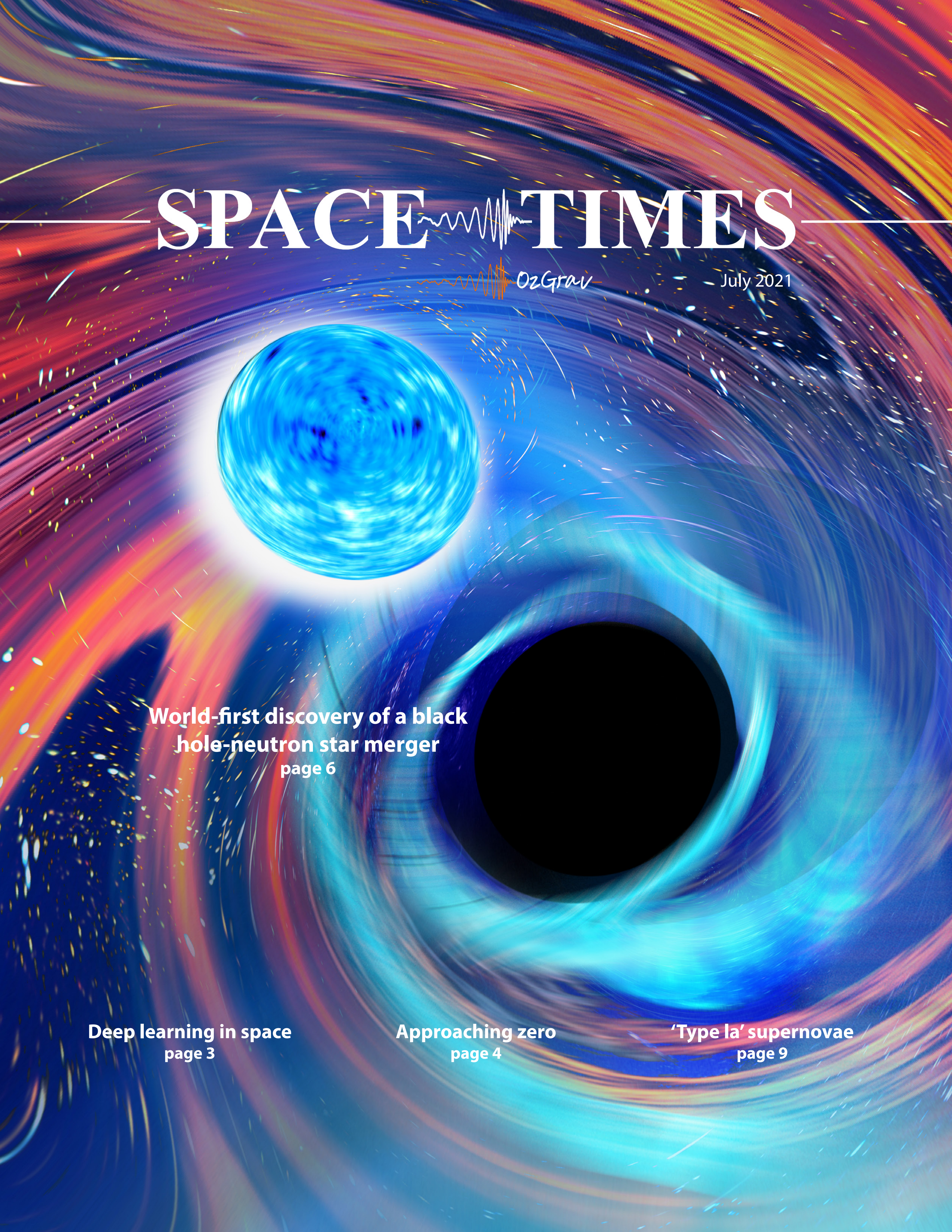

SPACE TIMES

OzGrav

July 2021

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Welcome

Welcome to another edition of Space Times!

Despite the latest round of lockdowns (groan) we've had some great outcomes since our last newsletter. Firstly, OzGrav received its official feedback from the mid-term review which was incredibly positive. Thanks to everyone for their help in the review process, especially those who fronted the panel and assisted with the written submission, led ably by Yeshe and her team, and to everyone who contributes to OzGrav on a daily basis.

Secondly, OzGrav ran a very successful online international conference "Amaldi 14" last week. It seemed to go without a hiccup, barring the odd "you're on mute" and some timezone mix-ups. I'm especially grateful to those who stepped in to chair the session I missed—I was queuing for a COVID test in country Victoria after fleeing South Australia at very short notice. Thanks to those on the SOC/LOC, speakers, participants, volunteers (especially those in the West doing the 11pm-1am shift) and to Erin and Yeshe. Team OzGrav wins again!

And finally, after an 8-month process led by Prof Tamara Davis, I was elected to lead a second OzGrav ARC Centre bid and we submitted the 100-page expression of interest last Wednesday. I was delighted by the final product and, win, lose or draw, I think we've given ourselves a great chance of getting to the final round of

Managed to visit the University of Adelaide OzGrav node between lockdowns last week, albeit briefly!

the process. I just want to acknowledge the many colleagues who I couldn't fit inside the Chief Investigator's "salary cap" and assure them that they'll be welcome to participate in OzGrav research if we're fortunate enough to gain a second Centre of Excellence.

On top of conferences and the bureaucracy that keeps OzGrav functioning, there's been some great science happening that you can read about in this issue.

Sincerely yours,
Matthew Bailes

P.S. My thoughts are with all of you affected by the lockdowns, especially those who suddenly find themselves with a second job as a school teacher.

NEWS IN BRIEF

- The European Strategy Forum on Research Infrastructures (ESFRI) has announced the 11 new Research Infrastructures in its Roadmap 2021, including the Einstein Telescope (ET). This confirms the relevance of this major international project for a next-generation gravitational waves observatory and gravitational wave research at a global level.
- The Gravitational Wave International Committee Reports on the Future Ground-based Observatories have been released. See here.
- OzGrav received very positive, useful feedback from our 2021 OzGrav member survey. While the final report is still being prepared, the data show that the overall experience of members of OzGrav is very positive, with 97% rating this as 'Good' or 'Excellent' (rising from 94% in 2019). The final report will be circulated to members soon, along with our action plan to address any areas for improvement.

Editor-in-chief: Luana Spadafora
Subscribe or submit your contributions to lspadafora@swin.edu.au

RESEARCH HIGHLIGHT

Extraction of binary black hole gravitational wave signals from detector data using deep learning

One of the major challenges involved in gravitational wave data analysis is accurately predicti properties of the progenitor black hole and neutron star systems from data recorded by LIGO and Virgo. The faint gravitational wave signals are obscured against the instrumental and terrestrial noise.

LIGO and Virgo use data analysis techniques that aim to minimise this noise with software that can 'gate' the data – removing parts of the data which are corrupted by sharp noise features, called 'glitches'. They also use methods that extract the pure gravitational-wave signal from noise altogether. However, these techniques are usually slow and computationally intensive; they're also potentially detrimental to multi-messenger astronomy efforts, since observation of electromagnetic counterparts of binary neutron star mergers—like short-gamma ray bursts—relies heavily on fast and accurate predictions of the sky direction and masses of the sources.

In our recent study, we've developed a deep learning model that can extract pure gravitational wave signals from detector data at faster speeds, with similar accuracy to the best conventional techniques. As opposed to traditional programming, which uses a set of instructions (or code) to perform, deep learning algorithms generate predictions by identifying patterns in data. These algorithms are realised by 'neural networks'—models inspired by the neurons in our brain and are 'trained' to generate almost accurate predictions on data almost instantly. The deep learning architecture we designed, called a 'denoising autoencoder', consists of two separate neural networks: the Encoder and the Decoder. The Encoder reduces the size of the noisy input signals and generates a compressed representation, encapsulating essential features of the pure signal. The Decoder 'learns' to reconstruct the pure signal from the compressed feature representation.

For the Encoder network, we've included a Convolutional Neural Network (CNN) which is widely used for image classification and computer vision tasks, so it's efficient at extracting distinctive features from data. For the Decoder network, we used a Long Short-Term Memory (LSTM) network—it learns to make future predictions from past time-series data.

Our CNN-LSTM model architecture successfully extracts pure gravitational wave signals from detector data for all ten binary-black hole gravitational wave signals detected by LIGO-Virgo during the first and second observation runs. It's the first deep learning-based model to obtain > 97% match between extracted signals and 'ground truth' signal 'templates' for all these detected events. Proven to be much faster than current techniques, our model can accurately extract a single gravitational wave signal from noise in less than a milli-second (compared to a few seconds by other methods).

The data analysis group of OzGrav-UWA is now using our CNN-LSTM model with other deep learning models to predict important gravitational wave source parameters, like the sky direction and 'chirp mass'. We're also working on generalising the model to accurately extract single signals from low-mass black hole binaries and neutron star binaries.

Written by OzGrav researcher Chayan Chatterjee, UWA.

Background image by Carl Knox, OzGrav-Swinburne University

OZGRAV IN THE MEDIA

Approaching zero: super-chilled mirrors edge towards the borders of gravity and quantum physics

The LIGO gravitational wave observatory in the United States is so sensitive to vibrations it can detect the tiny ripples in space-time called gravitational waves. These waves are caused by colliding black holes and other stellar cataclysms in distant galaxies, and they cause movements in the observatory much smaller than a proton.

Now we have used this sensitivity to effectively chill a 10-kilogram mass down to less than one billionth of a degree above absolute zero. Temperature is a measure of how much, and how fast, the atoms and molecules that surround us (and that we are made of) are moving. When objects cool down, their molecules move less.

"Absolute zero" is the point where atoms and molecules stop moving entirely. However, quantum mechanics says the complete absence of motion is not really possible (due to the uncertainty principle).

Instead, in quantum mechanics the temperature of absolute zero corresponds to a "motional ground state", which is the theoretical minimum amount of movement an object can have. The 10-kilogram mass in our experiment is about 10 trillion times heavier than the previous heaviest mass cooled to this kind of temperature, and it was cooled to nearly its motional ground state.

The work, published today in Science, is an important step in the ongoing quest to understand the gap between quantum mechanics — the strange science that rules the universe at very small scales — and the macroscopic world we see around us.

Plans are already under way to improve the experiment in more sensitive gravitational wave observatories of the future. The results may offer insight into the inconsistency between quantum mechanics and the theory of general relativity, which describes gravity and the behaviour of the universe at very large scales.

How it works

LIGO detects gravitational waves using lasers fired down long tunnels and bounced between two pairs of 40-kilogram mirrors, then combined to produce an interference pattern. Tiny changes in the distance between the mirrors show up as fluctuations in the laser intensity.

The motion of the four mirrors is controlled very precisely, to isolate them from any surrounding vibrations and even to compensate for the impact of the laser light bouncing off them.

This part may be hard to get your head around, but we can show mathematically that the differences in the motion of the four 40-kilogram mirrors is equivalent to the motion of a single 10-kilogram mirror. What this means is that the pattern of laser intensity changes we observe in this experiment is the same as what we would see from a single 10-kilogram mirror.

Although the temperature of the 10-kilogram mirror is defined by the motion of the atoms and molecules that make it up, we don't measure the motion of the individual molecules. Instead, and largely because it's how we measure gravitational waves, we measure the average motion of all the atoms (or the centre-of-mass motion).

There are at least as many ways the atoms can move as there are atoms, but we only measure one of those ways, and that particular dance move of all the atoms together is the only one we cooled.

The result is that while the four physical mirrors remain at room temperature and would be warm to the touch (if we let anyone touch them), the average motion of the 10-kilogram system is effectively at 0.77 nanokelvin, or less than one billionth of a degree above absolute zero.

Squeezed light

Our contribution to Advanced LIGO, as members of Australia's OzGrav gravitational wave research centre, was to design, install and test the "quantum squeezed light" system in the detector. This system creates and injects a specially engineered quantum field into the detector, making it more sensitive to the motion of the mirrors, and thus more sensitive to gravitational waves.

The squeezed light system uses a special kind of crystal to produce pairs of highly correlated or "entangled" photons, which reduce the amount of noise in the system.

What does it all mean?

Being able to observe one particular property of these mirrors approach a quantum ground state is a by-product of improving LIGO in the quest to do more and better gravitational wave astronomy, but it might also offer insights into the vexed question of quantum mechanics and gravity.

At very small scales, quantum mechanics allows many strange phenomena, such as objects being both waves and particles, or seemingly existing in two places at the same time. However, even though the macroscopic world we see is built from tiny objects that must obey quantum phenomena, we don't see these quantum effects at larger scales.

One theory about why this happens is the idea of decoherence. This suggests that heat and vibrations from a quantum system's surroundings disrupt its quantum state and make it behave like a familiar solid object.

In order to measure gravitational waves, LIGO is designed to not be affected by heat or vibrations from its surroundings, but LIGO test masses are heavy enough for gravity to be a possible cause of decoherence.

Despite a century of searching, we have no way to reconcile gravity and quantum mechanics. Experiments like this, especially if they can get even closer to the ground state, might yield insight into this puzzle.

As we improve LIGO over the next few years, we can re-do this quantum mechanics experiment and maybe see what happens when we cross over from the classical world into the quantum world with human-sized objects.

Written by OzGrav Chief Investigator David McClelland, OzGrav Associate Investigator Robert Ward and OzGrav Postdoctoral Researcher Terry McRae from the Australian National University. As featured in The Conversation, Cosmos Magazine and Science Mag.

UPCOMING AWARDS & PRIZES

- 2021 Victorian Prize for Science & Innovation. Closes 19 July. Not open to non-Aus citizens.
- 2021 Victoria Prize Fellowships - closes 26 July. Not open to non-Aus citizens.

UPCOMING EVENTS

- **National Science Week 2021** in August - see page 7.

AMALDI 14

OzGrav was honoured to host the 14th Edoardo Amaldi Conference on Gravitational Waves last week. Amaldi14 is the premier international meeting on gravitational wave science, and we were pleased to have over 500 participants from all across the globe at this year's virtual event. We have received positive feedback on both the scientific program and the logistical organisation, so well done team OzGrav!

Background image: One of the four Advanced LIGO 40-kg mirrors that are cooled near their quantum ground state. Danny Sellers / Caltech / MIT / LIGO Lab

Australian scientists lead milestone discovery of two neutron star-black hole collisions

An entirely new phenomenon in the Universe was revealed today: the death spiral and merger of the two most extreme objects in the Universe—a neutron star and a black hole. The observations were officially announced by the Laser Interferometer Gravitational-Wave Observatory (LIGO), in the US, and the Virgo gravitational-wave observatory in Italy. A milestone for gravitational-wave astronomy, the discovery will now allow researchers to further understand the nature of the space-time continuum and the building blocks of matter.

The first observation of the neutron star-black hole merger was made on 5th January 2020 when gravitational waves—tiny ripples in the fabric of space and time—were detected from the collision event by LIGO and Virgo. When masses collide in space, they shake the whole Universe, sending out gravitational waves, like ripples on the surface of a pond. Detailed analysis of the gravitational waves reveal that the neutron star was around twice as massive as the Sun, while the black hole was around nine times as massive as the Sun. The merger itself happened around a billion years ago before the first dinosaurs existed, but the gravitational waves only just reached Earth.

Remarkably, on 15th January 2020 another merger of a neutron star and a black hole was observed from gravitational waves. This neutron star and black hole also collided around a billion years ago, but it was slightly less massive: the neutron star was around one and a half times as massive as the Sun, while the black hole was around five and a half times as massive.

Dr. Rory Smith, an astrophysicist at the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) at Monash University, who co-led the international team of scientists in this discovery, explains: "It's an awesome milestone for the nascent field of gravitational-wave astronomy. Neutron stars merging with black holes are amongst the most extreme phenomena in the Universe. Observing these collisions opens up new avenues to learn about fundamental physics, as well as how stars are born, live and die."

Thousands of international scientists teamed up for this world-first detection, with Australia playing a leading role. "From the design and operation of the detector, to the analysis of data, Australian scientists are working at the frontiers of astronomy," adds Smith. The SPIIR pipeline, at the University of Western Australia (UWA)—Australia's only real-time gravitational-wave search pipeline—detected a neutron star-black hole event in real-time for the first time. SPIIR is one of five pipelines that alerts astronomers around the world within seconds of gravitational events, so they can try to catch the potential flash of light emitted when a neutron star is torn apart by its companion black hole.

The Zadko telescope, also based at UWA, was one of the Australian facilities that searched for a counterpart to the merger event and, despite a well-organised search, the team led by Dr. Bruce Gendre and Eloise Moore could not secure a localised source. "During the next observing run, many more of these events are expected, providing more opportunities for SPIIR to catch them in real-time, and for astronomers to observe the light from these extreme events," says OzGrav Postdoctoral Researcher Dr Fiona Panther (UWA).

Black holes and neutron stars are two of the most extreme objects ever observed in the Universe—they are born from exploding massive stars at the end of their lives. Typical neutron stars have a mass of one and a half times the mass of the Sun, but all of that mass is contained in an extremely dense star, about the size of a city. One teaspoon of a neutron star weighs as much as all of humanity.

"This is a confirmation of a long standing prediction from binary stellar evolution theory which predicted these systems should exist!" explains Dr Simon Stevenson, OzGrav Postdoctoral Researcher at Swinburne University of Technology.

This article is an extract from the original media release. Also featured on The Australian, , The Financial Review, The ABC, Channel 10 News, Cosmos Magazine and more.

National Science Week events!

- Sunday 15th August 1pm to 4:30pm - **Black Hole Sunday:** Additional activity during playzone session at Twisted Science Moorabbin (Melbourne).
- Wednesday 18th August from 6pm - **SciVR Live Talk** at Burnley Brewing (Melbourne): explore the virtual universe with Prof Alan Duffy and Dr Rebecca Allen, and try the new space beer. Ages 18+. (Bookings aren't open yet).

- Saturday 21st August 11am AEST / 10:30am ACST / 9am AWST - **SciVR livestream**. The Universe is waiting to be discovered. SciVR will take you on a hunt out to Mars and then into the universe, tracking explosive events as they occur with Alan Duffy and Rebecca Allen with live Q&A. Check online for a live viewing party near you (including UWA and ANU) and pick up a mini VR head-set, or watch from home.

- Come and join the fun at the 2021 **National Science Quiz**! Hosted by Charlie Pickering (previous host of The Project), the all-star panel of science communicators and scientists will battle it out for the National Science Quiz champions! If you're in Melbourne, grab your FREE ticket for the live filming here, otherwise catch the live stream on Thursday 19th August 6pm to 7pm AEST to win cash and prizes.

Background image by Carl Knox, OzGrav-Swinburne University

FACES OF OZGRAV

Sebastian Ng: Research fellow at the University of Adelaide OzGrav

Sebastian's research centres on the development of high-power, low-noise laser systems and the development of adaptive optics for thermal compensation of laser interferometers. Throughout his undergraduate study, Sebastian was fascinated by the size and complexity of the laser-based gravitational wave detectors. This contributed to his pursuit of a PhD in laser physics developing high-power holmium-doped fibre lasers.

Fortuitously, OzGrav began at the completion of Sebastian's PhD and he was hired to lead the University of Adelaide's investigation into 2μm laser sources for cryogenic silicon detectors. In this role, he developed fibre seed lasers and amplifiers in collaboration with the Defence Science and Technology (DST) Group while expanding his knowledge base into wavefront sensing, high precision material characterisation and the design and installation of hardware into LIGOs vacuum enclosure. He also received the opportunity to visit the Hanford observatory where he worked on the laser upgrade and assembly of a CO2 laser actuator for thermal compensation. OzGrav and his node leader granted Sebastian many other opportunities for professional development, including chairing Ozgrav's Quantum program, undergraduate lecturing and course design, and the oversight of a range of research themes throughout the OzGrav node at the University of Adelaide.

QuantX Labs, a start-up company based in Adelaide that specialises in ultra-precise timing solutions, recently approached Sebastian to lead the development of optical clocks for space-based Positioning Navigation and Timing (PNT) delivery. In negotiation with QuantX Labs and OzGrav, Sebastian will continue his supervision responsibilities and oversee laser development at the University of Adelaide, while also capitalising on the experience he has gained from his time at OzGrav within the industry sector. As part of QuantX Labs, Sebastian leads the team developing optical clock technology, as well as seeking new avenues for investment. A primary goal of the company is to simplify the transition from university project to commercial product.

RESEARCH HIGHLIGHT

Supernova explosions in active galactic nuclear discs

'Type Ia' supernovae involve an exploding white dwarf close to its Chandrasekhar mass. For this reason, type Ia supernova explosions have almost universal properties and are an excellent tool to estimate the distance to the explosion, like a cosmic distance ladder. Collapsing massive stars will form a different kind of supernova (type II) with more variable properties, but with comparable peak luminosities.

To date, the most luminous events occur in core-collapse supernovae in a gaseous environment, when the circumstellar medium near the explosion transforms the kinetic energy into radiation and thus increases the luminosity. The origin of the circumstellar material is usually the stellar wind from the massive star's outer layers as they're expelled prior to the explosion.

A natural question is how will type Ia supernovae look like in a dense gaseous environment? And what is the origin of the circumstellar medium in this case? Will they also be more luminous than their standard siblings? To address this question, OzGrav researchers Evgeni Grishin, Ryosuke Hirai, and Ilya Mandel, together with an international team of scientists, studied explosions in dense accretion discs around the central regions of active galactic nuclei. They constructed an analytical model which yields the peak luminosity and lightcurve for various initial conditions, such as the accretion disc properties, the mass of the supermassive black hole, and the location and internal properties of the explosion (e.g. initial energy, ejecta mass). The model also used suites of state-of-the-art radiation hydrodynamical simulations.

The explosion generates a shock wave within the circumstellar medium, which gradually propagates outward. Eventually, the shock wave reaches a shell that is optically thin enough, such that the photons can 'breakout'. The location of this breakout shell and the duration of the photon diffusion determine the lightcurve properties. If the amount of the circumstellar medium is much smaller than the ejecta mass, the lightcurves look very similar to type Ia supernovae. Conversely, a very massive circumstellar mass can choke the explosion and it will not be seen. The sweet spot lies somewhere in between, where the ejecta mass is roughly comparable to the amount of circumstellar material. In the latter case, the peak luminosity 100 times bigger than the standard type Ia Supernovae, which makes it one of the brightest supernova events to date.

The research paper describing this work was recently published in Monthly Notices of the Royal Astronomical Society. The luminous explosions may be observed in accretion discs of accretion rate, or in galaxies with smaller supermassive black hole masses where background active galactic nucleus activity will not hinder observations with advanced instruments.

Written by OzGrav researcher Evgeni Grishin, Monash University. Read the full research brief and Evgeni's poem explaining the underlying physical processes of photon diffusion and shock breakout.

Background image by Carl Knox, OzGrav-Swinburne University

OZGRAV IN THE MEDIA

ANU spin-off Liquid Instruments launches new hardware

MokuGo: an engineering lab in a backpack

From gravitational wave science to global technology company: Liquid Instruments is a Canberra start-up bringing NASA technology to the world. Liquid Instruments (LI) Pty Ltd, a spin-off company from the Australian National University (ANU), is revolutionising the $17b test and measurement market.

Test and Measurement devices are used by scientists and engineers to measure, generate and process the electronic signals that are fundamental to the photonics, semiconductor, aerospace and automotive industries. The LI team has raised more than $25M USD in Venture Capital investment, and now has more than 1000 users in 30 countries.

LI was founded by researchers from the gravitational wave group at ANU to commercialise advanced instrumentation technology derived from both ground and space-based gravity detectors. OzGrav Chief Investigator Daniel Shaddock (ANU), CEO of Liquid Instruments, began as an engineer at NASA's Jet Propulsion Laboratory in 2002, working on the Laser Interferometer Space Antenna (LISA), a joint project between NASA and the European Space Agency. The work on LISA's phasemeter was the genesis for forming Liquid Instruments.

LI CEO and OzGrav Investigator Prof Daniel Shaddock at the ANU launch.

LI's software-enabled hardware employs advanced digital signal processing to replace multiple pieces of conventional equipment at a fraction of the cost and with a drastically improved user experience. Their first product Moku:Lab provides the functionality of 12 instruments in one simple integrated unit.

On 23 June, the company launched two new hardware devices, the Moku:Go—an engineering lab in a backpack for education, and the Moku:Pro – a multi-GHz device for professional scientists and engineers. Lik the Moku:Lab, this revolutionary new hardware includes a suite of instruments with robust hardware features giving a breakthrough combination of performance and versatility.

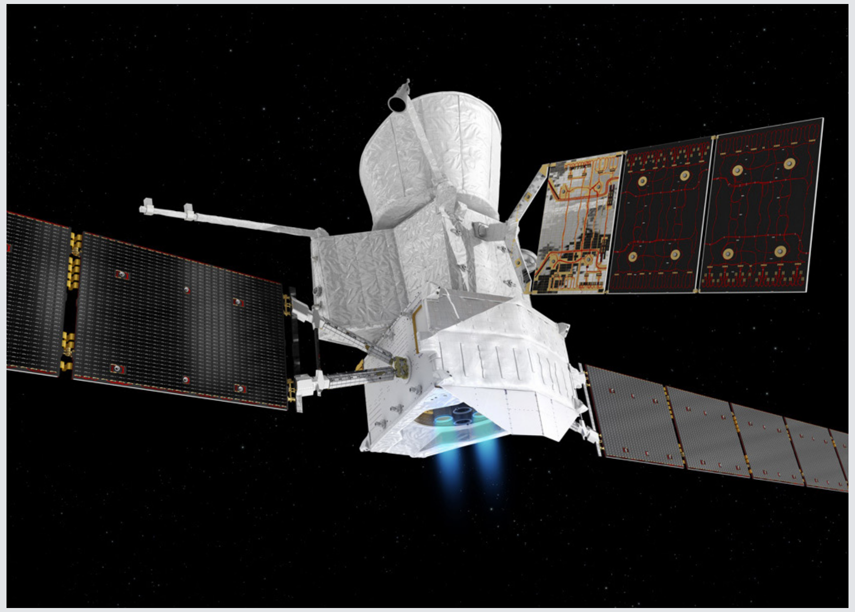
Daniel Shaddock says: "Moku:Pro takes software defined instrumentation to the next level with more than 10x improvements in many dimensions - it's a new weapon for scientists. Moku:Go takes all the great features of Moku:Lab but reduces the cost by 10x to make it more accessible than ever before. We hope it will help train the next generation of scientists and engineers in universities around the world."

The new Moku:Pro hardware with iPad user interface undergoing testing in the OzGrav lab at ANU.

Background image by Carl Knox, OzGrav-Swinburne University

Optical observations of BepiColombo as a proxy for a potential threatening asteroid

BepiColombo is a joint mission between the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) designed to study the planet Mercury. Launched in late 2018, its complex trajectory involved a fly-by past Earth on April 10, 2020. We took advantage of the event to organise a coordinated observing campaign. The main goal was to compute and compare the observed fly-by orbit properties with the values available from the Mission Control. The method we designed could then be improved for future observation campaigns targeting natural objects that may collide our planet.



An artist's impression of the ESA-JAXA BepiColombo spacecraft. Credit: ESA/ATG medialab

The incoming trajectory of the probe limited the ground-based observability to only a few hours, around the time when it was closest to Earth. The network of telescopes we used has been developed by ESA's NEO Coordination Centre (NEOCC) with capabilities to quickly observe imminent impactors, thus presenting similar orbits. Our team successfully acquired the target with various instruments such as the 6ROADS Chilean telescope, the 1.0 m Zadko telescope in Australia, the ISON network of telescopes, and the 1.2 m Kryoneri telescope in Corinthia, Greece.

The observations were difficult due to the object's extremely fast angular motion in the sky. At one point, the telescopes saw the probe covering twice the size of the moon in the sky each minute. This challenged the tracking capabilities and timing accuracy of the telescopes. Each telescope was moving at the predicted instantaneous speed of the target while taking images, "tracking" the spacecraft. Field stars appeared as trails, while BepiColombo itself was a point source, but only if the observation started exactly at the right moment. Because the probe was moving so fast, any date errors of the telescope images translate into position errors of the probe. To reach a precise measurement of 0.1 metres, the date of the images needed to have a precision of 100 milliseconds.

The final results were condensed into two measurable quantities that could be directly compared with the Mission Control ones, the perigee distance, and the time of the probe's closest approach to Earth. Both numbers were perfectly matched, proving our method a success: it calculated a more accurate prediction of BepiColombo's orbit; it also provided valuable insights for future observations of objects colliding with Earth:

- A purely optical observing campaign can provide trajectory information during a fly-by at sub-kilometre and sub-second levels of precision.
- A similar campaign would lead to a sub-kilometre and sub-second precision for the time and location of the atmospheric entry of any colliding object.
- Timing accuracy below 100 milliseconds is crucial for the closest observations.
- It's possible to organise astrometric campaigns with coverage from nearly every continent.

Written by OzGrav researcher Dr Bruce Gendre, University of Western Australia.

About OzGrav

The ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) is funded by the Australian Government through the Australian Research Council Centres of Excellence funding scheme. OzGrav is a partnership between Swinburne University of Technology (host of OzGrav headquarters), the Australian National University, Monash University, University of Adelaide, University of Melbourne, and University of Western Australia, along with other collaborating organisations in Australia and overseas.

The mission of OzGrav is to capitalise on the historic first detections of gravitational waves to understand the extreme physics of black holes and warped spacetime, and to inspire the next generation of Australian scientists and engineers through this new window on the Universe.

OzGrav is part of the international LIGO-Virgo collaboration. LIGO is funded by NSF and operated by Caltech and MIT, which conceived of LIGO and led the Initial and Advanced LIGO projects. Financial support for the Advanced LIGO project was led by the NSF with Germany (Max Planck Society), the U.K. (Science and Technology Facilities Council) and Australia (Australian Research Council-OzGrav) making significant commitments and contributions to the project. Nearly 1300 scientists from around the world participate in the effort through the LIGO Scientific Collaboration. The Virgo Collaboration is composed of approximately 350 scientists from across Europe. The European Gravitational Observatory (EGO) hosts the Virgo detector near Pisa in Italy, and is funded by Centre National de la Recherche Scientifique (CNRS) in France, the Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and Nikhef in the Netherlands.

The Kamioka Gravitational Wave Detector (KAGRA), formerly the Large Scale Cryogenic Gravitational Wave Telescope (LCGT), is a project of the gravitational wave studies group at the Institute for Cosmic Ray Research (ICRR) of the University of Tokyo. It will be the world's first gravitational wave observatory in Asia, built underground, and whose detector uses cryogenic mirrors. The design calls for an operational sensitivity equal to, or greater, than LIGO. The project is led by Nobelist Takaaki Kajita who had a major role in getting the project funded and constructed.

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Image credit: as stated on each page. Front cover by Carl Knox, OzGrav-Swinburne University

Background image by Carl Knox, OzGrav-Swinburne University