

SPACE-TIMES

OzGrav

February 2012

**Scientists track space junk on collision
path with the moon**
page 8

Fourier Space
page 5

Boson clouds & dark matter
page 6

Women in Physics
page 12

Welcome

Welcome to another edition of Space Times!

This summer was a reality check for many of us concerning the virus, with it finally penetrating Australia's defences with the appearance of the Omicron variant. I know many of you either personally caught the virus, or had infected family members.

I hope that you all make a full recovery and our research centre is soon no longer divided by border and travel restrictions in 2022, and that those of you kept apart from family and loved ones are soon reunited.

We recently had the very good news that OzGrav was the only current active Centre of Excellence to be selected for the 2023 full proposal and many of you have been helping me put forward a compelling case for a second Centre that concentrates on gravitational wave research.

In this issue you'll see how the remarkable double pulsar system is rewriting the records on tests of General Relativity, how gravitational wave research is opening new insights into everything from supermassive black hole binaries to more exotic explanations of dark matter via boson clouds and the evolution of binary

and clusters of stars.

Finally, two of our recently-alumni members have created a novel colouring book that features important women in physics. Buy one!

Yours sincerely - Matthew Bailes
(OzGrav Director)



NEWS IN BRIEF

- Congratulations to OzGrav student Nandini Sahu who won a competitive process to speak in the Hypatia colloquium (ESO).
- Congratulations to OzGrav students Lucy Strang from the University of Melbourne and Ben Grace from the Australian National University for jointly winning the Kerr Prize for the best student talk at the 11th Australasian Conference on General Relativity and Gravitation.
- Congratulations to Chayan Chatterjee (UWA) who won the prize for the best presentation at the AMSI Summer School which is "the biggest Maths event in Australia" for honours and postgraduate students in the mathematical sciences. Chayan also recently placed as runner-up J-P Macquart best student talk prize at the ANITA workshop.
- Congratulations to Ilya Mandel (Monash) for being appointed to the ARC's College of Experts
- Congratulations to Nutsinee Kijbunchoo (ANU) for winning the 2020/2021 Warsash Science Communication Prize by the Council of the Australian and New Zealand Optical Society (ANZOS) for her submission The Bumpy Little World: How Quantum Engineered Vacuum Increased Gravitational Waves Detection Rate.
- Congratulations to Ethan Payne, winner of the Australian Institute of Physics TH Laby Medal "for the best Honours or Masters thesis from an Australian University."

RESEARCH HIGHLIGHT

Orbital path shapes of colliding dead stars may indicate origin of binary stellar systems

The LIGO-Virgo-KAGRA Collaboration recently announced that the number of times we've seen dead stars crashing into each other on the other side of the Universe has grown to 90. It's clearly not uncommon for these dead stars—most of them black holes—to slam together in violent merger events. But one outstanding mystery pervades these detections: how do two compact stellar remnants find each other in the vast emptiness of space, and go on to merge together? [In our recent paper](#), we found clues to solve this mystery from the orbital path shapes formed by the stellar objects before they collided.

Often, stars are born into binary systems containing two stars that orbit each other. If these binary stars undergo specific evolutionary mechanisms, they can remain close when they die, and their corpses—black holes and/or neutron stars—can collide with each other. This kind of binary should trace a circular orbital path before it merges. However, sometimes stellar remnants meet in more exciting environments, like the cores of star clusters. In this kind of environment, binary stellar remnants can trace orbital paths around each other that look like 'squashed' circles—more egg-shaped or sausage-shaped.

Dense clusters of stars can produce binaries in circular orbits; however, about 1 in 25 of the mergers that combine in a dense star cluster are expected to have orbital shapes that are visibly squashed. To map the paths taken by cosmic couples in their pre-merger moments, we studied the space-time ripples produced by the collisions of 36 binary black holes. Two of these collisions—one of them being the monster binary black hole GW190521—contained the distinctive signatures of elongated (squashed) orbits. This means that more than a quarter of the observed collisions may be occurring in dense star clusters, because every squashed-orbit system indicates that 24 more mergers may also have happened in this environment.

While this result is exciting, it's not conclusive: other dense environments, like the centres of galaxies, can also produce merging stellar remnants with squashed orbital shapes. To distinguish the formation habitats of the observed population, we need to scrutinise the orbital shapes of more colliding stellar remnants. Luckily, the number of detected stellar-remnant collisions is growing quickly, so this merger mystery may be solved soon.

Written by OzGrav PhD student Isobel Romero-Shaw, Monash University

RESEARCH HIGHLIGHT

How stellar winds can create discs around black holes

The first evidence of the existence of black holes was found in the 1960s, when strong X-rays were detected from a system called Cygnus X-1. In this system, the black hole is orbited by a massive star blowing an extremely strong wind, more than 10 million times stronger than the wind blowing from the Sun. Part of the gas in this wind is gravitationally attracted towards the black hole, creating an 'accretion disc', which emits the strong X-rays that we observe. These systems with a black hole and a massive star are called 'high-mass X-ray binaries' and have been very helpful in understanding the nature of black holes.

After nearly 60 years since the first discovery, only a handful of similar high-mass X-ray binaries have been detected. Many more of them were expected to exist, especially given that many binary black holes (the future states of high-mass X-ray binaries) have been discovered with gravitational waves in the past few years. There are also many binaries found in our Galaxy that are expected to eventually become a high-mass X-ray binary. So, we see plenty of both the predecessors and descendants, but where are all the high-mass X-ray binaries themselves hiding?

One explanation states that even if a black hole is orbited by a massive star blowing a strong wind, it does not always emit X-rays. To emit X-rays, the black hole needs to create an accretion disc, where the gas swirls around and becomes hot before falling in. To create an accretion disc, the falling gas needs 'angular momentum', so that all the gas particles can rotate around the black hole in the same direction. However, we find it is generally difficult to have enough angular momentum falling onto the black hole in high-mass X-ray binaries. This is because the wind is usually considered to be blowing symmetrically, so there is almost the same amount of gas flowing past the black hole both clockwise and counter-clockwise. As a result, the gas can fall into the black hole directly without creating an accretion disc, so the black hole is almost invisible.

But if this is true, why do we see any X-ray binaries at all? In our paper, we solved the equations of motion for stellar winds and we found that the wind does not blow symmetrically when the black hole is close enough to the star. The wind blows with a slower speed in the direction towards and away from the black hole, due to the tidal forces. Because of this break of symmetry in the wind, the gas can now have a large amount of angular momentum, enough to form an accretion disc around the black hole and shine in X-rays. The necessary conditions for this asymmetry are rather strict, so only a small fraction of black hole + massive star binaries will be able to be observed.

The model in [our study](#) explains why there are only a small number of detected high-mass X-ray binaries, but this is only the first step in understanding asymmetric stellar winds. By investigating this model further, we might be able to solve many other mysteries of high-mass X-ray binaries.

Written by OzGrav Postdoc Ryosuke Hirai, Monash University

4

Background image by Mark Myers, OzGrav-Swinburne University

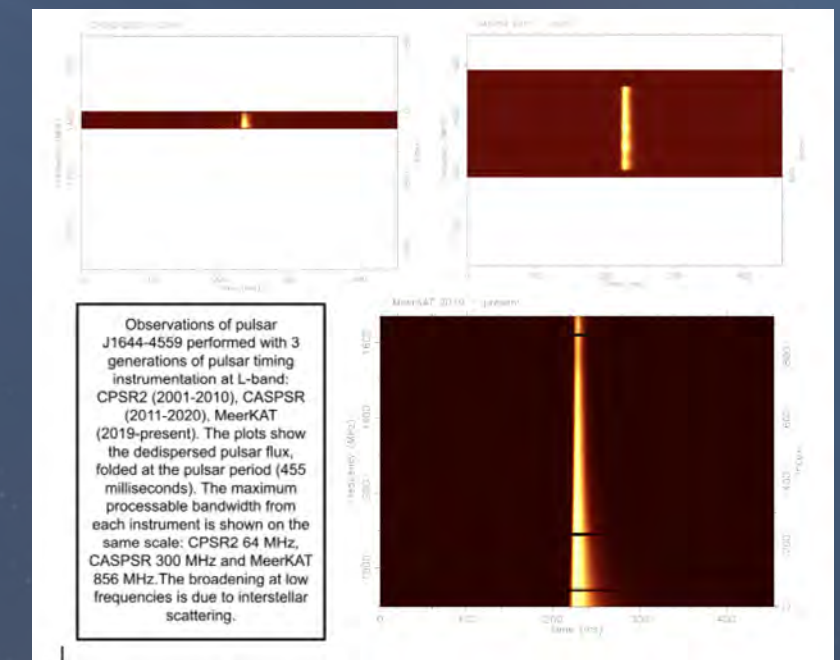
New spin-off company: Fourier Space

Fourier Space is a new spin-off company from Swinburne University that offers expertise in high performance digital signal processing and its use in astronomical instrumentation. Over the last 15+ years the team have designed, developed, and commissioned many generations of successively more capable, bespoke, high-time-resolution processing instruments for the iconic Parkes radio telescope. In more recent years, they have developed expertise in interferometry (beamforming and correlation), fast transient detection, spectrometry and baseband recording techniques. Software instruments have been designed and deployed by the team at some of the most capable observatories, including MeerKAT, Keck and UTMOST.

The development of the Pulsar Timing instrument for the MeerKAT radio telescope has been a most important recent development that has contributed to the foundation of Fourier Space. The instrument design, construction and commissioning has been supported by OzGrav and conducted at Swinburne and it now enables the timing of pulsars at the world's most sensitive radio interferometer. Gravitational wave searches with MeerKAT pulsar data will continue to provide rich dataset through the MeerTIME Key Science Program (led by Matthew Bailes) and will deliver direct benefits to OzGrav researchers for years to come.

At the heart of this work is the capability to receive extremely high data-rate streams from telescope systems and process them, in real-time, using the latest Graphics Processing Units (GPUs). This hardware is typically deployed on modest super-computers, built from commercial-off-the-shelf servers, which reduces cost of ownership, complex systems engineering and deployment timescales. Software libraries and algorithms that unlock the massive memory bandwidth and processing capabilities of GPUs have been developed to enable rapid development and deployment of coherent signal processing software. This software is available for licensing and can be coupled with consulting services to provide complete pipelines and systems. The team have also laid the foundations for many core software libraries and developed critical applications that are made available to the radio astronomy community.

Fourier Space are now leveraging their experience and existing software infrastructure to pursue opportunities in developing the next generation of astronomy instrumentation on facilities such as the Square Kilometre Array. The future for Fourier Space includes commercialisation opportunities outside of astronomy, with a focus to translate expertise digital signal processing research to applications in space and communications sectors.



5

A new clue to discovering dark matter from mysterious clouds circling spinning black holes.

An international team of scientists, co-led by Australian OzGrav researcher Dr Lilli Sun (Australian National University), is on the hunt for 'boson clouds' and gravitational wave detectors are a powerful tool to advance this search.

- Ultralight boson particles are a new type of subatomic particle that scientists have put forward as compelling dark matter candidates. However, these ultralight particles are difficult to detect because they have extremely small mass and rarely interact with matter (one of the key properties that dark matter seems to have).
- The discovery of these clouds would bring important insights about dark matter and help advance other searches for dark matter. It would also advance our understanding of particle physics more broadly.

Gravitational waves are cosmic ripples in the fabric of space and time that emanate from catastrophic events in space, like collisions of black holes and neutron stars--the collapsed cores of massive supergiant stars. Extremely sensitive gravitational-wave detectors on Earth, like the Advanced LIGO and Virgo detectors, have successfully observed dozens of gravitational-wave signals, and they've also been used to search for dark matter: a hypothetical form of matter thought to account for approximately 85% of all matter in the Universe. Dark matter may be composed of particles that do not absorb, reflect, or emit light, so they cannot be detected by observing electromagnetic radiation. Dark matter is material that cannot be seen directly, but we know that dark matter exists because of the effect it has on objects that we can observe directly.

Ultralight boson particles are a new type of subatomic particle that scientists have put forward as compelling dark matter candidates. However, these ultralight particles are difficult to detect because they have

extremely small mass and rarely interact with other matter -- which is one of the key properties that dark matter seems to have.

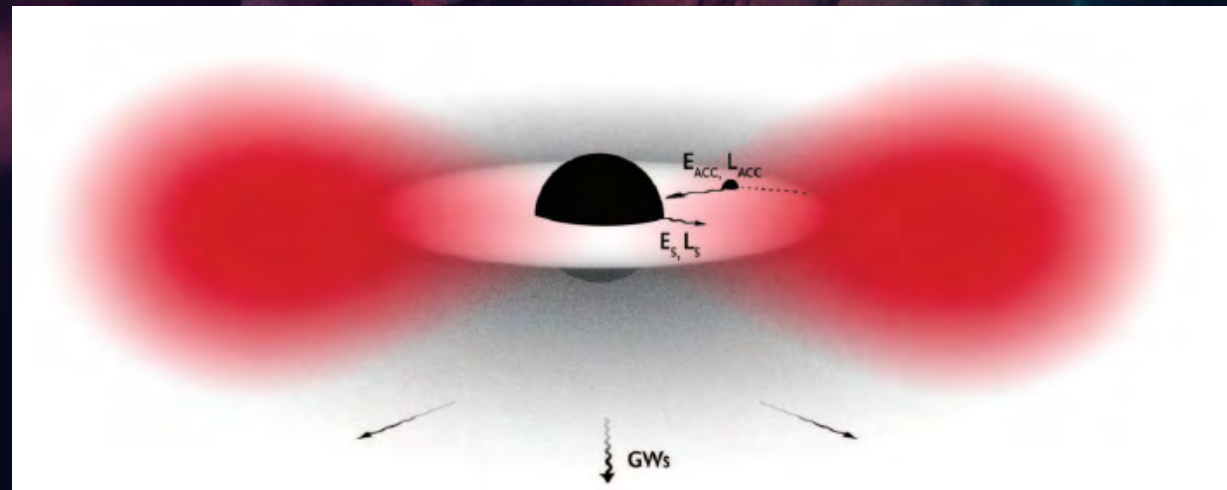
The detection of gravitational waves provides a new approach to detecting these extremely light boson particles using gravity. Scientists theorise that if there are certain ultralight boson particles near a rapidly spinning black hole, the extreme gravity field causes the particles to be trapped around the black hole, creating a cloud around the black hole. This phenomenon can generate gravitational waves over a very long lifetime. By searching for these gravitational-wave signals, scientists can finally discover these elusive boson particles, if they do exist, and possibly crack

fundamental physics. It provides not only direct information about mysterious compact objects in the Universe, like black holes and neutron stars, but also allows us to look for new particles and dark matter," says Dr Sun.

Although a signal was not detected, the team of researchers were able to draw valuable conclusions about the possible presence of these clouds in our Galaxy. In the analysis, they also took into consideration that the strength of a gravitational wave signal depends on the age of the boson cloud: the boson cloud shrinks as it loses energy by sending out gravitational waves, so the strength of the gravitational wave signal would decrease as the cloud ages.

"We learnt that a particular type of boson clouds younger than 1000 years is not likely to exist anywhere in our Galaxy, while such clouds that are up to 10 million years old are not likely to exist within about 3260 light-years from Earth," says Dr Sun.

"Future gravitational wave detectors will certainly open more possibilities. We will be able to reach deeper into the Universe and discover more insights about these particles."



Pictorial description of a bosonic cloud around a spinning black hole in a realistic astrophysical environment. Credit: Superradiance, *New Frontiers in Black Hole Physics*, Richard Brito, Vitor Cardoso, Paolo Pani.

the code of dark matter or rule out the existence of some types of the proposed particles.

[In a recent international study](#) in the LIGO-Virgo-KAGRA collaboration, with OzGrav Associate Investigator Dr Lilli Sun from the Australian National University being one of the leading researchers, a team of scientists carried out the very first all-sky search tailored for these predicted gravitational wave signals from boson clouds around rapidly spinning black holes.

"Gravitational-wave science opened a completely new window to study

Scientists track space junk on path to collision with moon

The University of Western Australia's Zadko Observatory team, in collaboration with the European Space Agency, have tracked an out-of-control booster rocket before it crashes into the dark side of the Moon. The booster rocket was originally believed to be a part of a Space-X rocket weather satellite but it is now believed to be 2014-065B, the booster rocket for the Chinese Chang'e 5-T1 lunar mission.

It is possible the booster rocket has been in orbit between the Earth and the Moon since 2014 and scientists predict this large piece of space junk will collide with the Moon on March 4. OzGrav Chief Investigator Associate Professor David Coward said there was a lot of junk in space. "The space around Earth is becoming increasingly busy with orbiting debris and this debris is for the first time reaching the Moon," Associate Professor Coward said.

The Zadko Observatory scientists at UWA's Department of Physics are contracted by the European Space Agency to track potentially hazardous debris near Earth. European Space Agency scientist Dr Marco Micheli said tracking the space junk with the Zadko Telescope was helping scientists refine the orbit and the location of the crash. Zadko Observatory systems manager Dr Bruce Gendre said acquiring accurate positional data on an object 177,118km from Earth and travelling at over 700km per minute was not trivial. "The exact impact site is uncertain because small effects, such as the rocket tumbling, changes the orbit slightly as it approaches the Moon," Dr Gendre said.

Making things more difficult, UWA astrophysics student Eloise Moore had to battle with the Zadko telescope to regain control as its robotic system went rogue just as she was trying to take the images. "We finally got control of the telescope only minutes before the critical imaging was due to start," Ms Moore said.

At 4am on February 10, she succeeded in capturing some of the last images of the booster, which showed signs of the rockets tumbling as it hurtled through space before the expected collision. "Even though the impact will occur on the dark side of the Moon, which is not visible from Earth, future lunar probes will be able to image the impact site to study effects of space junk on the lunar surface," Ms Moore said.

As featured on [UWA news](#).

Background image by Carl Knox, OzGrav-Swinburne University

The missing piece of the GW200115 puzzle

In our recently accepted paper, we examined the black hole-neutron star merger called GW200115, second observed by LIGO and Virgo in January 2020. Curiously, GW200115's black hole could have been spinning rapidly, with its spin misaligned with respect to the orbital motion. This is strange because it implies that the system would have formed in pretty unexpected ways.

So, is there something we're missing? In our paper we show that the puzzling black hole spin is probably due to something that was added to the LIGO-Virgo measurements instead. It has to do with things called 'priors' which encode assumptions about the population of black hole-neutron star binaries based on our current knowledge. We argue that a better explanation for the GW200115 merger is that the black hole was not spinning at all, and consequently, we place tighter constraints on the black hole and neutron star masses.

What is a prior?

Imagine you want to know the probability of having drawn an Ace from a deck of cards, given that the card is red. You'd need to know the separate probabilities of drawing an Ace and a red card. The probability of drawing an Ace, independent of the data ("the card is red") is the 'prior' probability of drawing an Ace. Astronomy is similar to a game of cards: we can think of observed gravitational-wave signals as having been dealt to us randomly by the Universe from a cosmic deck of cards. The prior should express our current best knowledge of this deck before we make a measurement, because it's used to calculate the probability of each possible black hole spin. In the LIGO-Virgo analysis of GW200115, it was assumed that all black hole spins are equally likely. This is fine if we have no strong preference for any value, but we do: observation and theory tell us we shouldn't expect a rapidly spinning black hole to be paired with a neutron star. This information is key to accurately measuring the properties of GW200115.

In our paper, we begin by demonstrating that if GW200115 originated from a black hole-neutron star binary with zero spin, the unrealistic LIGO-Virgo prior (which assumes the black hole can equally likely spin with any magnitude and direction) generates preference for a large misaligned black hole spin. We do this by simulating a gravitational-wave signal from a non-spinning binary, placing it into simulated (but realistic) LIGO-Virgo noise, and inferring its properties assuming any spin value is equally likely. Our simulated experiment yields a similar spin measurement to LIGO-Virgo's and we're able to explain analytically why signals from black hole-neutron star binaries with zero spin will generically yield such measurements when very broad spin priors are assumed. While this doesn't prove that GW200115 is non-spinning, it suggests that the puzzling LIGO-Virgo spin measurement is probably due to their unrealistic priors.

Next, we look to astrophysics to figure out a more realistic prior. We use current theoretical modelling to suggest that there's roughly a 95% probability that black hole-neutron star binaries do not spin at all, and only around 5% do spin. We use this astrophysical prior to update the LIGO-Virgo measurements of GW200115's spins and masses. When we do this, we find that there is almost zero probability that the black hole had any spin at all. While this might seem circular at first glance—after all, we're giving zero-spin almost 20 times more weight than non-zero spin—it's also a reflection of the fact that the data don't strongly support a rapidly spinning black hole. Additionally, we show that our prior reduces the uncertainty on the black hole and neutron star masses by a factor of 3. Reassuringly, the mass of the neutron star looks significantly more like those found in double neutron star systems in the Milky Way.

Written by Rory Smith and Ilya Mandel, Monash University

Einstein's theory passes multiple tests set by pair of extreme stars

An international team of researchers from ten countries has conducted a 16-year long experiment to confront Einstein's theory of general relativity with some of the most rigorous tests yet.

Their study of a unique pair of extreme stars, so called pulsars, involving six radio telescopes across the globe revealed new relativistic effects that have been expected but are now observed for the first time. Einstein's theory, which was conceived at a time when neither these types of extreme stars nor the techniques used to study them had been imagined, agrees with the observations at a level of 99.99%.

More than 100 years after Einstein presented his theory of gravity, scientists around the world continue their efforts to find flaws in general relativity. Any deviation would indicate a path towards understanding why general relativity is incompatible with quantum theory, which successfully describes the workings of the Universe on the very smallest scales.

This cosmic laboratory known as the "Double Pulsar" was discovered by members of the team in 2003. It consists of two radio pulsars which orbit each other in just 147 min with velocities of about 1 million km/h. One pulsar is spinning very fast, about 45 times a second. The companion is young and

has a rotation period of 2.8 seconds. It is their motion around each other which resembles a near perfect gravity laboratory.

Co-author Prof. Dick Manchester from CSIRO says: "Such fast orbital motion of compact objects like these - they are a bit more massive than the Sun but only about 25 km across - allows us to test many different predictions of general relativity - seven in total! Apart from gravitational waves and light propagation, our precision allows us also to measure the effect of "time dilation" that makes clocks run slower in gravitational fields. We even need to take Einstein's famous equation $E = mc^2$ into account when considering the effect of the electromagnetic radiation emitted by the fast-spinning pulsar on the orbital motion. This radiation corresponds to a mass loss of 8 million tonnes per second! While this seems a lot, it is only a tiny fraction - 3 parts in a thousand billion billion(!) - of the mass of the pulsar, per second."

The researchers also measured, with a precision of 1 part in a million, that the orbit changes its orientation, a relativistic effect also known from the orbit of Mercury, but here 140,000 times stronger. They realized that at this level of precision they also need to consider the impact of the pulsar's rotation on the surrounding spacetime, which is "dragged along" with the spinning pulsar.

The technique of pulsar timing was combined with careful interferometric

measurements of the system to determine its distance with high resolution imaging. OzGrav Associate Investigator and team member Prof Adam Deller, at Swinburne University in Australia and responsible for this part of the experiment, highlights: "It is the combination of different complementary observing techniques that adds to the extreme value of the experiment. In the past similar studies were often hampered by the limited knowledge of the distance of such systems." This is not the case here, where in addition to pulsar timing and interferometry also the information gained from effects due to the interstellar medium were carefully taken into account.

The leader of the research team, Prof Michael Kramer from the Max-Planck-Institute for Radio Astronomy (MPIfR) in Bonn, Germany concludes: "We have reached a level of precision that is unprecedented. Future experiments with even bigger telescopes can and will go still further. Our work has shown the way such experiments need to be conducted and which subtle effects now need to be taken into account. And, maybe, we will find a deviation from general relativity one day..."

Also featured in *The Age*, *The Australian*, *Sydney Morning Herald*, *The Conversation*, *ABC Radio National*, *Cosmos Magazine* and *Space Australia*.

RESEARCH HIGHLIGHT

A new approach to rapidly localise gravitational waves

Multimessenger astronomy is an emerging field which aims to study astronomical objects using different 'messengers' or sources, like electromagnetic radiation (light), neutrinos and gravitational waves. This field gained enormous recognition after the joint detection of gravitational waves and gamma ray bursts in 2017. Gravitational waves can be used to identify the sky direction of an event in space and alert conventional telescopes to follow-up for other sources of radiation. However, following up on prompt emissions would require a rapid and accurate localisation of such events, which will be key for joint observations in the future.

The conventional method to accurately estimate the sky direction of gravitational waves is tedious—taking a few hours to days—while a faster online version needs only seconds. There is an emerging capacity from the LIGO-Virgo collaboration to detect gravitational waves from electromagnetic-bright binary coalescences, tens of seconds before their final merger, and provide alerts across the world. The goal is to coordinate prompt follow up observations with other telescopes around the globe to capture potential electromagnetic flashes within minutes from the mergers of two neutron stars, or a neutron star with a black hole—this was not possible before. The University of Western Australia's SPIIR team is one of the world leaders in this area of research. Determining sky directions within seconds of a merger event is crucial, as most telescopes need to know where to point in the sky. In our recently accepted paper [1], led by three visiting students (undergraduate and Masters by research) at the OzGrav-UWA node, we applied analytical approximations to greatly reduce the computational time of the conventional localisation method while maintaining its accuracy. A similar semi-analytical approach has also been published in another recent study [2].

The results from this work show great potential and will be integrated into the SPIIR online pipeline going forward in the next observing run. We hope that this work complements other methods from the LIGO-Virgo collaboration and that it will be part of some exciting discoveries.

Written by OzGrav PhD student Manoj Kovalam, University of Western Australia.

[1] <https://doi.org/10.1103/PhysRevD.104.104008>

[2] <https://doi.org/10.1103/PhysRevD.103.043011>

This work is now accepted by PRD: <https://journals.aps.org/prd/abstract/10.1103/PhysRevD.104.104008>

Melbourne-based astrophysicists launch colouring book encouraging more girls to become scientists

Two Melbourne-based astrophysicists from the ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) have collaborated on a colouring book called *Women in Physics*. The recently launched book encourages girls to follow their passions in science and learn about the amazing women who changed the course of history with their physics research.

The authors Debatri Chattopadhyay (Swinburne University) and Isobel Romero-Shaw (Monash University)—who are both completing their PhDs in astrophysics with OzGrav—are determined to educate children and young people about the pivotal scientific discoveries and contributions made by women scientists. They also want to encourage more girls, women, and minorities to take up careers in Science, Technology, Engineering, Mathematics and Medicine (STEMM), which is a male-dominated field.

Debatri, who is originally from India, came to Australia pursuing her PhD at Swinburne University in 2017. She was acutely aware of the lack of women in STEMM fields, as both of her parents worked in biological sciences. “My father is a scientist, so I was aware that this was a field I could go into, and he would talk about amazing biologists like Barbara McClintock, but there was almost no representation of female scientists on TV or in newspapers,” she recalls.

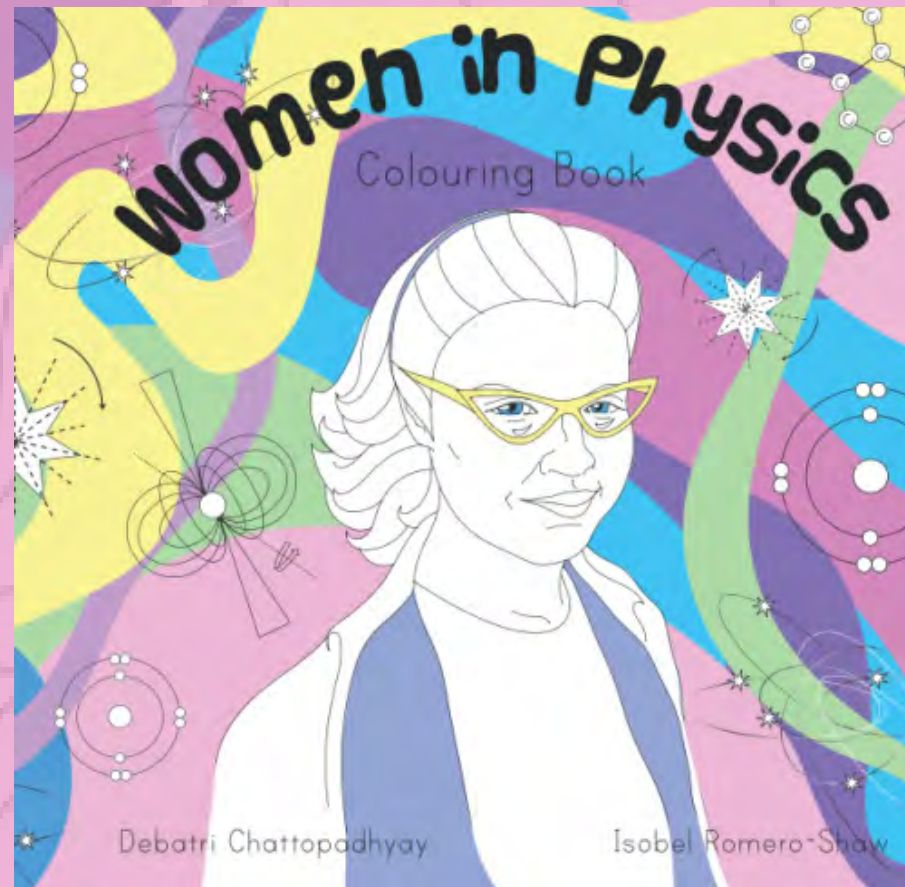
“This colouring book will help children learn about the colourful lives and brilliant minds of these amazing women scientists. As a colouring book, it encourages creative minds to think about scientific problems - which is very much needed for problem solving”, says Isobel, who designed the book and illustrated each of the featured scientists. “These women, who made absolutely pioneering discoveries, used their creativity to advance the world as we know it.”

“I did intense research for the biographies of the women featured in the book and at every nook and crevice was amazed at the perseverance they showed. It is for them and countless others, unfortunately undocumented, that we can do what we do today,” says Debatri.

Last year, both Isobel and Debatri were also selected to participate in Homeward Bound, a global program designed to provide cutting-edge leadership training to 1000 women in STEMM over 10 years. To raise awareness of climate change, this journey will also take Isobel and Debatri all the way to Earth’s frozen desert, Antarctica.

The initiative aims to heighten the influence and impact of women with a science background in order to influence policy and decision making as it shapes our planet. In 2017-18, OzGrav Chief Investigator Distinguished Prof Susan Scott was also selected to participate in this program and embark on the journey to Antarctica.

“The saying that ‘you can’t be what you can’t see’ is addressed in this new colouring book,” says Distinguished



Prof Scott. “The important women scientists depicted in the book come to life as role models as they are coloured in. Women are under-represented in physics education and work in Australia. Educating children about women scientists throughout history is an important step in encouraging more girls and women to take up STEMM careers and boost diversity.”

In their “day jobs”, Isobel tries to figure out how the collapsed remains of supergiant stars—black holes and neutron stars—meet up and crash together. She does this by studying the vibrations that these collisions send rippling through space-time—these are called gravitational waves. She also recently published an illustrated book, available on Amazon, called *Planetymology: Why Uranus is not called George* and other facts about space and words. *Planetymology* explains the ties between ancient history, astronomy, and language, and introduces the reader to the harsh realities of conditions on other planets.

Debatri is involved in doing simulations in supercomputers of dead stars in binaries or in massive collections of other stellar systems - called globular clusters. Her detailed theoretical calculations help us to understand the astrophysics behind the observations of gravitational waves and radio pulsars, as well as predict what surprising observations might be made in the future. Debatri is also a trained Indian classical dancer and was a voluntary crew member of the Melbourne-based tall ship ‘Enterprize’. She has recently submitted her thesis and joined as a postdoctoral fellow at the Gravity Exploration Institute, Cardiff University.

[CLICK HERE](#) TO BUY THE WOMEN IN PHYSICS COLOURING BOOK.

Searching for elusive continuous gravitational waves from the densest objects in the Universe

A new international study, led by an Australian researcher from the ARC Centre of Excellence for Gravitational Wave Discovery, searched for elusive continuous gravitational waves from the densest objects in the Universe - neutron stars. A detection of a continuous gravitational wave would allow scientists to peer into the hearts of these neutron stars—they are extremely dense, collapsed cores of massive supergiant stars. The hunt for continuous gravitational waves is one of the top challenges in gravitational wave science, but Australia has a strong track record in this area of research.

Take a star similar in size to the Sun, squash it down to a ball about twenty kilometres across and you'd get a neutron star: the densest object in the known Universe. Now set your neutron star spinning at hundreds of revolutions per second and listen carefully. If your neutron star isn't perfectly spherical, it will wobble a bit, causing it to continuously send out faint ripples in the fabric of space and time. These ripples are called continuous gravitational waves.

So far, these elusive continuous gravitational waves haven't been detected; however, in a recent study, an international collaboration of scientists, led by Australian OzGrav researcher Julian Carlin (from the University of Melbourne), searched for them from a specific category of neutron star: accreting millisecond X-ray pulsars (AMXPs).

To break it down, AMXPs are:

Pulsars - The Universe's lighthouses; they are extremely dense collapsed cores of massive supergiant stars (called neutron stars) that beam out radio waves, like a lighthouse. As a pulsar rotates, we can see a pulse in radio telescopes every time the beam points towards the Earth.

Accreting pulsars - they have a companion star and this is called a binary star system. The accreting pulsar feeds off its companion star, sucking up matter from the star and accumulating it on their surface.

X-ray pulsars - they emit X-ray pulses. AMXPs have times of "outburst"

where the X-ray pulses are observable and times of "quiescence" when X-ray pulses are either not emitted or are too weak to see.

Millisecond pulsars - they spin very fast (a millisecond is one thousandth of a second). The fastest spinning AMXP takes just 1.7 milliseconds to do a full rotation. That means if you were standing on the surface you would be whipping around at 15% the speed of light (or about 45,000 km/s)!

As AMXPs accumulate matter from their companion star, they're likely to send out stronger signals than a lone neutron star. This is because the strength of a neutron star's signal is proportional to its asymmetry. Astronomers theorise that this build up of matter on the AMXPs could create small mountains on the surface as material is funnelled by the magnetic field onto the magnetic poles. This is illustrated by the artist's impression shown in Figure 1.

This search uses data from the third observing run of LIGO, Virgo, and KAGRA which lasted from April 2019 to March 2020. The team searched for continuous gravitational waves from 20 AMXPs - 14 of which hadn't been searched before.

The search method used in this work is the result of a collaboration between physicists and engineers at the University of Melbourne. "The methods we are using to search for continuous gravitational waves from spinning neutron stars are similar to those used in speech recognition software!" said Hannah Middleton (an OzGrav postdoc at both the University of Melbourne and Swinburne University).

Unfortunately, continuous gravitational waves were not convincingly detected this time. However, as detector technology and data analysis algorithms keep improving, it's possible that a detection will be made in the next observing run.

Julian Carlin said: "It may turn out that the weak candidates we've spotted here are the first signs of a real signal, and we just need a little bit more data to pull it out of the noise".

"If a detection were made, it'd allow us to peer into the hearts of neutron stars - teaching us how matter behaves in extremely dense environments," he continues. "Detecting continuous gravitational waves from neutron stars would give us great insights into how these fantastic astronomical clocks really tick."

"The hunt for continuous gravitational waves is one of the top challenges in gravitational wave science", said Andrew Melatos, an OzGrav Chief Investigator whose research group at the University of Melbourne has been chasing these tiny signals for more than a decade. "Pulsars are one of Nature's most bountiful gifts. Their radio signals revolutionised astronomy, shedding new light on everything from the gas between the stars to Einstein's theory of gravity and the strongest magnetic fields in the Universe. Who knows what surprises their gravitational wave murmurs will reveal?"

Dr. Karl Wette, an OzGrav research fellow at The Australian National University and co-chair of the LIGO continuous wave working group, said: "Gravitational waves are becoming an essential tool for fundamental physics and astronomy. We've now heard the echoes of nearly 100 pairs of black holes and neutron stars smashing into each other. We're keeping our ear to the ground, and hope to pick out the tell-tale hum of a rapidly-spinning neutron star in the coming years. Australia has a strong track record in this area of research, and it's particularly pleasing to see Australian students and junior researchers making important contributions."

"With improved detectors in the fourth observation run, the number of detections is expected to increase manifold," said OzGrav PhD student Chayan Chatterjee at the University of Western Australia. "So, it will be extremely exciting to watch out for more continuous gravitational wave candidates as well as other ground-breaking discoveries!"

RESEARCH HIGHLIGHT

Unexpected changes in the most predictable of stars

Pulsars, a class of neutron stars, are extremely predictable stars. They are formed from the hearts of massive stars that have since collapsed in on themselves, no longer able to burn enough fuel to fend off the crushing gravity the star possesses. If the conditions are right, the star will continue to collapse in on itself until what's left is a remnant of what was there before, usually only about the size of the Melbourne CBD, but 1-2 times as heavy as our Sun, making these some of the densest objects in the Universe.

These stars don't produce much visible light, but from their magnetic poles, they emit surprisingly bright beams of radio waves. If we're lucky, as the star rotates, those beams will wash over the Earth and we observe 'pulses'. While most pulsars spin around in about a second, there is a subclass of these stars that spin around in just a few thousandths of a second—they're called 'millisecond' pulsars.

Observing the pulses from these millisecond pulsars gives physicists clues to many questions, including testing General Relativity and understanding the densest states of matter. But one of the main goals of observing these incredibly fast, dense stars is to detect ultra-long wavelength gravitational waves. And by long, we mean many light-years long. These gravitational waves distort space-time between us and the pulsars, causing the pulses to arrive earlier or later than expected. It's likely that these gravitational waves come from a background produced by all the binary supermassive black holes in the Universe, which form from galaxies crashing into one another.

As part of OzGrav, we try and detect this gravitational wave background by looking at collections of the most predictable stars (called pulsar timing arrays) and measuring how they change over time. We did this by using the world's most sensitive radio telescopes, including the Australian Murriyang telescope (also known as the Parkes telescope) and the ultra-sensitive MeerKAT array telescope in South Africa.

But it's not quite that simple. [From our observations with MeerKAT](#) we found that the most precisely timed (read: predictable) pulsar, J1909-3744, was misbehaving. We found that the pulses were changing shape, with bright pulses arriving earlier and narrower than faint ones. This led to greater uncertainty in its predicted emission. Fortunately, we were able to establish a method to account for this change and time tag the pulsar more precisely than ever before. This method could be of use for other pulsars and will be important when more advanced telescopes are available in the future.

Written by OzGrav PhD student Matthew Miles, Swinburne University

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.

Website: www.ozgrav.org **Email:** info@ozgrav.org

Editor-in-chief: Luana Spadafora, lspadafora@swin.edu.au

Image credit: as stated on each page.

Front cover by Carl Knox, OzGrav-Swinburne University

Background image by Carl Knox, OzGrav-Swinburne