock-Cook representation of a quantum field has a much larger state space that is a direct sum of all possible n-particle spaces [6, 7]. However it relies on the existence of a relativistically invariant vacuum state. This is fine for Lorentz-invariant wave equations on flat Minkowski space but it is sometimes problematic for general relativistic wave equations. When there does not exist a state that is invariant under the isometries of a curved space-time, one must either choose a vacuum state that lacks some invariance properties or give up on the Fock representation since it is even difficult to define a particle number in an invariant way.

In first quantised systems of finite degrees of freedom, all irreducible representations of the algebra of observables, built from canonical operators q_n and p_n, are unitarily equivalent and they lead to the same physical predictions. For quantum field equations with infinite degrees of freedom, there are infinitely many unitarily inequivalent irreducible representations of the quantum algebra of observables. The Fock representation is not well defined for unstable field dynamics and beyond the Fock representation, we don't know how to physically interpret the states.

The simplest relativistic quantum field is the free charge-neutral scalar field on Minkowski space, governed by the Klein-Gordon wave equation. The free field may be decomposed into an infinite system of independent harmonic oscillators [8]. If we minimally couple the scalar field to a maximally symmetric stretching space-time which is an exponentially expanding de-Sitter universe with flat space-like cross sections, then a coordinate system can be chosen so that the field appears to be closely analogous to the free field but the fundamental oscillator modes do not conserve energy, as their frequencies of oscillation decrease in time, eventually hitting zero and then becoming imaginary and repulsive. This does not happen in the single quantised oscillator on an accelerating platform but the evolution of that system might give a little insight on the relativity of oscillatory behaviour.

Harmonic Oscillator on an Accelerating Platform

The linear harmonic oscillator with force constant $m\omega_0^2$ and natural angular frequency ω_0, in either its classical form or its quantum form, is one of the basic building blocks that all physi-cists come to know and appreciate. However the simple regular oscillatory behaviour that we have come to expect, relies on the platform of the oscillator being at rest in an inertial reference frame, which itself is an idealised concept. The oscillator can indicate whether the platform is accelerating relative to the set of local inertial reference frames whose special status is awarded to them according to Mach's principle [9], by the mass distribution in the universe at large.

Now consider the platform from which the oscillator is suspended, to be accelerating exponentially in the direction of decreasing x, with its position given in a Galilean inertial frame of a one-dimensional Euclidean space as $y(t) = y_0[1 - e^{\alpha t}]$. The centre of mass of the suspended bob of mass m is at $x(t)$. The ex-tension of the oscillator is $x - y(t) - \ell$ where ℓ is the rest length. As usual, the origin of the coordinate system will be taken to be at $X = x - \ell = 0$ so that ℓ is swept under the carpet and x will now denote the extension X in the stationary frame. The kinetic energy, potential energy and Lagrangian are respectively $T = \frac{1}{2}m\dot{x}^2$, $V = \frac{1}{2}m\omega_0^2[x - y(t)]^2$ and $L = T - V$. In terms of the momentum $p = m\dot{x}$, the Hamiltonian is

$$H = p^2/2m + \frac{1}{2}m\omega_o^2[x - y(t)]^2, \qquad (1)$$

which in this case is not conserved because of the explicit dependence of y on t. With q identified as the classical coordinate x, the system obeys Hamilton's equations

$$\dot{q} = \frac{\partial H(q,p,t)}{\partial p},$$
$$\dot{p} = -\frac{\partial H}{\partial x},$$

from which it follows that for any dynamical function $F(x,p,t)$,

$$\frac{dF}{dt} = \frac{\partial F}{\partial t} + \{F, H\}.$$

The Poisson bracket is defined in n degrees of freedom by

$$\{F, G\} = \sum_{j=1}^{n} \frac{\partial F}{\partial q_j}\frac{\partial G}{\partial p_j} - \frac{\partial G}{\partial q_j}\frac{\partial F}{\partial p_j}.$$

In particular, $\frac{dH}{dt} = \frac{\partial H}{\partial t} = -m\omega_0^2\dot{y}[x - y(t)]$.
The usual interpretation is that the acceleration of the platform is due to some external agent that supplies energy. By either Newton's laws or the Lagrange equations of motion, the location x satisfies

$$\ddot{x} + \omega_0^2 x = \omega_0^2 y_0(1 - e^{\alpha t}), \qquad (2)$$

for which the general solution in terms of amplitude A and phase δ is

$$x = \frac{-\omega_0^2 y_0}{\alpha^2 + \omega_0^2}e^{\alpha t} + y_0 + A\cos(\omega_0 t + \delta); \qquad (3)$$
$$A \geq 0, \quad \delta \in \mathbb{R}.$$

Now the velocity of the bob is

$$\begin{aligned} \dot{x} &= \frac{\alpha\omega_0^2 y_0}{\alpha^2 + \omega_0^2}e^{\alpha t} - \omega_0 A\sin(\omega_0 t + \delta) \qquad (4) \\ &> \frac{\alpha\omega_0^2 y_0}{\alpha^2 + \omega_0^2}e^{\alpha t} - \omega_0 A. \end{aligned}$$

Certainly when

$$t > \frac{1}{\alpha}\ln\left(\omega_0 A\frac{\alpha^2 + \omega_0^2}{\alpha\omega_0^2 y_0}\right),$$

there can be no stationary points and x must increase monotonically in time. In that sense, oscillations are finite in number and they must cease! The same phenomenon will occur if the change of reference frame is passive rather than active; i.e. when the physical platform remains at rest in some inertial frame but the observer is at location $-y(t)$, accelerating in the direction of increasing x. The motion of the observer does not need to be oscillatory in order to cancel out the physical oscillations. This observation is elementary but it provides a useful entrée to the question of what this means for a quantised field whose fundamental oscillatory modes are coupled to our exponentially expanding universe.

Relativity of oscillatory behaviour is closely related to relativity of the vacuum state and to relativity of particle numbers. Quantum mechanics is fundamentally an algebraic construct based on non-commuting operations $[q_j,p_k] = i\hbar\delta_{j,k}I$; $[q_j,q_k] = 0$; $[p_j,p_k] = 0$, among conjugate variables that may be represented as unbounded self-adjoint operators with real spectral values. The Schrödinger wave representation has operators acting on square-integrable complex-valued wave functions ψ as

$$q : \psi(x,t) \mapsto x\psi(x,t), \tag{5}$$

$$p : \psi(x,t) \to -i\hbar\frac{\partial\psi(x,t)}{\partial x}. \tag{6}$$

The particulate nature of a field is more conveniently described by the equivalent Fock representation of 1927 [6], wherein states are linear combinations of n-particle states $|n\rangle$ that are the result of a creation operator $a^\dagger$ acting on a vacuum state $|0\rangle$.

$$\begin{aligned} |n\rangle &= (a^\dagger)^n\,|0\rangle\,; \\ aa^\dagger - a^\dagger a &= I \text{ (Boson commutation relations).} \\ q &= \left(\frac{2\omega_0 m}{\hbar}\right)^{-1/2}[a+a^\dagger], \\ p &= -i\left(\frac{\hbar\omega_0 m}{2}\right)^{1/2}[a-a^\dagger]. \end{aligned}$$

For a simple harmonic oscillator, n is an eigenvalue of the number operator $a^\dagger a$ that counts the number of phonons absorbed in a discrete energy eigenstate of the Hamiltonian operator

$$H = \frac{p^2}{2m} + \frac{1}{2}kq^2 = \frac{1}{2}\hbar\omega_0 I + \hbar\omega_0 a^\dagger a.$$

The second term is the energy of absorbed phonons. The first term is the vacuum energy that is the same as the energy eigenvalue of the lowest energy eigenstate ψ_0 that takes a Gaussian form in the Schrödinger representation,

$$\psi_0(x) = \left(\frac{m\omega_0}{\pi\hbar}\right)^{1/4} e^{-m\omega_0 x^2/2\hbar}.$$

The other discrete energy eigenstates are $|n\rangle$ with eigenvalues $(n+\frac{1}{2})\omega_0\hbar$.

Now recall the explicitly time-dependent Hamiltonian (1) which can be expressed in Boson form

$$H = \hbar\omega_0 a^\dagger a + \frac{1}{2}\hbar\omega_0 + \frac{1}{2}ky(t)^2 - ky(t)q.$$

In the Schrödinger picture,

$$i\hbar\frac{\partial\psi}{\partial t} = H(q,p,t)\psi.$$

As explained by von Neumann, this is equivalent to the Heisenberg equation of motion through the Hilbert space formalism. Consider an observable operator F that is a function of q and p but not explicitly depending on t. Then the time derivative of the expectation value of F is

$$\begin{aligned} \frac{d}{dt}\langle\psi(t)|F\psi(t)\rangle &= \langle\frac{d\psi}{dt}|F\psi\rangle + \langle\psi|F\frac{d\psi}{dt}\rangle \\ &= \langle\frac{-i}{\hbar}H\psi|F\psi\rangle + \langle\psi|\frac{-i}{\hbar}FH\psi\rangle \\ &= \frac{-i}{\hbar}\langle\psi,[F,H]\psi\rangle\,. \end{aligned}$$

Since this is true in an arbitrary state ψ, it gives the equation for evolution of an operator F in the Heisenberg picture, with the classical Poisson bracket replaced by $\frac{-i}{\hbar}$ times the quantum commutator bracket according to the Dirac correspondence principle. When N is the number operator $a^\dagger a$,

$$\frac{dN}{dt} = \frac{iky(t)}{\hbar}[N,q] \tag{7}$$

$$= i\sqrt{\frac{m\omega_0^3}{2\hbar}}\,[a^\dagger a, a+a^\dagger] \tag{8}$$

$$= i\sqrt{\frac{m\omega_0^3}{2\hbar}}(-a+a^\dagger). \tag{9}$$

In this simple example, $\frac{dN}{dt}$ still has a vacuum expectation value of 0 even though energy is not conserved.

Covariant wave equation coupled to de Sitter space-time

An isotropic expanding space-time with expansion factor $a(t)$ is the Friedmann-Lemaître space-time (usually referred to as FLRW although the Robertson-Walker effort made almost no reference to physics), with metric

$$ds^2 = g_{\alpha\beta}dx^\alpha dx^\beta = c^2dt^2 - a(t)^2dx^idx^i \tag{10}$$

$$= a(t)^2[c^2d\eta^2 - dx^idx^i]. \tag{11}$$

Repeated indices are summed in the Einstein summation convention. x^i are material coordinates, co-moving with the representative expanding isotropic continuum for the cosmological mass distribution, t is co-moving proper time and η is conformal time,

$$\eta = \int_0^t \frac{dt_1}{a(t_1)}. \tag{12}$$

Einstein's field equation is a direct relationship between the geometric Einstein tensor and the stress-energy tensor. The component equation for energy density leads to the so-called Friedmann equation (although Fridman was Russian, not German),

$$\left(\frac{\dot a(t)}{a}\right)^2 = \frac{8\pi G}{3}\rho(t) + \frac{\Lambda c^2}{3}. \tag{13}$$

In the above, the energy density due to massless radiation has been neglected as has been the contribution due to spatial curvature. The cosmological constant Λ is the simplest model for dark energy at constant density, which currently is the main driver for the expansion. The energy density of the dark component is $\frac{\Lambda c^4}{8\pi G}$. Although its nature is not understood, the current estimate from the Planck Mission team [10] has dark energy accounting for 68% of the total, along with 27% dark matter and 5% hadronic matter, the latter small fraction along with electromagnetic radiation making up the currency of our lives. At large times, $a(t)$

will be asymptotic to $e^{\sqrt{\Lambda/3}ct}$, which is the de Sitter model. In that case,

$$\eta = \eta_\infty \left[1 - \exp\left(-ct\sqrt{\Lambda/3}\right)\right], \tag{14}$$

$$\text{where } \eta_\infty = \sqrt{3/\Lambda c^2}, \tag{15}$$

$$\text{consequently } a = \frac{\eta_\infty}{\eta_\infty - \eta}. \tag{16}$$

The de-Sitter model has the largest group of isometries of all the FLRW models. Two copies of it, requiring a second coordinate patch covering a contraction period before the singularity at $t = -\infty$, make up the full mathematical de Sitter space which is a 5-dimensional Minkowski space with an extra restriction to a hyperbolic surface (e.g. Chap. 5.4 of [4]). Not only is exponential expansion approximately true at the present time, it is often used as a model of the initial inflationary period that required an enormous expansion rate over a period of less than $10^{-32}s$, needed to explain the small but significant large-scale anisotropy in the observable universe whose radius of 47 billion light years is much larger than its age multiplied by the speed of light (approximately 13.8 billion light years).

A general covariant scalar wave equation is

$$\nabla^\nu\nabla_\nu\Phi(\mathbf{x},t) + (\frac{m^2c^2}{\hbar^2} + \xi R)\Phi = 0 \tag{17}$$

where ∇_ν represents the covariant derivative, m is the particle rest mass, ξ is the coupling constant for matter wave-gravitational field interaction, and $R = \frac{6}{c^2a^2}(a\ddot{a}(t) + \dot{a}^2) = 6a''(\eta)/a^3 = 4\Lambda$ is the Ricci scalar.

$\nabla^\nu\nabla_\nu$ is the divergence of the gradient or the Laplace-Beltrami operator,

$$\nabla^\nu\nabla_\nu\Phi = |\det g|^{-1/2}\partial_\mu\left[|\det g|^{1/2}g^{\mu\nu}\partial_\nu\Phi\right].$$

In terms of the scaled-up field variable $\phi = a\Phi$, the wave equation is closely related to the standard Klein-Gordon equation

$$\frac{\partial^2\phi}{\partial\eta^2} - c^2\frac{\partial^2\phi}{\partial x^j\partial x^j} + \mu^2\phi = 0 \tag{18}$$

except that instead of being a constant rest mass, μ is now time-dependent,

$$\mu^2 = \left(\frac{3m^2}{\Lambda\hbar^2} - \frac{2-12\xi}{c^2}\right)(\eta_\infty - \eta)^{-2}. \tag{19}$$

If the coupling constant ξ is small or zero, μ^2 may be negative and with a magnitude that increases with time. This is certainly the case when Λ is the enormous logarithmic inflation rate, so large that the squared rest mass of any known particle is minuscule compared to $\Lambda\hbar^2$. It is also the case under the present rate of expansion when $m = 0$ or when m is the mass of an unlikely Boson-like Cooper pair of the lightest of the three neutrino masses.

In terms of spherical polar coordinates, after non-dimensionalisation the general solution is of the form [11]

$$\phi = \sum_{n=1}^{\infty}\sum_{l=0}^{2n}\sum_{m=-l}^{l}\frac{J_{l+\frac{1}{2}}(k_{nl}\,r)}{\sqrt{k_{nl}\,r}}Y_l^m(\theta,\varphi) \times \{a_{nlm}f_{n\ell}(\eta) + (-1)^m a^\dagger_{nl-m}f^*_{n\ell}(\eta)\}. \tag{20}$$

$Y_l^m = (-1)^m(Y_l^{-m})^*$ are spherical harmonic functions, while J is the standard Bessel function. For free fields on Minkowski space, the time dependent factors are simply trigonometric $f_k(t) = e^{i\omega_k t}$ so the field may be regarded as a collection of independent harmonic oscillators [8]. Now in terms of Bessel functions, the oscillatory time dependent factors have real part

$$f_{n\ell}(\eta) = \sqrt{\eta_\infty - \eta}\,J\left(\sqrt{\frac{1}{4} + 2 - 12\xi}, k_{n\ell}(\eta_\infty - \eta)\right).$$

$k_{n\ell}$ are radial wave numbers that take discrete values after specifying boundary conditions. For an unbounded universe, n, ℓ and m are identifiable as the principal quantum number, angular momentum quantum number and component angular momentum quantum number that are familiar from atomic physics. In the above, ℓ takes a different range of values because boundary conditions have been imposed on a finite domain. It is important to see that whatever reasonable boundary conditions are imposed, $f_{n\ell}(\eta)$ describes only a finite number of oscillations from now ($\eta = 0$) until the end of time ($\eta = \eta_\infty \leftrightarrow t = \infty$). Not surprisingly, with so little understanding of the outer reaches of the observable universe, the boundary conditions are contentious but some reasonable choice will give indicative outcomes. In [11] we assumed Neumann boundary conditions at a material boundary $r = 1$. This is mathematically convenient because it leads to a relatively simple Lagrangian density, canonical Hamiltonian and canonical stress-energy tensor. The Neumann boundary condition then guarantees zero energy flux across the material boundary. A surface $r = 1$ is not invariant under the isometry group of the de Sitter space. A local Lorentz transformation will transform the sphere to an ellipse. However the boundary can still be represented in this way if there is a physically identifiable reference frame in which the boundary is a sphere. For the first time in history, this is now the case. Planck observations identify a reference frame in which the cosmic microwave background is maximally isotropic. Relative to that frame, our planet has a speed of 370 km s^{-1} [12]. Since the time of the Michelson-Morley experiment until now, our textbooks have denigrated the idea of an absolute reference frame such as the Maxwell aether. What was Einstein's view, after the development of the general theory of relativity? Quoting from a translation of his lecture given in Leiden in 1920 [13]: *"But on the other hand there is a weighty argument to be adduced in favour of the ether hypothesis. To deny the ether is ultimately to assume that empty space has no physical qualities whatever. The fundamental facts of mechanics do not harmonize with this view...... As to the part which the new ether is to play in* *the physics of the future we are not yet clear. We know that it determines the metrical relations in the space-time continuum, e.g. the configurative possibilities of solid bodies as well as the gravitational fields; but we do not know whether it has an essential share in the structure of the electrical elementary particles constituting matter. Nor do we know whether it is only in the proximity of ponderable masses that its structure differs essentially from that of the Lorentzian ether; whether the geometry of spaces of cosmic extent is approximately Euclidean. But we can assert by reason of the relativistic equations of gravitation that there must be a departure from Euclidean relations, with spaces of cosmic order of magnitude, if there exists a positive mean density, no matter how small, of the matter in the universe."*

Underlying harmonic oscillators, quasi-particles and repellers

With second quantisation, the field ϕ is operator-valued and it is supposed to satisfy canonical equal-time commutation relations with the conjugate field $\Pi(\mathbf{r},\eta) = \partial\phi/\partial\eta$, so that $[\phi(\mathbf{r_1},\eta),\Pi(\mathbf{r_2},\eta)] = i\delta(\mathbf{r_2}-\mathbf{r_1})$. Just as in the free field theory, after a lot of algebra it can be shown that the basis functions $f_{n\ell}$ can be scaled in such a way that the canonical commutation relations are equivalent to Boson commutation relations

$$[a_{nlm}, a_{n'l'm'}] = 0 \qquad (21)$$

$$[a^\dagger_{nlm}, a^\dagger_{n'l'm'}] = 0 \qquad (22)$$

$$[a_{nlm}, a^\dagger_{n'l'm'}] = i\delta_{nn'}\delta_{ll'}\delta_{mm'}. \qquad (23)$$

The Hamiltonian is then a quadratic combination of the Boson creation and annihilation operators. In [14] it is shown how to reduce such a combination to canonical form by a Bogoliubov transformation that has a_{nlm} expressed as a linear combination of b_{nlm} and $b^\dagger_{nlm}$ that obey the same Boson commutation relations. Consequently, H can be expressed

$$H = H_L + H_D \qquad (24)$$

with

$$\begin{aligned} H_L = \sum_{\substack{n,l \\ k^2_{n,l}>|\mu^2|}} & \frac{\omega_{nl}(\eta)}{2}\left[b_{nl0}b^\dagger_{nl0} + b^\dagger_{nl0}b_{nl0}\right] \\ &+ \frac{\omega_{nl}(\eta)}{2}\sum_{m=1}^{l}\Big[b_{nl-m}b^\dagger_{nl-m} + b_{nlm}b^\dagger_{nlm} \\ &\qquad + b^\dagger_{nlm}b_{nlm} + b^\dagger_{nl-m}b_{nl-m}\Big] \end{aligned} \qquad (25)$$

and

$$\begin{aligned} H_D = \sum_{\substack{n,l \\ k^2_{n,l}<|\mu^2|}} & \frac{i\alpha_{n,l}(\eta)}{2}\left[b_{nl0}b_{nl0} - b^\dagger_{nl0}b^\dagger_{nl0}\right] \\ &+ \frac{i\alpha_{n,l}(\eta)}{2}\sum_{m=1}^{l}\Big[b_{nl-m}b_{nl-m} + b_{nlm}b_{nlm} \\ &\qquad - b^\dagger_{nlm}b^\dagger_{nlm} - b^\dagger_{nl-m}b^\dagger_{nl-m}\Big]. \end{aligned} \qquad (26)$$

Each component of H_L is recognisable as the Hamiltonian of an independent harmonic oscillator, $H = \frac{1}{2}p^2 + \frac{1}{2}\omega^2_{n\ell}q^2$ with

$$\omega^2_{n\ell} = k^2_{n\ell} - 2(\eta_\infty - \eta)^{-2}.$$

Classically the energy of each mode is decreasing at rate

$$\frac{dH}{dt} = \frac{\partial H}{\partial t} = \frac{-2q^2}{(\eta_\infty - \eta)^3},$$

no matter whether it is stable or unstable. The quantum excitation level of a stable mode, counted by an eigenvalue of the number operator $N_{nlm} = a^\dagger_{nlm}a_{nlm}$, is raised by absorbing one quasi-particle of the system.

On the other hand each component of H_D is of the form

$$H_{nlm} = \frac{1}{2}\begin{bmatrix} a^\dagger_{nlm} & a_{nlm} \end{bmatrix} D_{nlm} \begin{bmatrix} a_{nlm} \\ a^\dagger_{nlm} \end{bmatrix} \text{ for } m \neq 0 \qquad (27)$$

where

$$D_{nlm} = \frac{\alpha_{nlm}}{2} \times \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}. \qquad (28)$$

By the correspondence between the Boson algebra and the Heisenberg algebra discussed in Section 2, this subsystem Hamiltonian is equivalent to $\frac{1}{2}p^2 - \frac{1}{2}\alpha^2q^2$. This has an inverted quadratic potential for a repulsive force. There is a well-known but incorrect folk-lore theorem that every quadratic Hamiltonian can be written as a sum of quasi-particle number operators. In fact this is true only for stable systems. Bogoliubov transformations preserve the eigenvalues of $\hat{I}D$, with $\hat{I} = diag[1,-1]$. A harmonic oscillator has real eigenvalues $\pm\omega$ for $\hat{I}D$ whereas the eigenvalues are pure imaginary $\pm i\alpha$ for the repeller units. No Bogoliubov transformation will convert a repeller or any of four other types of inequivalent quadratic Hamiltonian system, to an oscillator or to a sum of number operators [14]. Like the unbound ionized states of an atom, the Hamiltonian of a repeller has continuous spectrum. Worse, its spectrum has no lower bound, which usually signifies runaway instability. There is no number operator that commutes with the repeller Hamiltonian. The energy eigenstates cannot be viewed as oscillatory radiation or as particles. Schroer [15] called these "jelly states" but at the present time, they have no generally accepted physical description. The frequencies of the oscillator modes evolve from being real to imaginary. It is hard to imagine a well defined particle state that evolves through the attraction-repulsion transition. However in [11] we have solved the non-autonomous Schrödinger equation exactly for that case. The quantum expected value of location x (or of ϕ in the case of a scalar field) behaves similarly to the classical solution $f_{k\ell}(\eta)$. It oscillates a finite number of times and then retains one sign or another.

Whereas the number of oscillator components is infinite, the number of repeller modes is finite but increasing in time, as $|\mu^2(\eta)|$ is increasing. At successive discrete times, each fundamental mode $(n\ell m)$ transitions from attractive to repulsive. At large t, the critical wave number is proportional to $a(t)$. As is familiar from the H atom, states with principal quantum number n have degeneracy of order n^2. The number of independent unstable states is roughly proportional to n^3 which is proportional to the total volume.

Conclusion

It is fair to say that our current knowledge of cosmology is quite rudimentary as we grapple with many alternative ideas on the nature of dark energy, dark matter, the big bang singularity and the inflaton field. The massless scalar field is not realistic but is an illustrative model. Conceivably, a similar runaway phenomenon may occur in the more complicated massless Boson photon field. It does not occur in a Fermion field since quadratic self-adjoint Fermion operators can always be written in terms of number operators (e.g. [16]). At the current rate of expansion in a de Sitter Klein-Gordon field, few modes would have become unstable. Due to the enormous rate of expansion of the inflation epoch, much of the inflaton field energy would have been converted to non-particulate form, or transferred to other interacting fields. In the minimal chaotic inflation model [17], the self-interaction potential is indeed quadratic at low-ϕ but it flattens to a plateau at large-ϕ.

Proposed explanations of dark energy generally belong to one of three categories. The first says that expansion of the universe exposes more vacuum energy. However there is a very large discrepancy between observations and calculations of vacuum energy, by many orders of magnitude. The second says that the apparent dark energy is a misinterpretation due to some missing factor in general relativity over cosmic scales. The third says that dark energy is produced by some process that involves fields apart from vacuum effects. Rather than inventing complicated new physical structures, it pays to first explore the consequences of standard theory of second quantisation that has been used successfully at least since the 1940s. For unstable field modes the very concept of the vacuum state is irrelevant. For that finite number of unstable modes, there is no state of lowest energy from which to build a cyclic representation of the algebra of observables. The quantum mechanical representation of that finite number of unstable modes is unique up to unitary equivalence. That representation has the additional complexity that the number of degrees of freedom increases at various discrete transition times. The remaining infinite degrees of freedom of the field carry a well defined vacuum representation.

Acknowledgements

The work described here was supported by the Australian Research Council for project DP160101366. The author is grateful to S. Becirevic, K. Deutscher and D. Hoxley for recent discussions. The article is dedicated to the memory of Freeman Dyson who gave me inspiration in my student days.

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Report on 44th Condensed Matter and Materials Conference

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The 44th Australian and New Zealand Institutes of Physics Condensed Matter and Materials Conference (colloqually called "Wagga" 2020) was hosted by a New Zealand Organising Committee and held at the Holiday Inn, Rotorua, from 4th to 7th February. The Committee, Dr Philip Brydon, University of Otago (Chair), Professor Tilo Söhnel and Dr Ben Mallett, University of Auckland, had assembled a programme of invited and contributed oral presentations together with a number of poster presentations. This article provides a report on the Conference and at the same time, should encourage Condensed Matter and Materials Physicists to look forward to attending the 45th Conference in this series in February, 2021.

Introduction

Most delegates arrived on the afternoon/evening of Tuesday, 4th February, to check into residence at The Holiday Inn and to prepare for the usual early opening session on the following morning. Those who arrived on internationl flights into New Zealand, were made aware of the approaching COVID-19 pandemic, given that already on 4th February, New Zealand authorities had abandoned the usual electronic passport examination and all arrivals had to be checked personally by an immigration officer.

But once we settled into The Holiday Inn in Rotorua, the subsequent conference sessions through until lunchtime Friday, as is the established format for any "Wagga", comprised invited presentations, each of 30-minutes duration and contributed oral presentations of 20 minutes. While poster presentations were exhibited throughout the Conference, there were two poster sessions each of two hours duration, on the afternoons of Wednesday and Thursday.

As is the established custom for the "Wagga" conference series, all delegates were invited to take part in a Trivia Quiz, held this year on the Wednesday evening, and a Conference Dinner featuring an invited speaker, was held on the Thursday evening.

The conference ended with lunch on the Friday, 7th.

The Conference Delegates

The overall attendance at the conference was 82 comprising 33 each from New Zealand and Australian research organisations, 10 from other countries overseas and six from industrial organisations. Amongst the New Zealand delegates, the University of Auckland with 14 and Victoria University of Wellington, 13, were in the majority and with the Universities of Canterbury, Massey and Otago also being represented. From Australia, University of New South Wales (Sydney) with nine delegates was in the majority but with representatives from the Australian National University, the Universities of Melbourne, New South Wales (Canberra), Queensland, Sydney, Western Australia and Wollongong, Queensland University of Technology, as well as the Australian Nuclear Science and Technology Organisation and CSIRO (Lindfield).

The international delegates came from Germany (3), Japan (3), Korea (2), Poland (1) and Slovenia (2) while the Industrial representatives were from Ezzi Vision, Nano Vacuum, Scitek and AXT Pty. Ltd.

Invited Lectures

The programme featured 12 invited lectures. The topics covered were: "Remarkable fluorgentates (II) – the ultimate siblings of oxocuprate materials" by Wojciech Grochala (University of Warsaw), which reported on the interesting electronic and magnetic properties of particularly AgF_2 and $AgFBF_4$; "The anomalous Hall effect of antiferromagnetic Mn_3Ge and amorphous ferromagnetic Fe_xSi_{1-x} and $Fe_yCo_{1-y}Si$" by Julie Karel (Monash University), which advanced a mechanism for the anomalous Hall effect in these materials, and experimental results were compared with some recent theoretical calculations;

"$FeMn_3Ge_2Sn_7O_{16}$: a spin-liquid candidate with perfectly isotropic 2-D kagome lattice" by Chris Ling (University of Sydney), in which the relationship between structure and magnetic properties for this compound were discussed;

"Spin-liquid state in planar Heisenberg models" by Peter Prelovsek (Jozef Stefan Institute, Slovenia);

"From sticky hard spheres to Leonard-Jones potentials and many-body expansions for rare gas solids" by Peter Schwerdtfeger (Massey University, Auckland), in which it was illustrated how effective can be this traditional potential known to most students of condensed matter physics, in predicting physical properties of rare gas solids;

"Electron holography of high temperature superconductors" by Ruth Knibbe (University of Queensland), an experimental presentation in which the current challenges in imaging magnetic vortices in YBCO were discussed;

"Towards a single-model description of cuprates in the pseudogap state" by James Storey (Victoria University of Wellington), which summarised the use of known physical property data for the cuprate materials leading to a Fermi surface reconstruction and hence the pseudogap;

"Rare-earth nitride: Mixed valence, strongly correlated heavy fermions" by Joe Trodahl (Victoria University of Wellington), in which the intriguing semiconducting properties of particularly europium, samarium and neodymium nitrides in thin-film form, were discussed;

"Superconducting computing memory using rare-earth nitrides" by Eva Anton (Victoria University of Wellington), to some extent related to the previous presentation but focussed specifically on the potential for these nitride materials to be used in a magnetic memory device;

"Exotic criticality and symmetry-protected topological states in dimerised fermion, boson and spin chain models" Holger Fehske (University of Greifswald, Germany),

"Spectral function of the Holstein polaron at finite temperatures" by Janez Bonca (Josef Stefan Institute, Slovenia);

"Topological electronic transport properties of magnetic Wehl semi-metal Co2MnGa" by Simon Granville (Victoria University of Wellington), which at least for this member of the audience was a welcome return to some traditional condensed matter physics, namely anomalous Hall and Nernst effects in some Heusler alloys but in thin-film form.

Other Presentations

The above invited lectures were suitably interspersed with 26 oral presentations, to some extent related to the invited one, given by a mix of graduate student and more experienced presenters, as has become the tradition for the "Wagga" conference series.

Also, as has become the established format for "Wagga" conferences, adequate time in two separate sessions in the program, was allowed for the presentation of posters of which there were 34 in total.

A broad range of both topics and materials was covered in these presentations, with a strong focus on theoretical studies. Considerable interest remains in aspects of superconductivity amongst the high-Tc ceramics as evidenced by six contributed oral presentations and four posters, representing this research area.

From the diversity of topics, one did not envy those who had been assigned the task of selecting the oral and poster presentations by post-graduate students for the usual "Wagga" awards which were as follows:

Oral Presentations Awards:

"Magnetic ordering in superconducting sandwiches" by Andrew Chan (University of Auckland); and

"Anomalous spectral broadening from an infrared catastrophe in 2D quantum antiferromagnets" by Matthew O'Brien (University of New South Wales).

Post-graduate student award winners; (L to R): Sneh Patel, Andrew Chan, Matthew O'Brien and Henry Nourse. (Picture courtesy of Glen Stewart.)

Figure 3: Most of the "Wagga" 2020 delegates. (Picture courtesy of Tilo Söhnel.)

Poster Awards:

> "Substitutional doping of trirutiline phases, AB_2O_6" by Sneh Patel (University of Auckland); and
>
> "A menagerie of strongly correlated phases on the decorated honeycomb lattice" by Henry Nourse (University of Queensland).

The passing of three significant contributors to the "Wagga" conference series, within the previous year, namely, Dr. Ralph Severin (Sev) Crisp (1933-2019), Dr. Eric Raymond (Lou) Vance (1942-2019) and Professor Geoffrey (Geoff) Victor Herbert Wilson (1938-2020), was acknowledged through three Tribute Presentations by Trevor Finlayson, (University of Melbourne), Dan Gregg (ANSTO) and Glen Stewart (University of NSW (Canberra), respectively. Contributions to "Waggas" by Sev Crisp were from 1982 to 1994 while he was an academic at the University of Western Australia. Contributions by Lou Vance were throughout his employment at ANSTO on the Synroc Project (1989 to 2018). Geoff Wilson's contributions to "Waggas" were from the beginning in 1977 to 1990, during his time initially as Professor of Physics at the UNSW Faculty of Military Studies, Royal Military College, Duntroon, and later as inaugural Rector of the Military College, Australian Defence Force Academy.

"Wagga" Social Interactions

Another "Wagga" tradition, the Trivia Night, had been arranged by the Organising Committee with the author as "Trivia Master" and with Glen Stewart and Wayne Hutchison as completely impartial "Trivia Judges." Question Sets covered topics such as Geography, Sport, Music, Trivial Science, "What Happened in 2019", Favourite Foodstuffs and "A Few Bits of General Knowledge for Aussies and Kiwis". The winning team, "Meme Lords", secured the coveted Lindsay Davis Cup (or at least a picture of the cup, given that the real award was back in Australia) by the narrowest of margins, 92 points to 91, from rivals, "Poke People", out of a possible 140.

For the record, the "Meme Lords" team who were Simon Granville, (Victoria University of Wellington), Dana Goodacre, Sneh Patel, Mark Smith, Tilo Söhnel, and Huihua Zhoa (University of Auckland), Gabrielle Motta, (Queensland University of Technology), and Sebastian Wolf, (University of Melbourne), is pictured in Figure 2.

A Conference Dinner was again an aspect of the Conference, programmed for the Thursday night. The after-dinner speaker was Professor Joe Trodahl from Victoria University of Wellington, who summarised his "Wagga" experiences with a focus on those conferences which have been organised at various venues by New Zealand committees. The first three of these, 1980, 1984

Figure 2: The winning Trivia team, "Meme Lords", proudly displaying their picture of the coveted, Lindsay Davis Cup. (Picture courtesy of Glen Stewart.)

and 1987, and subsequently 1997, were held on Pakatoa Island, in Waitemata Harbour off Auckland. Hanmer Springs, in the hills west of Christchurch and also noted as a respite centre for New Zealanders suffering problems from alcoholism, was the venue for the 1992 "Wagga". Some years then passed before a group chaired by Joe himself, organised a most memorable "Wagga" at Portage, in the beautiful area of Marlborough Sound. There was then another significant delay, before Tilo Söhnel offered to host two "Wagga" conferences, 2010 and 2014, on Waiheke Island, in a residential conference centre just a 40-minute ferry trip from down-town Auckland. Also, as has become a social custom for recent "Waggas", a conference photograph was taken, shown in Figure 3. Two particular "old Wagga-ites" were missing from this photograph, since they were deep in discussion about high-Tc superconductivity at the time of the photograph, so they were captured in an image with "Wagga" 2020 Chairman, Philip Brydon, slightly later (Figure 4).

Sponsorship

A group of sponsors for "Wagga" 2020, some of whom are regular supporters of this conference, should be acknowledged. These were: Ezzi Vision, Nano Vacuum, Scitek and AXT Pty. Ltd., as well as the Centre for Quantum Science (University of Otago), the School of Chemical Sciences (University of Auckland), and ANSTO. Several of these sponsors exhibited during the conference within the same room adjacent to the lecture room, where the posters were exhibited throughout the conference. This provided many opportunities for interactions between delegates and sponsors, so it is hoped that the time of the sponsors who were also exhibiters was worthwhile.

Concluding Comments

The Organising Committee, Dr Philip Brydon (University of Otago), Professor Tilo Söhnel and Dr Ben Mallett (University of Auckland), should be acknowledged for another most-successful, NZ "Wagga".

For anyone interested, a pictorial record of "Wagga" 2020 (courtesy of Glen Stewart) is available on the CMM website (cmm-group.com.au) which can be conveniently accessed via the website of the Australian Institute of Physics (aip.org.au) and under the "Branches and Groups" menu item.

The 45th "Wagga" Conference will return to its traditional "home", Charles Sturt University (CSU) Conference Centre, Wagga Wagga, N.S.W. and Professors Michael Cortie (University of Technology, Sydney) and Chris Ling (University of Sydney) have offered to organise the conference. Unfortunately, on account of COVID-19 restrictions, the Events Management at CSU have indicated that the Centre will not be available in time, to enable a residential conference to be held in the first week of February, 2021. Hence, while Michael and Chris will organise the **45th "Wagga" conference, it will be held at the CSU Conference Centre from Tuesday, 1st February to Friday, 4th February, 2022.** Let us hope that the current COVID-19 restrictions will have ended and interested Condensed Matter Physicists will again be able to gather together to discuss their latest results.

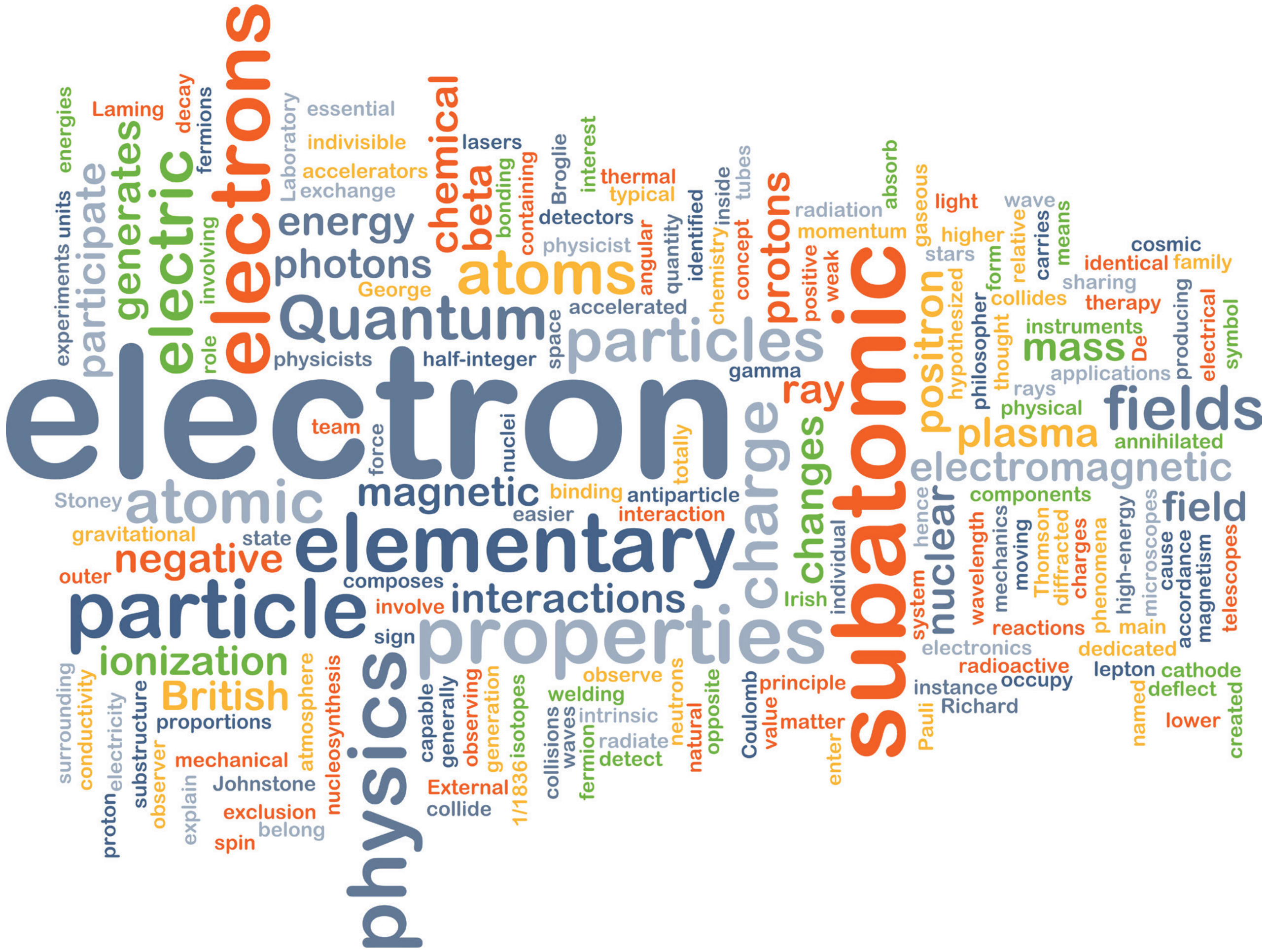
Figure 4: (L>R): "Wagga" 2020 Chair, Dr Philip Brydon, the Author and Professor Jeffrey Tallon, missing from the Conference Photograph. (Picture courtesy of Tilo Söhnel.)

About the Author

Trevor Finlayson is an Honorary Principal Fellow at The University of Melbourne. He was an academic at Monash University, Clayton, Victoria, for 35 years where he was responsible for the introduction and teaching of Materials Science as well as various courses in Physics. His research has embraced several aspects of Condensed Matter Physics/Materials Science and he has been in his current position at The University of Melbourne for the past 14 years. He has been a supporter of the "Wagga" conference series since its inception in 1977 and, with the exception of a few "Waggas" when he was on sabbatical leave/outside studies programmes, he has attended all of them.

The Young Physicist and names - Part 2

Last time we looked at ways that words are used differently in everyday life, compared to when we are working in physics. Let's explore this theme further by thinking about some physics 'concepts'. That is, scientific ideas which we want to help someone else understand through words.



Language is our uniquely human way of communicating thought and ideas. When we talk or write we want others to understand concepts that are dreamed up by our wonderfully sophisticated brains. That's how humankind makes progress. It's true to say we all think differently, but there are some ways of thinking that we share. If we know the way that others think, we may be able to short-cut long and detailed explanations, replacing them with much shorter descriptions. For concepts encountered in everyday life it is often not necessary to go into detail. When talking about Physics, though, it might be different. I will give you an example. At my school our physics teacher introduced the class to computer language, by asking us to write down a program for how we would get to school by car. Since we were all familiar with cars and how to drive them, talking to our classmates all we needed to say is we 'My Mum/Dad drove me from home to school'. No need for much more. We knew what a car looks like, roughly how it works, what is does, and who our Mum and Dad were. Our teacher then asked: now suppose we were telling this to a young robot friend. The robot knows simple things, and how to move its arms and legs, but it has no idea about cars, or driving. You might like to think about the words you would use to explain this to your robot friend. I think you will end up writing pages and pages of instructions. This shows how concepts that are simple for some humans, can require large amounts of explanation and extra understanding, when they are not part of our life experience.

Science in general, and Physics in particular, is a wonderful source of out-of-the-ordinary concepts.

Often our thoughts move away from everyday life, and concentrate on the universe. We move away from common human experiences to concepts that are way beyond that experience, but not our imaginations. These concepts can be very strange and hard to understand at first. A good example might be ideas about the very large (for example cosmology) or the very small (for example particle physics). To describe these concepts to others we need to use language in a more disciplined way. We must not assume that others will understand the words we use in the same way Physicists would do. That is unless we have explained them in some detail first.

Let's think of an example. The idea that matter is made up of extremely small, indivisible atoms is very old. It goes back over 2500 years to the famous Greek philosopher Democritus. He used the word 'atom' – meaning 'uncuttable', to describe the smallest components of the universe. Now remember that philosophy is the practice of thinking deeply about things and is therefore closely related to science. In fact, as you pursue your scientific career towards research you may earn a degree called a PhD. This is short for Doctor of Philosophy, a traditional naming showing how closely related science and philosophy were, and still are.

It was not until some 2,200 years after the birth of Democritus that scientists came up with evidence that atoms really exist. Observations made of how matter behaved gave clues that there are several distinct types of atoms. We now call these materials made of single atoms the 'elements'. As you might expect this is an old word. Starting in ancient Greek and Latin, then adopted in old French. As more elements were discovered they were given names. The names of places, names from mythology, and of course the names of scientist who made the discovery, or who were honoured. Perhaps you could do some research and find where the name of some elements names comes from. (Try Selenium and Tellurium to start with ☺)

Here's a fun thought. What would happen if we asked this question about technical versus everyday words the other way around. That is: how would a thinking computer tell us about its own marvellous thoughts. We are not as far away from having this problem as you might think. You may have heard of Deep Learning. Humankind has created artificial neural networks, used in Artificial Intelligence (AI) systems. These are special computers, or computer programs that work in a similar way to the network of cells (neurons) in our brains. Neural networks learn from their creator what is right and wrong, and the subtleties in between; just as we do from our parents and teachers. People have taught them to do amazing things like recognise faces or diagnose disease. However, the way neural networks use their learning is not fully understood. It's true to say even the inventors of these networks don't understand how they make the decisions they do. We may even have to invent new words to understand and describe this learning.

One of my favourite science fiction authors Douglas Adams once wrote a story about this idea. He imagined a huge thinking computer invented by really intelligent beings of the future (which turned out to look like white mice). The computer's name was Deep Thought, and its programmers set it about using it to answer the biggest question of all. The question of Life, the Universe, and Everything. After seven and a half million years of computing is came up with the answer. The computer said 'You're not going to like this, but the answer is: 42'. So next time you want to explain physics to someone who is not a young physicist, make sure you use your words clearly.

#PhysicsGotMeHere

Phil Dooley
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This occasional column highlights people who have a qualification in physics but are in roles we might not traditionally associate with physicists. The information is drawn from the 'Hidden Physicists' section of the AIP e-bulletin.

I'm a freelance science communicator and trainer with a secret ambition to inspire scientists to wow the world with creative communication! Or at least competent communication. The rise of pseudo-science and pseudo-experts has appalled me, so I feel that, as a community, we scientists need to get on the front foot by doing something pretty different.

That different thing for me is a science-theatre collaboration, called Dramatis Scientificae. I set this up with a couple of friends who are career writers/directors/actors. We're making science shows, skits, music and interviews that feature real scientists alongside our comedic characters. The foremost goal is to entertain, but in the process we can come from different angles, and ask awkward questions that degenerate conversations that others might shy away from. We've got to break the science education mould, the obsession with always teaching people when we talk to them. Over the last 20 years we've effectively proven that this approach (the deficit model – if you haven't heard of it look it up!) doesn't work– just look at the climate change debacle.

Only problem so far is funding… there are only so many Science Week grants we can win so I do paid work too (we've also started a Patreon account – here's your chance to be our first supporter!). I run pub events, write for Cosmos, American Physical Society, and Nature, (recently selected for The Anthology of Best Australian Science Writing for the third time in a row) and run training courses for scientists, alongside some casual work for ANU Physics.

My career started with a PhD in laser physics at ANU, from which I ran screaming! I was burnt out, and my new wife wanted to do Australian Volunteers Abroad. She's an environmentalist, and we ended up in Rarotonga, where I picked up IT work in the local bank. It was part time, which was perfect, as it allowed me to follow my dream of turning my years of classical piano into being a rock star. The resulting album was, if I'm honest pretty bad, but I'm still proud of it.

Coming back to Australia I decided to try to get rich, working in IT – ending up in software training – while joining bands that somehow never got anywhere.

In 2004 my parents both died, which prompted me to realise that I really missed science. I started following leads to get into science communication – such as joining the Australian Science Communicators, which gave me all kinds of amazing connections. I'm now on the national committee and still love the get-togethers for conferences and the inspiration that comes from it.

I scored a job running the outreach programs at Sydney Uni Physics, and then landed a job in UK, doing comms at the current biggest fusion experiment, JET. Not only was it an amazing science experience, but the UK science communication

scene blew my mind – when I saw a guy called Dr Mark Lewney play Bohemian Rhapsody on electric guitar while the crowd sang quantum mechanics words I was blown away.

Since coming back to Australia I've taken up Dr Lewney's mantle – I love performing, so I've organised Science in the Pub gigs with AIP and other institutions in Canberra, Sydney Melbourne, Brisbane and Adelaide – getting scientists up on stage too, doing something fun themselves. (Stay tuned for the video of my rap song about Schrodinger's Cat.) My day job at this time was in the ANU media office, working for a former journalist with 30 years of experience. It was hell in many ways, but cheese, I learned a lot, writing 300 press releases, on everything from Alzheimer's disease to the discovery of gravitational waves.

Then I reconnected with my old friend Patrick, who'd pursued a career in the theatre and TV. I told him about my quest to change the way scientists engage, and next thing I knew, he and his wife had written a play and I was just about to step onstage as an actor for the first time in my life. That play, The Poet's Guide to Science, featured scientists as part of the narrative, conversing with the characters about 'controversial' research, such as GM, vaccines or climate science, and we knew we were on to something. We've since taken it to the Sydney and Adelaide Fringe Festivals (and had it rejected by Sydney Science Festival!)

Of course, with COVID the live gigs have dried up, so to get the truly global audience that scientists deserve we need the internet. I've now done my first film shoot with a crew and we streamed our first chat show during Science Week 2020. Our show focussed on women scientists' adventures, featuring online interviews, pre-recorded videos and live shenanigans onstage in Star Trek costumes. As a PhD graduate, I would not have expected that!

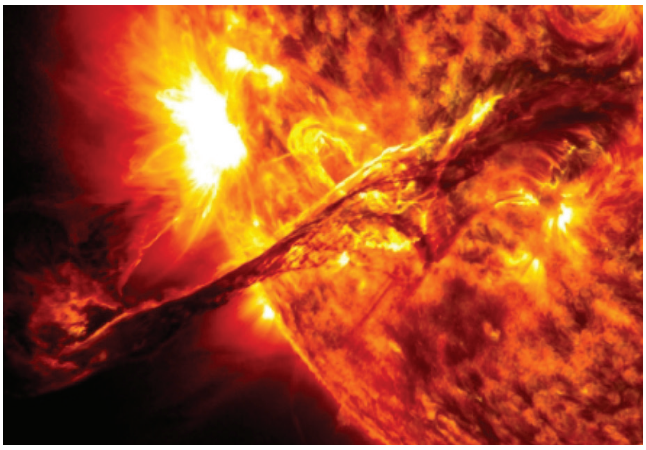
Physics around the world

Calculating the speed of coronal mass ejections could avoid unneeded satellite shutdown

Currently, many satellite operators adopt a "better safe than sorry" approach when responding to these coronal mass ejection (CME) forecasts. Whenever a CME is predicted to arrive, they will completely shut down their systems to avoid any damage. However, the Reading trio argue that these current early warning systems do not account for a simple yet crucial fact: while all solar storms are triggered by CMEs, not all CMEs cause damaging events.

Many false alarms

The researchers believe that this oversight is now causing many false alarms, forcing satellites to shut down when they can be operated safely. Furthermore, the cost of unneeded shutdowns could be even greater than the cost associated with solar storm damage. To improve the response to CMEs, the team suggest that alongside arrival times, it is just as important for CME forecasts to incorporate information about their speeds, and the intensities of their accompanying magnetic fields – both key indicators of solar storm severity.



Reaching out: a huge coronal mass ejection that was spotted in 2012 by the ESA/NASA Solar Heliospheric Observatory. (Courtesy: NASA/Goddard Space Flight Center)

Owens and colleagues tested this principle through a simple analysis of solar wind data, in which they calculated the costs of shutting down satellite systems only when CME speed and magnetic field measurements indicated that damaging weather was about to occur. Compared with more frequent shutdowns which only considered CME arrival times, they found that the resulting costs were significantly reduced.

By quantifying the costs of false alarms in this way, the team's findings could inform more sophisticated approaches to mitigating the damage of solar storms in the future.

(extracted with permission from item by Sam Jarmin at physicsworld.com)

Rocky icebergs and deep anchors – new research on how planetary forces shape the Earth's surface

View of Mt Cook/Aoraki, rising 3724m above sea level at the head of Lake Pukaki in New Zealand's South Island. The mountain is underlain by crust about 45km thick. (Courtesy: Pixabay, CC0 1.0)

Have you ever wondered why the Earth's surface is separated into two distinct worlds – the oceans and large tracts of land? Why aren't land and water more mixed up, forming a landscape of lakes? And why is most of the land relatively low and close to sea level, making coastal regions vulnerable to rising seas? Our new research uncovers the fundamental forces that control the Earth's surface. These findings will help scientists calculate how land levels will respond to the melting of ice sheets and rises in sea level, as a consequence of global warming, as well as providing insights into changes in land area throughout our planet's history.

Rocky icebergs

The research draws on the work by an inspiring early geologist. In 1855, the British Astronomer Royal George Biddell Airy published what is arguably one of the most important scientific papers in the earth sciences, setting out the basic understanding of what controls the elevation of the planet's surface.

Airy was aware the shape of the Earth is very similar to a spinning fluid ball, distorted by the forces of rotation so that it bulges slightly at the equator and flattens at the poles. He concluded the interior of the Earth must be fluid-like.

His measurements of the force of gravity in mine shafts showed the deep interior of the Earth must be much denser than the shallow parts. Airy then made an extraordinary leap of scientific thinking. He proposed that the outer part of the Earth, which he called the crust, must be floating on underlying "fluid". An analogy might be an iceberg floating in water — to rise above the surface, the iceberg must have deep icy roots.

Applying the same principle to the Earth, Airy proposed the Earth's crust also had iceberg-like roots, and the higher the surface elevation, the deeper these roots must be, creating thicker crust. Airy's idea provided a fundamental explanation for continents and oceans. They were regions of thick and thin crust respectively. High mountain ranges, such as the Himalaya or Andes, were underlain by even thicker crust.

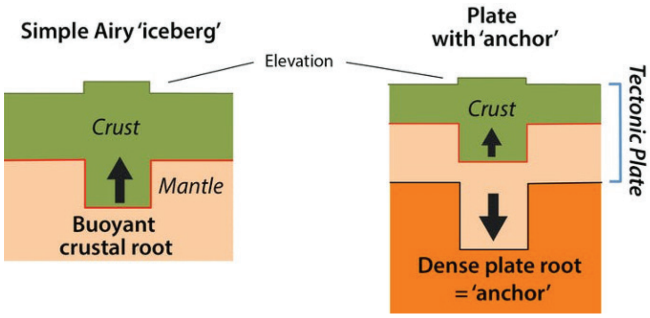
Tectonic plates

In the 1960s, the new theory of plate tectonics introduced a complication. It added the concept of tectonic plates, which are colder and denser than the deeper mantle (the geological layer beneath the crust). Over the past two decades, geophysicists have finally put together an accurate picture of the crust in the continents.

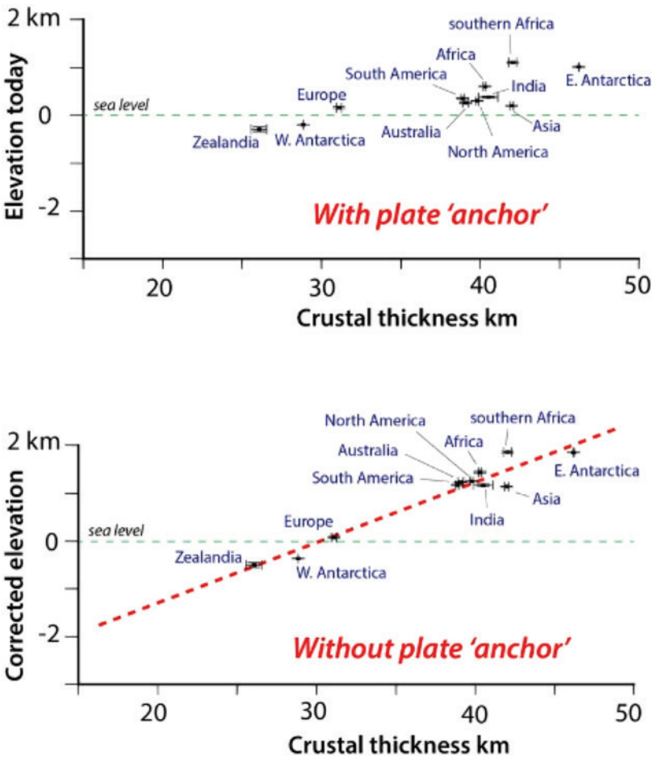
We found a surprising result – there seems to be little relation between the average elevations of the continents and the thickness of the underlying crust, except that the crust is much thicker than beneath the oceans. Most of the land area is within a few hundred metres of sea level, yet the thickness of the crust varies by more than 20km.

So why don't we see the differences in crustal thickness below a continent reflected in its shape above? Our research shows the underlying thick tectonic plate is acting as an anchor, keeping the elevations relatively low even though the buoyant crust wants to rise higher.

We used measurements of the thickness of the tectonic plates, recently determined from the speed of seismic waves. The base of the continental plates reaches up to 250 km deep, but most is between 100 km and 200 km deep. We also worked out the densities of the different layers from variations in the strength of gravity. It was clear that the dense roots of the plates were capable of pulling down the surface of the Earth in exactly the way needed to explain the actual elevations.



Airy imagined the crust as a rocky iceberg with buoyant roots holding up the surface. Plate tectonics adds a dense root of the plate that acts as an anchor. (Courtesy: Simon Lamb, Author provided)



The average elevations of the continents are surprisingly insensitive to their average crustal thicknesses, contrary to Airy's prediction that they float on the underlying mantle like rocky 'icebergs'. If the effect of the deep 'anchor' of the underlying dense root to the plates is removed, the continents bob up, floating as the iceberg principle would predict, with a straight-line relation between crustal thickness and elevation. (Courtesy: Simon Lamb, Author provided)

Europe and Asia have very similar average elevations of around 175 m above sea level. In Asia, both the crust and tectonic plate are thicker than underneath the European continent, but the weight of the extra thickness balances the tendency for the thicker crust to rise up.

A balance of planetary forces

But why is there so much land close to sea level? The answer is erosion. Over geological time, major rivers wear away the landscape, carrying rock fragments to the sea. In this way, rivers will always reduce the continents to an elevation close to sea level.

East Antarctica is the exception that proves the rule. It has been close to the South Pole for hundreds of millions of years, with a climate too cold for large rivers to significantly erode the landscape.

(extracted with permission from an item by A/Prof Simon Lamb at theconversation.com)

Positronium formed during PET scans could detect hypoxic tumours

A variation on positron emission tomography (PET) offers a new way to diagnose hypoxia in tumours. Researchers at the University of Tokyo and Japan's National Institute of Radiological Sciences demonstrated that positronium, which forms in tissues due to positron emission from a radiopharmaceutical agent, decays differently depending upon its chemical environment, and is especially sensitive to local oxygen saturation. This means that signs of tumour hypoxia could be spotted among the gamma rays collected routinely during PET imaging, providing clinicians with an additional source of information to guide treatment decisions.

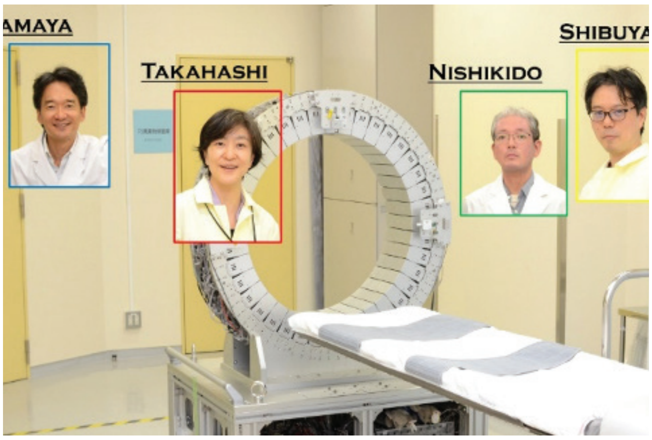
Most positrons created during a PET scan are annihilated almost as soon as they are emitted: they lose energy through interactions with nearby molecules, then collide with electrons in those molecules to produce pairs of 511 keV photons. Some positrons hang around a little longer, however, and instead of annihilating the electrons that they encounter, they capture them, forming metastable positronium atoms.

When this happens, the positronium is created in one of two distinct configurations. The least stable is para-positronium (p-Ps), in which the spins of the electron and positron point in opposite directions. p-Ps atoms have a mean lifetime of only 125 ps, after which they decay into a pair of 511 keV photons. This process therefore adds to the near-immediate gamma signal produced by annihilation of those positrons that never form a positronium atom.

The other configuration is ortho-positronium (o-Ps), in which the spins of the electron and positron are parallel. Left alone, o-Ps would decay into three photons (with energies ranging from 0 to 511 keV) after a mean lifetime of 142 ns. This much longer period means that o-Ps atoms have more time to interact with their surroundings before they decay.

One of the routes open to o-Ps atoms is an interaction called spin exchange. In this process, the positronium's electron switches with an electron of opposite spin in a nearby molecule. This converts the positronium atom into the less stable p-Ps form, hastening its decay.

The likelihood of spin exchange occurring depends on the availability of unpaired electrons in the vicinity of the o-Ps atoms. In tissues, such unpaired electrons are present primarily in oxygen molecules. This means that in oxygen-poor environments such as hypoxic tumours, more o-Ps atoms survive long enough to decay via the three-photon route. Measuring the timing and spectrum of the gamma rays emitted during the PET procedure should, therefore, yield information about the oxygen saturation.



Researchers in Japan aim to use PET scans to detect oxygen concentrations in tumours, which may lead to more effective cancer treatment. From left to right: Taiga Yamaya, Miwako Takahashi, Fumihiko Nishikido and Kengo Shibuya. (Courtesty: Taiga Yamaya, CC BY 4.0)

As they report in *Communications Physics*, Kengo Shibuya and colleagues tested this principle by preparing samples of water saturated with either air, nitrogen or oxygen. Each sample also contained the unstable sodium isotope ^{22}Na.

When ^{22}Na undergoes beta decay, it simultaneously emits a high-energy gamma ray at 1.27 MeV. The researchers used this signal as the starter pistol for each measurement. In instances where the positron emission resulted in a positronium atom, the end of the measurement was marked by the detection of sub-511-keV photons announcing the positronium's final decay.

By comparing the timing and energy of the photons emitted during millions of measurement intervals for the three samples, the team derived a linear relationship between oxygen saturation and positronium decay rate. They calculated that, in a clinical PET scanner, an acquisition time of around 30 min would yield enough measurements to distinguish a hypoxic tumour from normally oxygenated healthy tissue.
(extracted with permission from item by Marric Stephens at physicsworld.com)

Electrocaloric devices show potential for greener air conditioning

Staying cool: the new electrocaloric device show potential for air conditioning. (Courtesy: iStock/KMNPhoto)

Ever-growing in their use, air conditioning systems use refrigerants that are powerful greenhouse gases. But independent teams in Europe and the US reckon they may have found a more environmentally friendly way to keep cool by using electricity to soak up heat by controlling the entropy of ceramic "electrocaloric" materials. They have shown how to increase the cooling power of the technique and say it could become competitive with conventional vapour-compression cooling systems.

Air conditioning currently consumes about 10% of the world's electricity and could use far more in the future – with cooling units projected to grow from 1.2 billion in 2018 to about 4.5 billion in 2050, according to the Rocky Mountain Institute. The hydrofluorocarbons often employed as the refrigerant in these systems are efficient and nonflammable, but they are also very potent greenhouse gases – trapping far more heat when released to the atmosphere than carbon dioxide.

Caloric materials can in principle do a similar job as these refrigerants while emitting no pollution. The idea is to pump heat from a cool room to the hot outdoors, not by alternately compressing and expanding a fluid but instead by raising and lowering the entropy of a material by controlling its elastic, magnetic or electrical properties. In the latter case, this means using electric fields to control the polarization of dipole moments within a dielectric material.

Promising start

Research on the electrocaloric effect in ceramics got off to a roaring start in the early 1990s when scientists at the Moscow Power Engineering Institute in Russia claimed they could support a temperature difference as high as 12.7 °C between heat source and heat bath. Not relying on large compressors, pumps or magnets, the work held the promise of efficient, cheap and environmentally friendly air conditioners. But transforming those results into practical devices has proved hard going, with material properties quite different in bulk components compared to the thin films used in labs.

New research from David Schwartz, Yunda Wang, and colleagues at PARC, part of Xerox in California, does not break any temperature records but does, they say, show how lab-scale devices could be scaled up. They have used a large-volume fabrication technique often employed in the electronics industry to produce a solid-state device from multi-layer ceramic capacitors. The capacitors, each just a few millimetres across and made from lead scandium tantalite, were supplied by Japanese company Murata Manufacturing.

The heart of the PARC device has two layers of multi-layer capacitors lined up between copper rails and separated by insulators. The upper layer contains five capacitors, while the lower one has four although it is capped by an aluminium heat sink at each end. An actuator moves the top layer left and right so that four of its capacitors are always aligned with those below, while the extra one at either end comes into and out of thermal contact with the heat sink below it.

The Brayton cycle

Schwartz and colleagues used their device to carry out many rounds of a thermodynamic Brayton cycle, with one of the heat sinks being progressively cooled while the other served as the external heat bath. Cooling takes place in the first stage, with heat flowing from the four capacitors and the cold sink below to the five capacitors above. Then in the second stage the top layer is moved, and the electric field applied, which lines up the dipoles and thereby reduces their entropy. In compensation, however, the vibrational entropy of the material's molecules goes up – resulting in an adiabatic temperature rise.

With the temperature of the upper layer now higher than that of the hot bath, the third stage sees the capacitor on the end dumping some of its heat into that sink. Finally, the electric field is turned off and the temperature of the upper layer drops below that of the lower, again adiabatically. The cycle then repeats.

Schwartz and co-workers found that when they applied an electric field of just over 10 MV/m, the capacitors underwent an adiabatic temperature rise (and fall) of 2.5 °C per cycle. With the cold sink slowly but steadily cooling over the course of about 100 cycles, they found that its temperature dropped by up 5.2 °C compared with the hot sink. They also measured a heat flux of 135 mWcm-2, which they say is more than four times higher than other electrocaloric cooling systems.

The researchers reckon that by adjusting the size and shape of their capacitors and making other tweaks to their system, they should be able to raise the heat pumping efficiency to over 50%. And that, they say, would make it "competitive with vapor compression cooling".

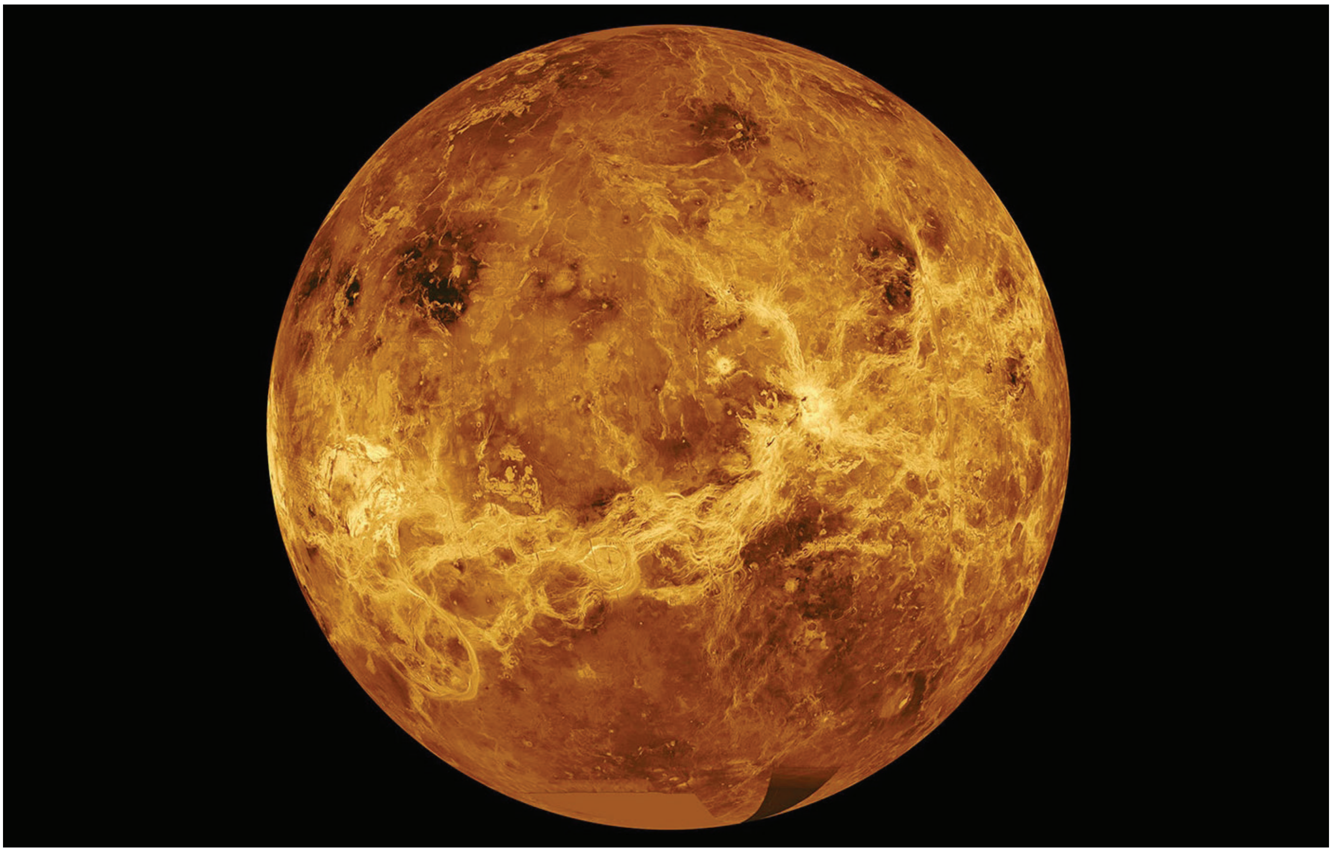
Much higher temperature differential

In fact, Emmanuel Defay, Alvar Torelló and colleagues at the Luxembourg Institute of Science and Technology in Luxembourg have achieved a much higher temperature differential of up to 13 °C in a slightly different system. They also used multi-layer capacitors made from lead scandium tantalate supplied by Murata but achieved greater cooling by sending a dielectric fluid back and forth through the (porous) caloric solid.

Venus: could it really harbour life? New study springs a surprise

Earth's sister planet, Venus, has not been regarded as a high priority in the search for life. Its surface temperature of around 450°C is thought to be hostile to even the hardiest of micro-organisms, and its thick, sulphurous and acidic atmosphere has kept the surface almost completely free from visiting spacecraft.

We have only had the briefest of glimpses of a barren landscape from the two Russian landers that made it



Surface of Venus; composite of data from NASA's Magellan spacecraft and Pioneer Venus Orbiter (image: NASA/JPL-Caltech).

down to the ground back in the 1980s. So it's no wonder that a report published in Nature Astronomy that the upper levels of Venus' atmosphere contain a molecule that is a potential signature of life, comes as something of a shock.

The molecule in question is PH_3 (phosphine). It is a highly reactive and flammable, extremely smelly toxic gas, found (among other places) in heaps of penguin dung and the bowels of badgers and fish. It is present in Earth's atmosphere in only trace quantities – less than around a few parts per trillion – because it is rapidly destroyed by the process of oxidation. The fact that this molecule is nevertheless present in our oxidising atmosphere is because it is continuously produced by microbes. So phosphine in the atmosphere of a rocky planet is proposed to be a strong signature for life.

It shouldn't be stable in the atmosphere of a planet like Venus where it would be rapidly oxidised unless, like on Earth, there is a constant new supply. So why were the authors of the study looking for phosphine in such an unpromising environment? And are they certain that they have found it?

Reading between the lines of the report, it seems that the team was not expecting to find phosphine. Indeed, they actively seemed to be looking for its absence. Venus was to supply the "baseline atmosphere" of a rocky planet, free from a phosphine biosignature. Scientists investigating rocky exoplanets would then be able to compare the atmospheres of these bodies with that of Venus, to identify any potential phosphine biosignature.

Detective work

So to find a global concentration of the molecule around 1,000 times higher than that of Earth was something of a surprise. In fact, it caused the authors to conduct one of the most detailed forensic dissections of their own data that I've seen.

The first set of data was acquired in June 2017 using the James Clerk Maxwell Telescope (JCMT) in Hawaii. It unambiguously indicated the presence of phosphine, so a second set of data was recorded, using a different instrument on a different telescope. These observations were taken in March 2019, at higher spectral resolution, using the Atacama Large Millimetre Array (ALMA) in Chile. The two datasets were almost indistinguishable. Phosphine is present in Venus' atmosphere, with a patchy distribution across the mid-latitudes, decreasing towards the poles.

(extracted with permission from an item by Professor Monica Grady at theconversation.com)

PRODUCT NEWS

Coherent

Next Generation NeoScope Benchtop SEM

The new NeoScope JCM-7000 from Jeol produces high magnification up to 100,000x with large depth of field. It features a large sample chamber, high and low vacuum modes, secondary and backscatter electron detectors, real-time 3D imaging, highly advanced auto functions and the option to add a fully-embedded EDS with real time “Live” Analysis.

The new JCM-7000 introduces the “Zeromag” function, enabling seamless transition from the colour optical image to an SEM image. This allows users to quickly focus on areas of interest, acquiring high resolution images instantly, along with live elemental analysis (EDS required). Such a function has previously only been available on full-sized SEM’s.

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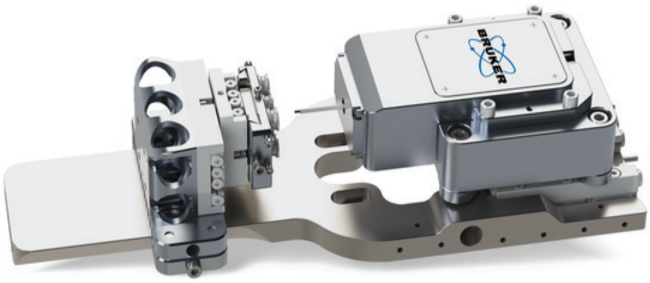
New ContourX Family of Optical Promfilometers

The ContourX family of optical profilometers uses numerous advances in Bruker’s white light interferometry technology to deliver the industry’s most capable benchtop metrology system with easy to use surface measurement software. Available in three models, the ContourX profilers feature new, robust design and provide a range of capabilities and price points optimised to match individual metrology and budget requirements.

New hardware features include an innovative stage design for larger stitching capabilities and a 5MP camera with a 1200 x 1000 measurement array for lower noise, larger field-of-view, and higher lateral resolution.

Next Generation In-Situ Nanomechanical Test Instrument

The Hysitron PI 89 SEM PicoIndenter leverages the advanced imaging capabilities of scanning electron microscopes (SEM, FIB/SEM), making it possible to perform quantitative nanomechanical testing while simultaneously imaging. Based upon Bruker’s leading-edge capacitive transducer technology, this new system is the next-generation descendant of the first commercial, market-leading in-situ SEM nanomechanics platforms. Throughout the years, the Hysitron brand has steadily expanded the range of PicoIndenter capabilities, and extended force and displacement ranges with patented xR transducer technology and other exclusive advances.



Innovative features of the PI 89 include the electrical characterisation module (ECM), Push-to-Pull (PTP) tension for thin films and nanowires, direct-pull tension, fatigue, rotation/tilt stage (patent), elevated temperature testing, and nanoscratch, making it the most comprehensive in-situ nanomechanical test instrument for SEM and FIB/SEM available today.

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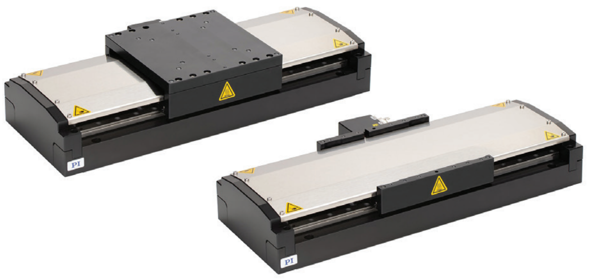
V-817 precision industrial automation stage

Physik Instrumente, a global leader in the design and manufacture of high precision motion control systems has launched the V-817 high load linear stage series.



The V-817 linear stages are specifically designed for industrial applications with high operating cycles: 3-phase linear motors with recirculating ball bearing guides offer constant loads up to 600 N and velocities up to 3000 mm/s.

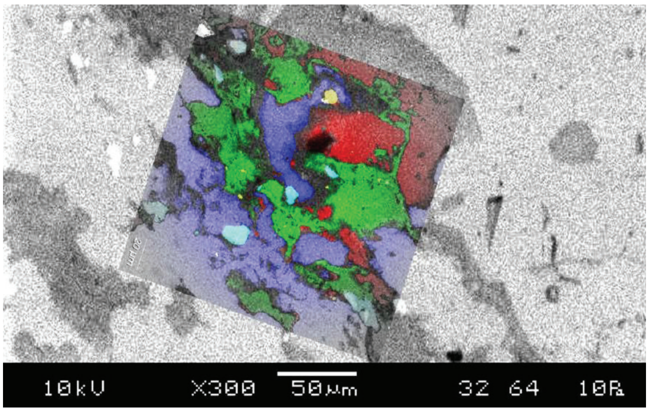
In addition, the incremental linear encoder with a resolution down to 0.3 nm ensures high path accuracy, minimum tracking errors, and short settling times. The calibrated positioning accuracy of the linear stages is up to ±2.5 µm. The travel range extends to 813 mm.

Image combining software for multiple microscopy techniques

Modern laboratories host a variety of different microscope systems which are usually used in isolation. Although they are often viewed separately, many of the techniques are complementary and can be used together to get a better interpretation of your sample. By overlaying images from multiple techniques, a deeper understanding and easier interpretation of multiple microscopy methods is possible.

Renishaw's Correlate software module is ideal for analytical scientists who want to combine Raman spectroscopic images with other imaging techniques. It enables the comparison of Raman results with other commonly used microscopes including SEM, fluorescence, AFM, Infra-Red and optical microscopes.

The Correlate module is available as part of the WiRE 5.3 software and can be used with the inVia™ confocal Raman microscope, the Virsa™ Raman Analyser and Renishaw RA800 series.



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AAPPS Bulletin

Volume 30 | Number 5 | OCTOBER 2020
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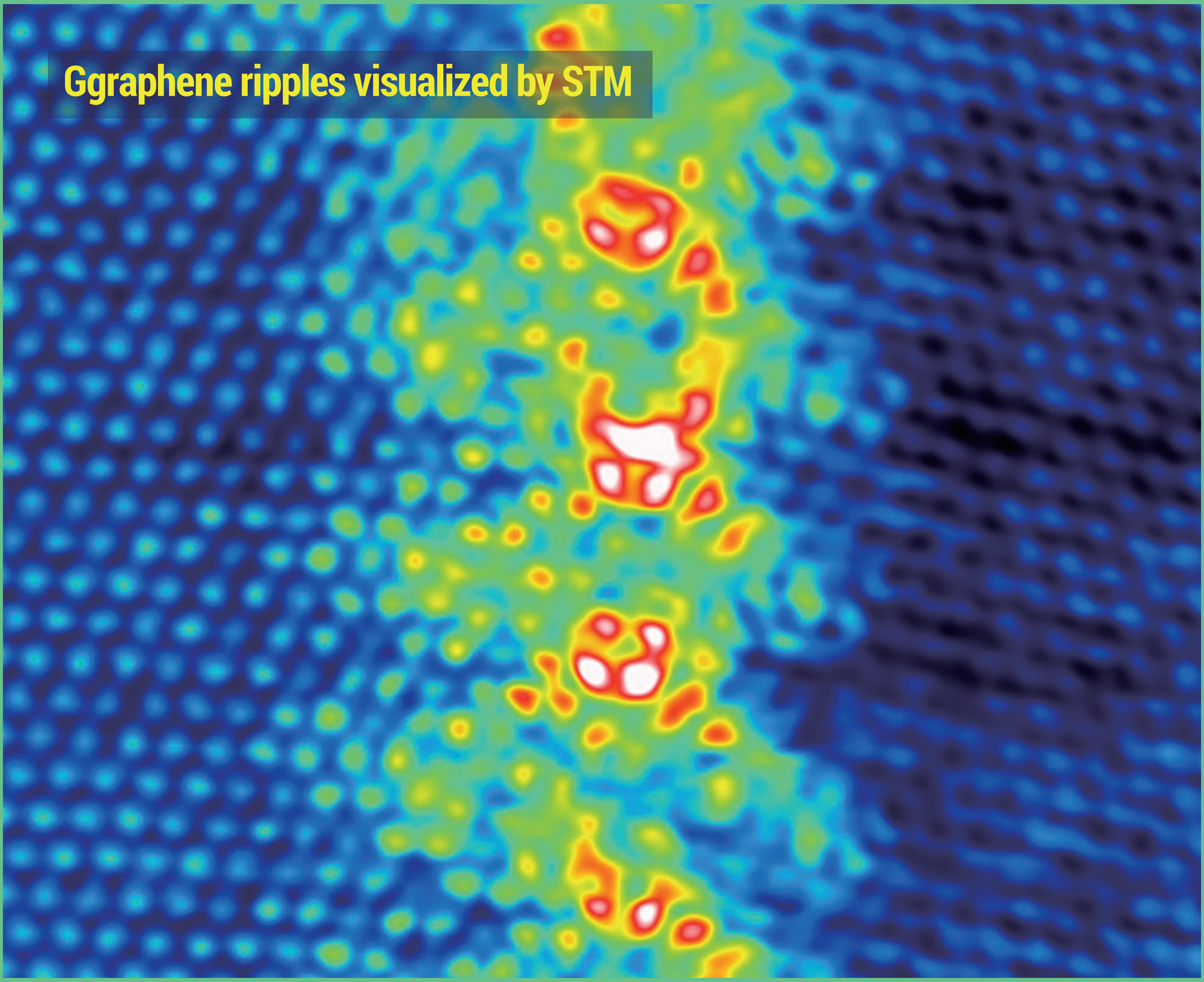
Ggraphene ripples visualized by STM

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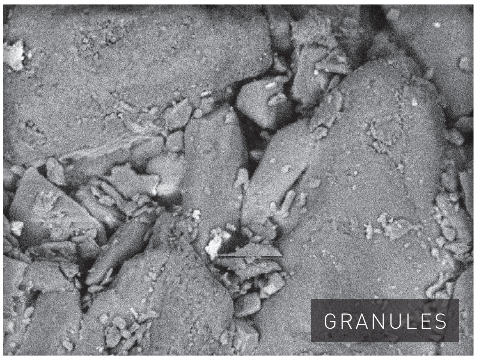
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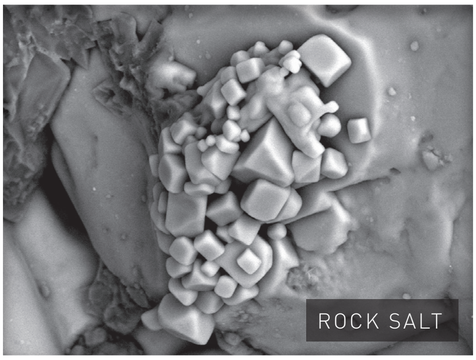
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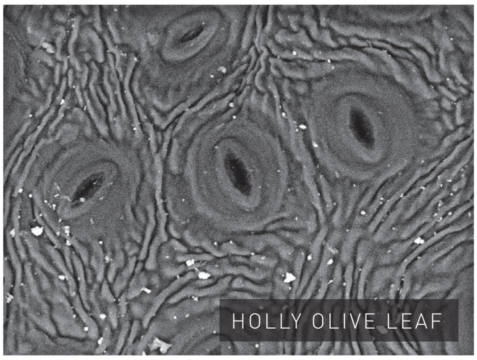
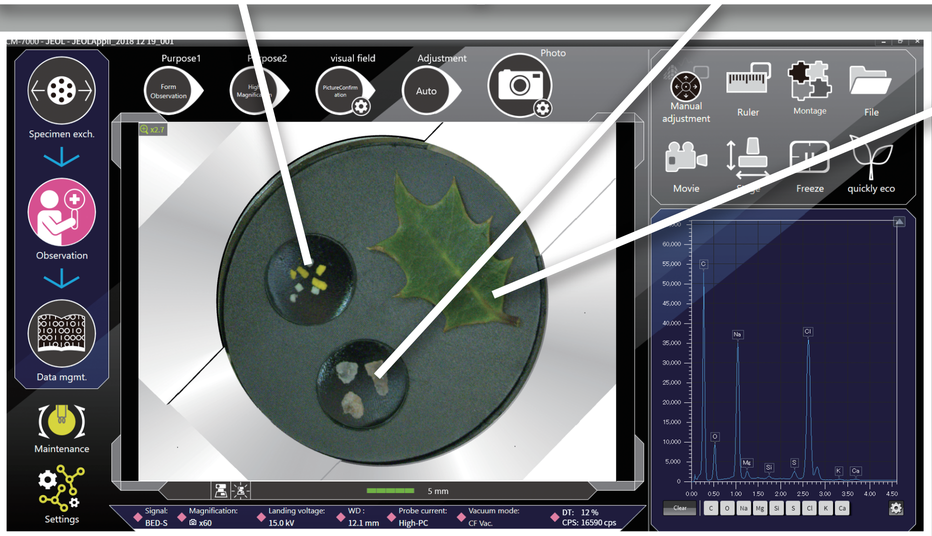

HOLLY OLIVE LEAF



Signal: BED-S
Magnification: x60
Landing voltage: 15.0 kV
WD : 12.1 mm
Probe current: High-PC
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