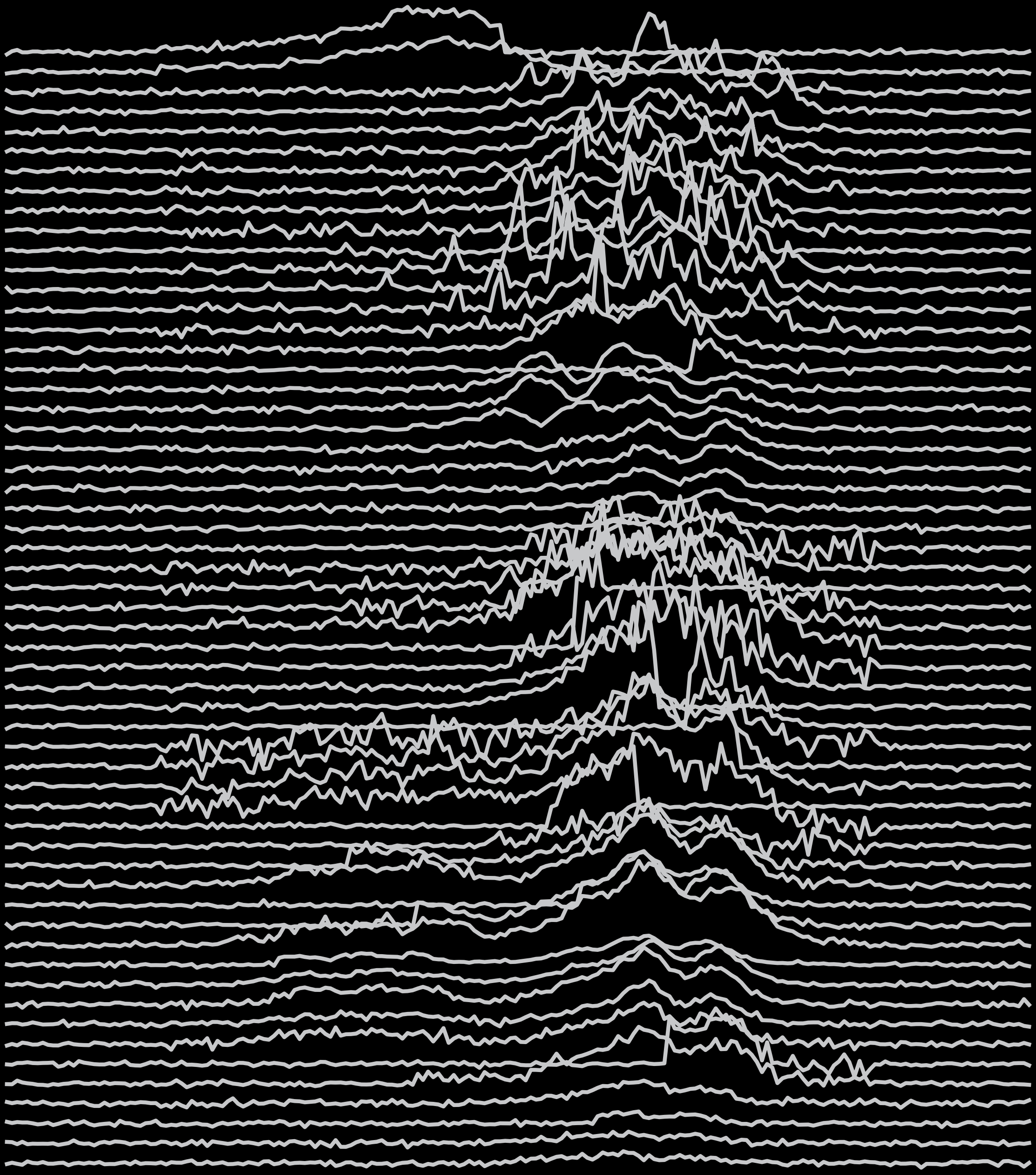
CIRA
2022

CURTIN INSTITUTE OF
RADIO ASTRONOMY

EXPLORING THE RADIO UNIVERSE
WITH SCIENCE AND ENGINEERING



Curtin University

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This annual report covers the calendar year 2022.

EDITORS
Mia Walker
Emmaline Yearsley
Aoife Stapleton
Ali Smith

CONTACT
Tel: +61 9266 9899
Email: cira.admin@curtin.edu.au

Curtin Institute of Radio Astronomy
Curtin University
Building 610, Technology Park
1 Turner Avenue
Bentley, WA 6102

GPO Box U1987,
Perth WA 6845

astronomy.curtin.edu.au

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ON THE COVER
Pulses of the long-period radio transient GLEAM-X J1627 detected by the Murchison Widefield Array over January to March 2018, aligned by its measured period of 18 minutes. The style of this image is adapted from the iconic cover art of Joy Division's album, *Unknown Pleasures*, based on Harold D. Craft, Jr.'s visualisation of the pulses from the first pulsar ever discovered, CP1919.
IMAGE: Dr Natasha Hurley-Walker

Details of this object were published in *Nature* on 27 January 2022, in a paper titled 'A radio transient with unusually slow periodic emission', by Dr Natasha Hurley-Walker et al. Follow-up work on another mysterious, repeating object can be found in Dr Hurley-Walker's article, page 32.

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Executive Director's Report

PROFESSOR STEVEN TINGAY
CIRA EXECUTIVE DIRECTOR

Sitting to write my contribution for the CIRA Annual Report is one of the highlights of the year. Looking over all the contributions to the Report from the Science, Engineering, Operations, and Translation and Impact teams always hammers home to me the skills and dedication at CIRA, and the efforts made to direct those skills to achieve impact. There is no doubt that CIRA is well resourced ($12.5M of expenditure in calendar year 2022), but the bang for those bucks is pretty extraordinary.

Each of the Program Director reports summarises the highlights of the 2022 year, and the many articles that follow go into a lot of detail as to those achievements. Across the board, they are impressive, from the continuation of more than a decade of our work in contribution to the SKA, to the publication of very high impact science papers in the world's best journals, to the wide-ranging contributions across our programs to Demand Driven research, including into the world of Defence Industry.

In our SKA work, the team has achieved the design and prototyping of the Power and Signal Distribution system, that will result in the largest procurement of SKA equipment in Australia (excluding infrastructure and software). This has been a massive undertaking, and not simply on the technical front.

As the Science Director reports, we had well over 100 publications in 2022, all of a high quality. The emergence of transient studies with the MWA, led by Natasha Hurley-Walker, is certainly the highlight and this work is going from strength to strength.

Our Engineering team is the engine room of Translation and Impact, as well as fundamental engineering research, and the emerging highlight is our increasing work aligned with Defence Industry, led by high power microwave studies sponsored by DSTG. But also our Space Domain Awareness work with industry partner Nova Systems. While governments applaud the fundamental science and research, the Translation and Impact of that research into other sectors is a big part of why we receive the support we do. So, it is wonderful to see success in that domain. We invest actively in Translation and Impact, and I expect to see this grow in the future.

Speaking of the future, we are in the midst of seeking a continuation of funding on multiple fronts. First, much of our underpinning support comes from ICRAR, and with our colleagues at The University of Western Australia, are seeking a transition year of ICRAR funding for 2024/25, with a follow-up proposal to the state government for ICRAR4 (2025/26 – 2029/30). In addition, we have recently been successful in securing on-going funding for MWA operations (and are also bidding for uplift funding). This puts the MWA in a strong position to enter into the Phase III upgrade and operate to the point when the SKA comes along around the end of the decade. The MWA underpins much of CIRA's and ICRAR's science program, so this is a very welcome outcome. The Australian SKA Regional Centre has also been supported with a decade of funding, which is very exciting.

Additionally, as you will see in David Davidson's Engineering program report, David has decided to step away from the Director of Engineering position in a transition to retirement. I want to take this opportunity to thank David for his work and effort in this role for the last ~5 years. As Executive Director, I've appreciated his support. We will take the opportunity to slightly re-organise the CIRA Executive, such that James will retain the Science Director role, Tom will lead a combined Engineering/Operations Program, and Aoife Stapleton will become the Director of Translation and Impact (also joining the ICRAR Executive team in that role). I'd like to congratulate Aoife and welcome her to the Executive team. I look forward to continuing to work productively with our Executive team.

The CIRA structure, the Executive team, the Project Leads, and the CIRA Development Committee (DevCom) all contribute to supporting CIRA's success and supporting all of our staff and students. I'd like to explicitly thank DevCom for their efforts across 2022, in particular Adelle Goodwin, the DevCom Chair.
It feels like DevCom has been reinvigorated and is energised, which is wonderful and adds to CIRA's ongoing commitment to our embedded principles for diversity, inclusion and equity. A significant contribution to this feeling is captured in our ASA Pleiades application, which is currently under review. I'd like to congratulate and deeply thank Ali Smith for stepping up late last year to be the champion for that application, putting in so much work to compile and describe our efforts, and for getting to submission.

Over the course of 2023, I expect we will bed down the MWA upgrade, ICRAR4 funding, AusSRC funding, and further SKA work. I expect that by the end of 2023, we will basically be able to chart a secure course to the end of the decade, which is pretty amazing. However, when tackling long-term and complex projects and science, such conditions really are a necessity, even if achieving those conditions is highly unusual. I'm greatly looking forward to the next 5 – 10 years.

Director's Report: Science

PROFESSOR JAMES MILLER-JONES
CIRA SCIENCE DIRECTOR

After two years of significant interruptions owing to the COVID-19 pandemic, 2022 saw the long-awaited shift back towards a more normal mode of operations. It was fantastic to be able to welcome students back to campus, enjoy in-person discussions with a range of interstate and overseas visitors, and reconnect with domestic and international colleagues at in-person meetings. However, this transition was not entirely smooth, with many of our staff and students forced to cope with the disruptions wrought by COVID. I would like to thank everyone who stepped up to fill in for their colleagues, ensuring that the successful operations of the group (particularly in the teaching and supervisory space) could continue.

The year saw another set of impressive research achievements. The CIRA Science team published 113 papers during 2022, with many of the highlights being presented in detail elsewhere in this Annual Report. The MWA continues to underpin much of the groundbreaking science being pursued at CIRA, with some of the most noteworthy results including a deep MWA image of the nearby radio galaxy Centaurus A, which made the cover of Nature Astronomy; and the discovery of an ultra-long period pulsating radio transient by the MWA, which was published in the prestigious multi-disciplinary journal Nature. Of particular note is that the original discovery of this exciting source was made by an Honours student, Tyrone O'Doherty, demonstrating the value of involving our talented undergraduate students in the cutting-edge science being performed at CIRA. The follow-up and interpretation of this surprising discovery drew on a wide range of expertise from across the group, showcasing the strengths of CIRA's diverse, highly-motivated team, and our broad range of skills. Thanks to the untiring efforts of lead author Dr Natasha Hurley-Walker and her team (well supported by both the ICRAR and Curtin media offices), the publication of this paper was accompanied by the most successful media release in CIRA's 15-year history, leading to over 2000 media articles with a global readership of over 8 million.

While the MWA provides the bedrock of CIRA's scientific activities, our researchers also continue to make use of other global facilities, choosing the most appropriate instruments for the scientific problem at hand. Particularly noteworthy in this regard is MeerKAT, the precursor facility for the mid-frequency component of the SKA. Engaging with this instrument is helping our team prepare to derive maximum benefit from the SKA, by making use of both low and mid-frequency arrays. An excellent example was the discovery of the most distant hydroxyl maser to date by Dr Marcin Glowacki and collaborators, which led to a second highly-successful media release, using the concept of galactic space lasers to capture the public's imagination.

It was especially pleasing to see many of our staff and students being recognised over the course of 2022, whether by the University, or by State or national bodies. I extend my particular congratulations to PhD candidate Kat Ross (the joint winner of the ExxonMobil Student Scientist of the Year category at the WA Premier's Science Awards), Dr Adelle Goodwin (winner of the Astronomical Society of Australia's Charlene Heisler Prize for the most outstanding PhD thesis, and also named as one of Science and Technology Australia's Superstars of STEM), and Dr Natasha Hurley-Walker (winner of the Astronomical Society of Australia's Anne Green Prize for the most outstanding mid-career researcher). A number of our staff and students were also recognised at the 2022 Curtin Research and Engagement Awards, and I congratulate them all.

A particular highlight of the year was the SKA's Construction Commencement Ceremony in December. This marked an important milestone in the project, and provides a sense of excitement as we move into 2023. With SKA operations intensifying in Western Australia, we continue to work closely with our SKA colleagues, as exemplified by Professor Cath Trott's part-time secondment to the SKA, which is helping to foster increased collaboration between the two organisations.

Over the course of 2022, the CIRA science team has also built closer links to the School of Electrical Engineering, Computing and Mathematical Sciences. In addition to teaching into multiple units within the Physics & Astronomy discipline, the group has for the first time delivered undergraduate teaching into the Mathematics & Statistics discipline. These new links have been further developed via an interdisciplinary PhD project, undertaken by Shih Ching Fu, and supervised by Dr Arash Bahramian and colleagues from the Statistics group within the School. It is fantastic to see CIRA staff and students building relationships across new areas of the University.

As ever, 2022 has seen significant staff movements. We bade farewell to Ben McKinley, Adela Kawka, Christene Lynch, and Tim Galvin, and wish them all the best in their new challenges. The relaxation of border restrictions in early 2022 allowed several new staff to relocate to Perth, after delays that in some cases amounted to years. We welcomed Dr Bradley Meyers, Dr Amir Forouzan, and Dr Apurba Bera, and look forward to other new staff members joining us over the coming months. Finally, it was a pleasure to see Dr Steve Prabu and Dr Kat Ross continue as postdoctoral researchers within the CIRA science team following their successful PhD completions.

In closing, I would like to thank the entire CIRA Science team for their efforts over what have been a difficult few years. I sincerely hope that we have finally turned the corner and can now move into a less disruptive mode, in which our staff and students can focus on the excitement of radio astronomy, as the MWA moves into its Phase 3 operations and the SKA construction continues to ramp up. With an excellent team to take advantage of these facilities, I look forward to the new opportunities that 2023 will bring.

Director's Report: Engineering

PROFESSOR DAVID DAVIDSON
CIRA ENGINEERING DIRECTOR

2022 finally saw light at the end of the global COVID-19 pandemic, with Western Australia re-opening its borders in March. The transition back to a more normal mode of operation was not without challenges; the first semester saw several disruptions in teaching programs as COVID started spreading in the community, and many staff became ill with COVID during the year.

This was the third year of the ICRAR-III programme, and technical work largely continued the trajectory started in 2019, with the initial focus on the SKA-Low prototype systems broadening to include related applications.

Commissioning work continued on the 256-element SKA-Low prototype station, the Aperture Array Verification System 2. Work on the new MWA correlator (MWAX) was completed, and the article by Greg Sleap and Ian Morrison provides more detail on this. One of the key science goals for SKA-Low is the early radio universe; both the Cosmic Dawn and Epoch of Reionisation projects need extremely accurate characterisation of the instrumentation to accomplish this. Danny Price's article describes some new methods for doing this. Danny was also the recipient of the Curtin STEM award for 2022. Work on using small satellites to characterise the ionosphere is reported by PhD student Ferry Lanter; such methods could improve the calibration of SKA-Low. Work on using GPUs to provide a high-time resolution imager for MWA and SKA-Low is reported by Marcin Sokolowski and his team.

Demonstrating radio astronomy for the purpose of education and outreach has been challenging, since the output of small-scale radio telescopes lack the "wow" factor of modest optical instruments. Randall Wayth and his team report on their progress on the Educational Radio Array, which aims to provide a more capable system than currently available for this purpose.

Outside traditional radio astronomy – but adjacent to it – the engineering team has been working on a portable Space Domain Awareness (SDA) system. This is a passive radar demonstration system designed to detect and monitor objects in space, leveraging CIRA's expertise in radio astronomy. A trial deployment of this system was undertaken mid-year. In their article, Jakes Jones and the SDA team, led by Randall Wayth, provide a system overview and present some impressive results from the trial.

Also in the space of translation and impact, work continued into investigating high power microwave effects on electronic circuits for Defence Science and Technology, and the team, led by Adrian Sutinjo, won the Science and Engineering Faculty's 2021 Research Award for Industry Engagement and Impact for this project.

As noted in the introduction, WA's borders opened early in the year, but with COVID far from contained internationally at that stage, we continued to attend most conferences in online or hybrid formats. I presented an online plenary lecture at ICEAA'22 on SKA-Low engineering. One of our first face-to-face meetings since the pandemic was the Phased Array Feeds and Advanced Receivers workshop, hosted by CSIRO in Sydney and attended by several engineering staff.

On the personnel front, Budi Juswardy and Aaron Silvestri moved on to roles in industry. Budi has been with CIRA for over a decade, and was closely involved with the SKAO, characterising fibre-optic systems on the SKA site. Recently, Budi and Aaron worked on the DST project mentioned earlier. Nipanjana Patra completed her contract, achieving first light on her all-sky instrument HYPEREION. Maria Koveleva was able to travel to the USA in the second half of the year, to take up her Fulbright scholarship. She has written an article on her experiences for this report.

The end of 2022 saw the official start of SKA construction; a large Construction Commencement Celebration was held in Perth in early December. Much of CIRA's management was in attendance and it was a fitting launch to SKA-Low.

Finally, on a personal note, I have decided to step down as Director of Engineering during 2023. With ICRAR-IV just around the corner, it seems appropriate to give a new director time to plan for ICRAR-IV and to steer the CIRA engineering team into the second half of this decade, as SKA-Low construction eventuates, and the CIRA engineering team addresses new challenges. I would like to thank the engineering team, my colleagues at CIRA, and the CIRA Executive Director, Steven Tingay, for a very stimulating and productive five years as engineering director.

Director's Report: Operations

TOM BOOLER
CIRA OPERATIONS DIRECTOR

2022 was a year of transition for the CIRA Operations Group (including T&I). Evolution of the landscape we inhabit drove evolution of our activities and priorities and these, in turn, drove evolution of the Ops Group itself.

SKA continued its transition into construction in 2022. The many challenges inherent in such a complex procurement and delivery activity began to manifest. Obstacles and constraints emerged, demanding compromises and new approaches. SKA's transition had a variety of implications for the CIRA Ops Group in 2022.

SKA's procurement schedule placed significant strain on the CIRA team working to design the Low Station Power and Signal Distribution (PaSD) system. SKA's recruitment of CIRA personnel contributing to the PaSD design effort further complicated the situation. Happily, cometh the hour cometh the Mihaela (Safta). Faced with the challenge of picking up a stalling design effort, targeting compliance with requirements ranging from optimistic to ambiguous, Mihaela has imposed (on SKA as well as us!) a level of rigour and discipline rarely encountered in this environment. The most pleasing thing about this, from my point of view, is that her approach ensures that the remarkable outcomes being achieved by the PaSD design team are finally being represented (and received) in a manner befitting the capability and endeavour that has gone into them.

The increase in SKA's 'footprint' and headcount –in Geraldton, in Perth, and on the MRO –also shaped 2022. CIRA Ops personnel were often the first port of call for freshly onboarded SKA staff (and CSIRO staff wearing SKA t-shirts) looking to understand what they'd gotten themselves into. The Ops Group's experience working on the MRO, with the MWA and the AAVS, is a resource the SKA values highly. Agreeing the mechanisms by which we continue to deliver that experience into the SKA will be a focus in 2023.

The MWA is (with deep affection) cantankerous. As providence would have it, the CIRA Ops Group is formidable. Throughout 2022 they – including 2022 addition, Cary Wintle – wrestled with and conquered the assortment of trials, mysteries and minor catastrophes that have come to typify a year in the life of the MWA. This effort doesn't go unnoticed by the community of MWA users and stakeholders and, in the second half of 2022, it was rewarded with the news that MWA would continue to be funded beyond its current funding horizon (mid-2023). The MWA was the only project in Australia's NCRIS funded astronomy program that didn't suffer a reduction in funding. This is testament to the outstanding value the CIRA Ops Group delivers in return for the MWA funding it receives. The MWA year finished on an even higher note when, in December, the Government announced an additional NCRIS funding opportunity – restricted to existing NCRIS capabilities, including the MWA—that represents a chance to secure a more robust operating model through to the retirement of the MWA when SKA-Low commences operations, in 2028-29.

As the scope of the Group's SKA work narrowed in 2022, the priority and effort invested in Space Domain Awareness (SDA) ramped up. The Ops Group supported the successful completion of a Defence Science Centre funded portable SDA project, led by Randall Wayth. In parallel, our relationship with Nova Systems matured into a collaborative project to build a demonstration system – at a Nova facility in Peterborough, South Australia – to showcase the unique capabilities that radio astronomy technology and techniques can bring to SDA. The need to ensure coordination and continuity between these efforts locally, and to provide our industry collaborators with a dedicated point of contact saw the addition of Rob Howes to the Ops Group in 2022. Looking ahead, SDA will be an increasing focus for the group.

2022 saw a changing of the guard in our Translation and Impact team. The baton was passed to Aoife Stapleton, Emmaline Yearsley, and Mia Walker. The T&I Team did an outstanding job of picking up the reigns of projects in progress, orienting to CIRA. This year saw Mia step into a new role, and together the team framed a positive T&I agenda despite capacity and resource constraints. Significantly, Aoife and Emmaline, who both came to CIRA from other areas of Curtin, have helped us forge much better links across campus than has historically been the case. They've deployed their respective networks and experience to great effect in charting a course for CIRA T&I that leverages the capabilities and capacity we can bring to bear.

Through the course of 2022 we said goodbye to Angela Hautmann (to SKA), Raunaq Bhushan (to SKA) and Brian Crosse (to the Grey Nomads). All made valuable contributions during their time at CIRA, particularly in support of our contributions to SKA.

I owe a special debt of thanks to Brian. Brian arrived at CIRA around the same time I did and, being much smarter than me, oriented to the tasks and challenges at hand far more quickly. Rather than let me flounder, Brian coached me along my (steep) learning curve. He even helped me decipher what Dave Emrich – who seemed, at the time, to speak entirely in riddles and puns – was saying! It's not exaggerating to say that if it weren't for Brian, I might not still be here these many years later. Thanks, Brian.

In closing, I thank the CIRA Ops Leads: Tina, Mihaela, Greg, Andy, Rob and Aoife. 2022 was a year of change and challenge. Your counsel and support through the course of the year were sincerely appreciated.

Diversity, Inclusion & Equity

ADELLE GOODWIN

> The CIRA Development Committee (DevCom) provides advice to the CIRA Directors, and aims to foster an environment where all staff can flourish irrespective of role, age, gender, sexual orientation, disability, race, religion, etc. It recognises that a way to promote diversity and representation, at all levels, is through development and support of existing, and future, staff and students. It draws on University and other resources to provide initiatives to develop CIRA's talent and to improve the overall working environment. The committee is also a portal to provide advice for academic and nonacademic staff on career development, progression and recognition.
>
> **DEVCOM MISSION STATEMENT**

The Development Committee (DevCom) continued its work throughout 2022 to support and increase diversity, inclusion, and equity among CIRA's growing staff and student bodies.

CIRA's community is truly an international one, with staff and students coming from many far-flung places around the world. To celebrate and showcase CIRA's racial and cultural diversity, DevCom ran numerous cultural activities, based on and coinciding with: the Lunar New Year, with treats and decorations traditional to the celebration; the holiday of Eid al-Fitr, which marks the end of Ramadan with delicious sweets and snacks; the mid-autumn or moon festival, a traditional festival in Chinese culture which we celebrated with a morning tea including traditional moon cakes; and finally the Indian festival Diwali, including painting our own *dias* (lamps). Volunteers from DevCom gave short explanations about the cultural significance of these cultural dates, accompanied by traditional foods from the respective cultures. All of these were well attended and enjoyed by CIRA members. We also celebrated the end of the year with a cultural lunch, in which CIRA members were each encouraged to bring a dish culturally significant to them, and to wear pyjamas for the day.

DevCom showed its recognition of and support for Indigenous Australian culture by running a series of initiatives coinciding with NAIDOC week. The Journal Club that week included a presentation on the deep ties to astronomy within the cultures of indigenous peoples, recognising First Nations peoples as the first astronomers in this region. Despite these initiatives,

↗ Pride Month.

Diwali celebration.

we recognise that Indigenous peoples are underrepresented at CIRA, and DevCom continues to explore ways to grow and foster inclusion and diversity in this area.

Another strong theme of 2022 has been the visibility and support of the diversity of gender and sexual orientation. While the paucity of women in astronomy (and more broadly, STEM) is a strong, ongoing focus of DevCom's activities, we also conducted some activities aimed at improving support and visibility of minority groups across the LGBTQIA+ spectrum.

J-P memorial ride.

ICRAR social sports archery.

Firstly, we facilitated CIRA becoming a bronze sponsor of the Women in Tech in WA (WiTWA) organisation, which is the leading advocate for diversity, inclusion, and equity for women in technology in Western Australia. To further promote an inclusive workplace for women, we facilitated the supply of feminine hygiene products in the women's bathrooms within our building. Finally, together with the UWA Diversity, Equity and Inclusion committee, we restarted the ICRAR senior women visiting fellowship, with the visit of Professor Tara Murphy during which she ran a career mentoring session for early PhD students and early career researchers.

We celebrated the LGBTQIA+ community during Pride month with a morning tea celebration including flag crafting and plenty of colourful snacks. DevCom also encourages all CIRA staff and students to put their pronouns on public display, either with pronoun stickers kindly provided by ICRAR-UWA, or including pronouns on various online platforms commonly used at CIRA (e.g. Slack, Teams, Webex).

DevCom supports a number of social initiatives aimed at fostering the physical and mental well-being of CIRA's members. Many of these activities are organised and run by volunteers (e.g. yoga sessions, hiking events, sporting clubs, social movie viewings). DevCom also organised activities such as the mental health session we ran during WA mental health awareness week which involved a dedicated journal club talk on mental health awareness and resources, and a wellness session in which we practiced guided meditation and stretching with the help of Vishwanath Deshmukh from the Art of Living Foundation. These events do a great deal to foster sociability and comradeship among CIRA's ever-growing staff and student bodies.

Mental health and wellbeing session.

The 2022 CIRA Development Committee consisted of Adelle Goodwin (Chair), Nipanjana Patra (outgoing), Budi Juswardy, Mia Walker, Anshu Gupta, Adelle Goodwin, Mawson Sammons, Ben Quici (outgoing), Kariuki Chege (outgoing), Garvit Grover, Susmita Sett, and Steve Prabu.

Tracking the debris of a star torn apart by a supermassive black hole

ADELLE GOODWIN
JAMES MILLER-JONES
GEMMA ANDERSON

What happens when a star gets too close to a supermassive black hole?

A tidal disruption event (TDE) occurs when an unlucky star wanders too close to a supermassive black hole and is destroyed, producing a bright flash that can be visible across the electromagnetic spectrum. While approximately half of the star swirls in towards the black hole, trapped by its massive gravitational field to eventually be consumed, the other half of the stellar debris is ejected out into the central regions of the host galaxy at high velocities.

Broadband radio observations of TDEs trace emission from these outflows or jets that are ejected from the vicinity of the supermassive black hole. As the outflowing material moves through the environment around the black hole it collides with the clouds of gas and dust that are there, producing light/energy and giving us rare insights into the environment close to the supermassive black holes at the centres of extremely distant galaxies. Observing how the radio emission of TDEs evolves over months to years allows us to trace the motion of this ejected material and gain insight into how black holes eject material. However, radio detections (and radio monitoring observations) of TDEs are very rare, with less than 20 published to date.

On February 23rd, 2021 we triggered a radio observation with the Karl G. Jansky Very Large Array (VLA) of a newly discovered TDE, AT2020vwl, as part of a program involving a large collaboration of TDE researchers around the world. We detected a point source, and subsequently triggered a monitoring campaign of this radio outflow spanning almost 2 years (Figure 2).

Figure 1
Artist's impression of a tidal disruption event.
IMAGE: DESY/Science Communication Lab

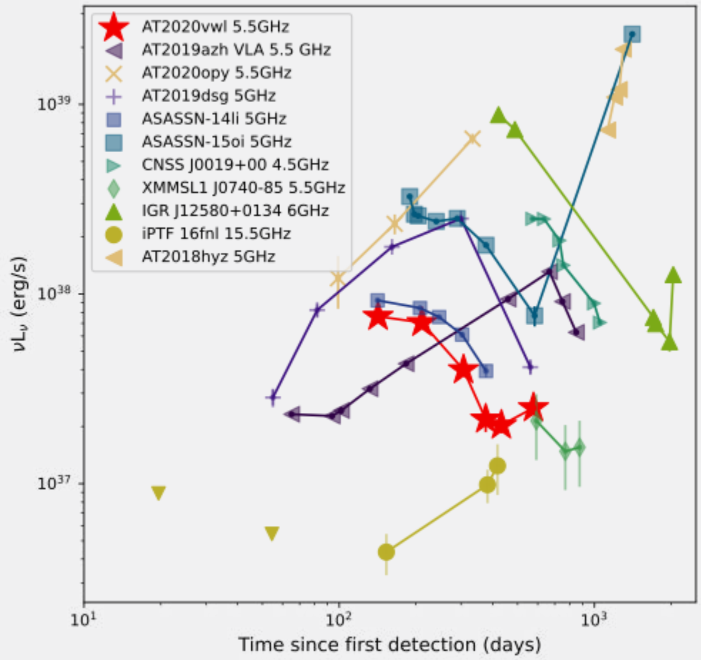
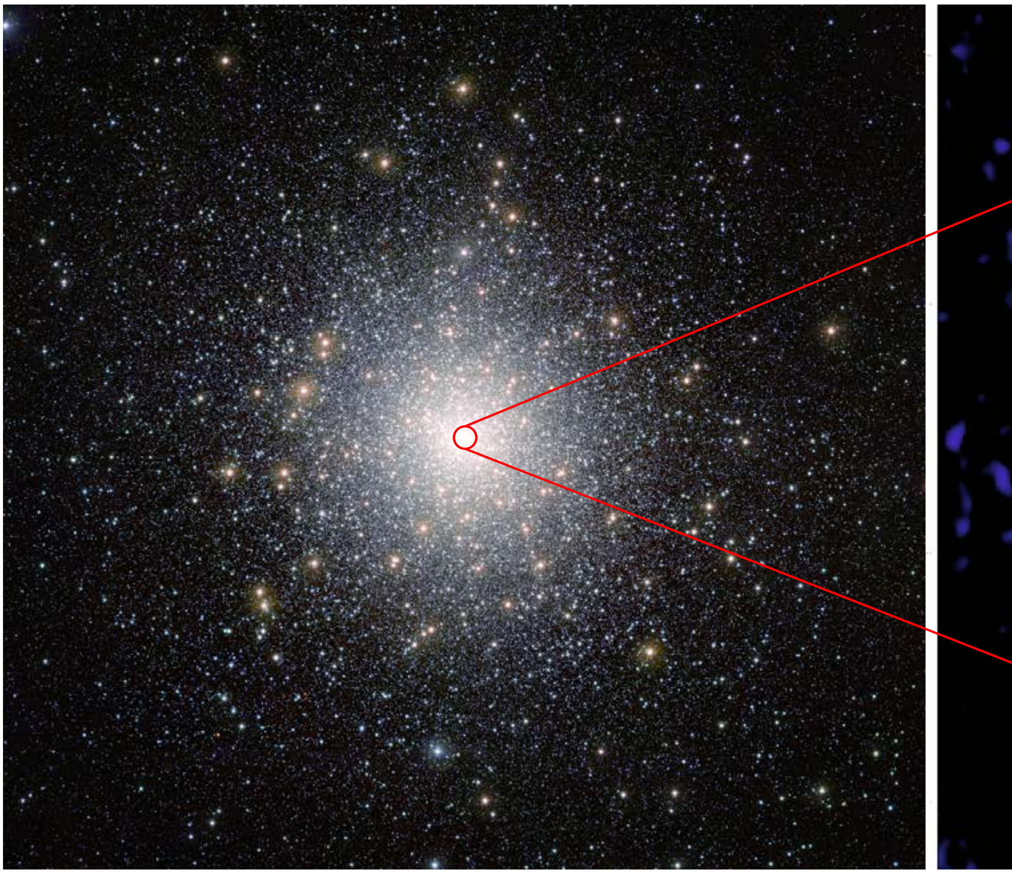


Figure 2
The 5.5 GHz radio luminosity curve of AT2020vwl (red stars) compared to those of selected other radio-bright TDEs. The x-axis indicates the time since the first detection (optical, radio, or X-ray depending on the source) of each TDE.

We tracked the evolution of the outflowing material as it expanded and moved away from the supermassive black hole. Through modelling the radio emission of the event we found that the outflow was moving at non-relativistic speeds (approximately 10% the speed of light) and was launched around the time of the initial optical detection. These details then allowed us to deduce the likely mechanisms that produced the outflow, a long standing unknown in the field. We found that the outflow is likely to have been launched by material ejected from stream-stream collisions of the stellar debris, the unbound debris stream, or a wind or jet driven by accretion onto the supermassive black hole. AT2020vwl joins a growing number of TDEs with well-characterised prompt radio emission, with future timely radio observations of TDEs required to fully understand the mechanism that produces this type of radio emission. This study, led by Adelle Goodwin, has now been accepted in MNRAS.

A faint radio source in the centre of a globular cluster

ALESSANDRO PADUANO
JAMES MILLER-JONES
ARASH BAHRAMIAN



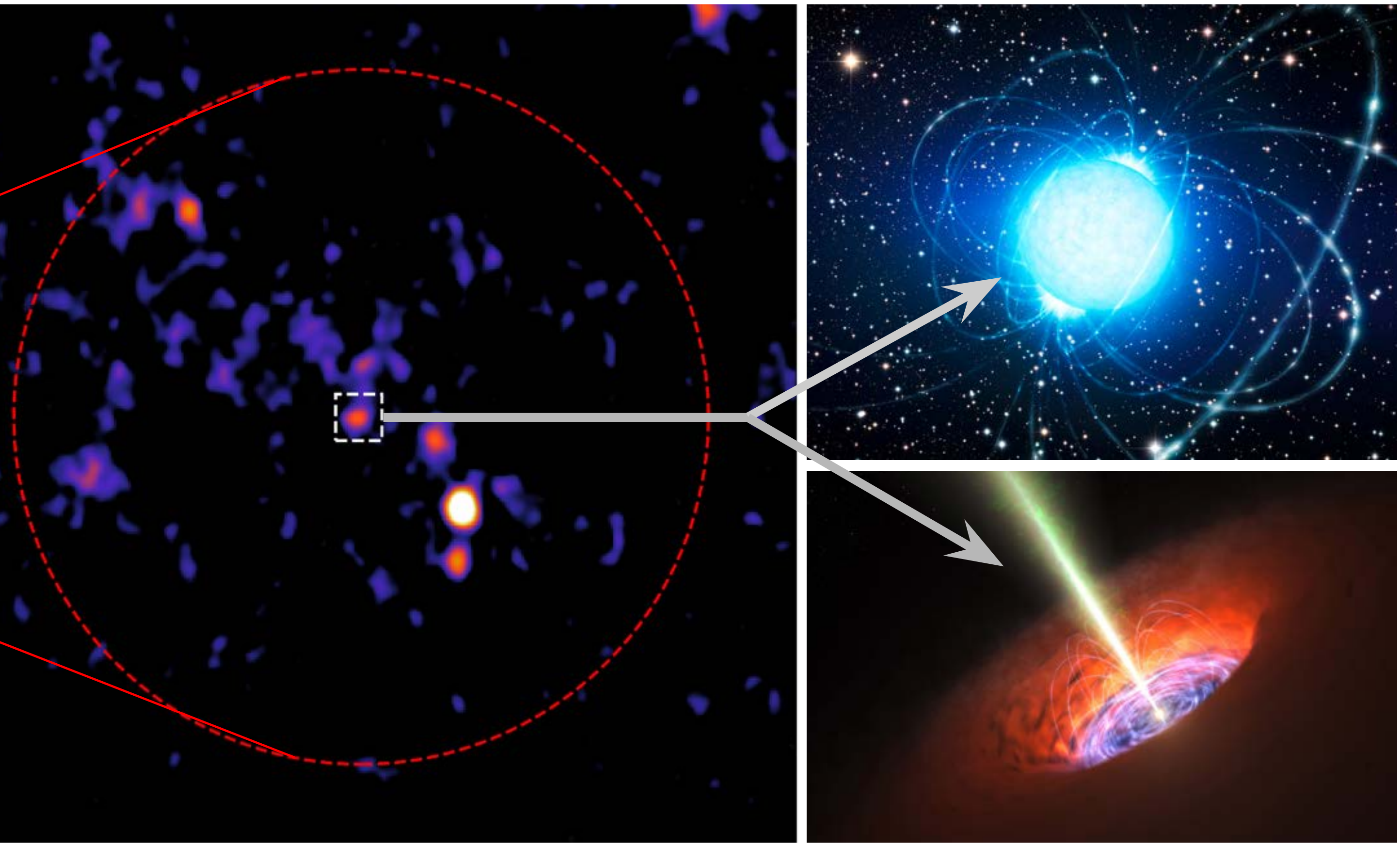
Black holes have been studied extensively in two mass regimes. *Stellar-mass* black holes formed from the deaths of massive stars, and have masses between 3 and 20 solar masses – although gravitational-wave observatories are detecting more massive objects, up to 140 times the mass of the Sun. There are thought to be up to 100 million such objects roaming our Milky Way galaxy. *Supermassive* black holes, on the other hand, weigh in at millions to billions of solar masses, and are found at the centres of galaxies. Our own supermassive black hole, known as Sagittarius A*, has a mass of 4.2 million solar masses, and was recently imaged by the Event Horizon Telescope.

Theory tells us that the supermassive black holes that we see today must have evolved from much smaller seed black holes, with masses of or perhaps thousands of solar masses, known as *intermediate-mass* black holes. Over time, accretion of gas and mergers with other black holes have grown them into the cosmic behemoths that we see today. However, despite decades of searching, scant evidence exists for black holes in this intermediate-mass range.

One potential venue for the formation and subsequent growth of intermediate-mass black holes is the centre of a dense star cluster. Either sequential mergers of multiple stellar-mass black holes in the densest regions of the cluster, or the runaway growth of a massive object through stellar collisions could lead to the formation of an intermediate-mass black hole. This then suggests that some modern-day globular clusters could host such a dark mass at their centres.

Many previous studies have searched for indications of an intermediate-mass black hole in the centres of globular clusters, by looking at the central stellar velocity dispersion or mass-to-light ratio. However, the gravitational sphere of influence of an intermediate-mass black hole is small, and such studies have typically been limited by shot noise, and their conclusions open to debate. Other studies have used the accelerations of pulsars in the centre of the cluster to constrain the presence of a massive, unseen central object. A final method of searching is to look for the signatures of accretion; detecting the X-ray emission arising from cluster gas falling into the black hole, and the radio signatures of any associated jets. The deepest such studies have constrained the mass of any intermediate-mass black holes in Milky Way globular clusters to less than a few hundred solar masses.

In 2021 and 2022, we used CSIRO’s Australia Telescope Compact Array (Narrabri, NSW) to observe the



↙ **Left panel:** The globular cluster 47 Tucanae as seen in optical light. Centre panel: Our deep radio image of the core of the cluster (denoted by the red dashed circle), with the central source indicated by the white box. The noise level is 790 nanoJy/beam.

↘ **Centre and Right panels:** Possible explanations for the central radio source are a millisecond radio pulsar (top) or an intermediate-mass black hole (bottom).
IMAGE: Left panel: ESO/M. R. Cioni/VISTA Magellanic Cloud survey; Centre panel: Paduano et al. (submitted); Right panel: ESO/L. Calçada.

nearby globular cluster 47 Tucanae for over 400 hours, aiming to study the population of faint radio sources in this well-known cluster. Our final image, made using all available archival and new data, comprised 480 hours of observation, and reached a noise level of 790 nanoJansky. This is the deepest image ever made with an Australian radio telescope, pushing the limits of what could be achieved with an existing radio facility to reach SKA-class sensitivity.

As well as a spectacular image, these data revealed a faint radio source that was positionally coincident with the centre of the cluster. It was also consistent with a faint X-ray source that had been detected in the deepest X-ray image of the cluster, made several years ago with NASA’s Chandra X-ray Observatory. The combination of faint radio and X-ray emission from this object could be explained by two possibilities. It could be the long-sought signature of an intermediate-mass black hole, of about 500 solar masses. Alternatively, it could be a previously-undetected millisecond radio pulsar. While the former would be particularly exciting, the detection of a pulsar so close (at least in projection) to the cluster centre could in future be used to constrain the presence of an intermediate-mass black hole.

Discriminating between these two possibilities will require sensitive radio searches for pulsations, either with the MeerKAT telescope in South Africa, or with the SKA itself. Should such searches draw a blank, it would build the case for an intermediate-mass black hole at the centre of 47 Tucanae. Deep radio observations with the SKA across a wide range of frequencies could be used to help ascertain the nature of this interesting object. Either way, we can look to the SKA to reveal its secrets!

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Galactic-scale gas outflows in the early universe

Image 1
Hubble image of galaxy M82 with blue and green indicating visible light, and red indicating infrared. The biconical and extended emission in infrared emission is produced by outflowing gas driven by the starburst activity.

ANSHU GUPTA

The first galaxies in the universe created bubbles of ionised gas that overlapped with each other, which led to the largest phase transition in the history of the universe known as the epoch of reionisation (EoR). However, we don't know much about the galaxies involved in the phase-transition due to the high opacity of the neutral intergalactic medium.

The MOSEL survey looks at galaxies that have similar properties to those in the neutral universe but are present in the ionised universe, the “EoR analogues”. We in Gupta et al., (2022) analysed the strength of galactic-scale outflows in the EoR analogues by stacking the [OIII] emission spectra. The data is taken by the *K-band Multi-Object Spectrograph (KMOS) on the Very Large telescope (VLT)* in Chile. Multiple kinematic components in the emission profile suggest that gas is either flowing in or out of the galaxy.

Galactic-scale outflows play a crucial role in the evolution of galaxies and the surrounding environment. These outflows occur when gas is pushed out of a galaxy by the energy released from star formation or from a supermassive black hole at the center of the galaxy. They transport energy and heavy elements created by stars, and thus are essential for the chemical enrichment of the intergalactic. They also create channels in the interstellar medium of galaxies, enabling the escape of ionised radiations. Theoretical models assume strong outflows in the early universe due to the high star formation densities in the first galaxies.

However, we could only detect weak outflow in the EoR analogues, despite their high star formation rates. In fact, the outflow strength in EoR analogues is similar to other samples, even if EoR analogues have 10 times higher star formation rates than the rest. Our result suggests that either the gas is too hot to contain oxygen atoms in lower ionisation state (>10^5K) or that efficient cooling in a dense medium prevents transport of gas to large distances.

In addition to weak outflows in the EoR analogues, we made another interesting observation in one subset of their sample. We found a secondary kinematic component that was detected as redshifted to the systematic velocity of the sample, which means it was coming from the inflowing gas around the low-mass galaxies. This finding is puzzling because there are currently no detections of ionised gas inflows around galaxies, and it is difficult to heat up the inflowing gas to temperatures high enough to produce [OIII] emission (~10^4 K). Gas inflows are more prominent in the early universe, and this observation could provide new insights into the inflow-outflow balance in the interstellar medium of galaxies.

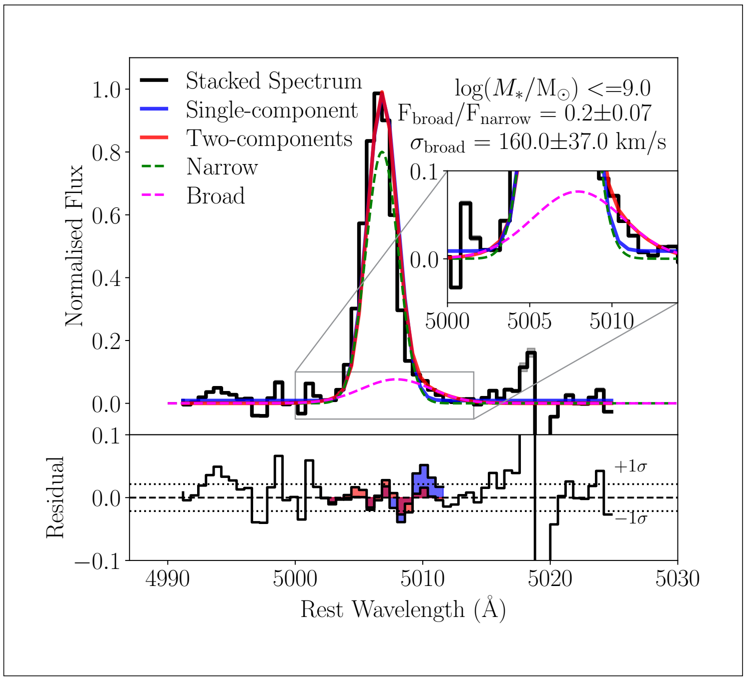


Image 2
Stacked [OIII] spectrum overlaid with best-fit 1-component (blue) and 2-component (red) spectrum. The 1-component fit has clear residuals redshifted to 5010 A that may be coming from the inflowing gas. Taken from Gupta et al., (2022).

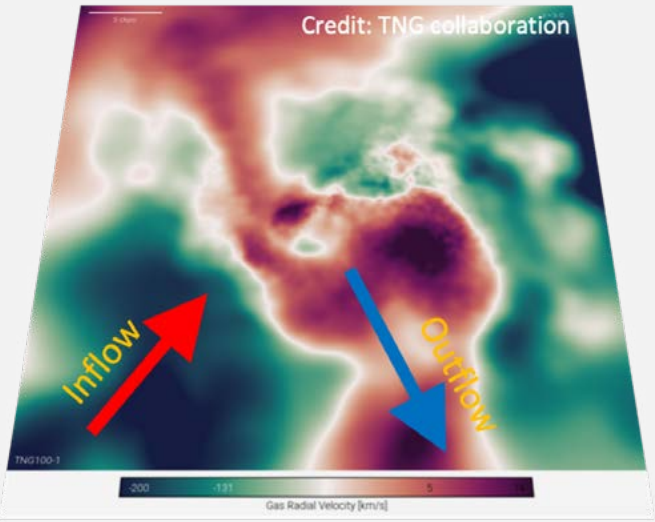


Image 3
Radial velocity of gas around a galaxy. The velocity components from the gas in galaxy are shown as a black curve, the inflowing gas as a red curve and the outflowing gas as a blue curve. IMAGE: TNG collaboration

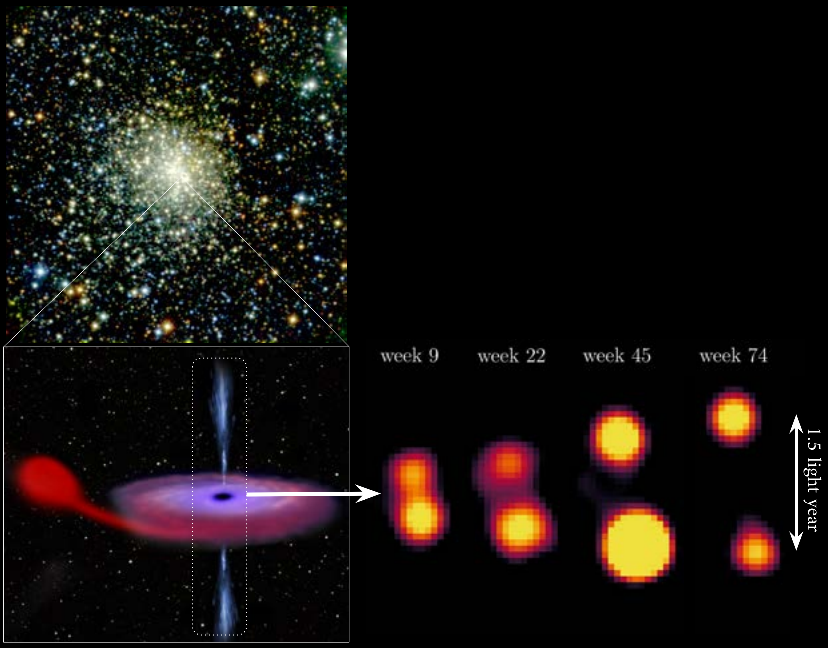
The Discovery of the First Microquasar in a Star Cluster

ARASH BAHRAMIAN
JAMES MILLER-JONES

Microquasars are binary systems that consists of a normal star in close orbit around a black hole or a neutron star. These systems are known for their high-energy emission, which is thought to be produced by the accretion of matter onto the compact object. One of the distinguishing features of microquasars is the launching of powerful radio jets, which can extend for several light years.

The launching mechanism of radio jets in microquasars is not well understood, but it is thought to involve the magnetic fields around the black hole or neutron star. The accretion disk surrounding the compact object can generate a powerful magnetic field, which can channel the inflowing matter into a narrow jet that is ejected at high speeds. The jet is then accelerated to relativistic velocities as it propagates away from the compact object, producing a powerful radio emission that can be detected from Earth.

After the discovery of a new accreting black hole candidate in the dense Galactic star cluster GLIMPSE-C01, we initiated a high-cadence radio monitoring campaign with the MeerKAT telescope, the South African precursor to the Square Kilometre Array, for more than 500 days, to study the jets in this system. Our observations led to the discovery of some of the brightest moving (near the speed of light) jets ever observed from a microquasar, and notably, for the first time in a star cluster. Our observations enabled us to estimate the immense amount of energy released in these jets, indicating that they are more likely to be produced by a black hole, as opposed to a neutron star. The discovery of a microquasar in a star cluster is particularly exciting, as these dense star clusters host a complex environment because of interactions between stars, interstellar gas, and the cluster as it travels through the Galaxy. These newly discovered jets allow us to probe the cluster environment for the first time in exquisite detail, as the jets propagate through the cluster medium.



▨ **Figure 1**
Infrared view of the Galactic star cluster GLIMPSE-C01 from the European Southern Observatory (credit: ESO, Ivanov et al. 2005). Bottom left: artist's depiction of a microquasar, where a black hole or neutron star accretes matter from a companion star in the form of a disk and ejects powerful jets (credit: ESA/ATG medialab). Bottom right: a timelapse of our MeerKAT observations of the radio jets ejected from the newly discovered microquasar in GLIMPSE-C01. These jets propagate through interstellar space at speeds comparable with the speed of light.

Tracking the Motions of Jets Launched by Accreting Black Holes

CALLAN WOOD
JAMES MILLER-JONES
ARASH BAHRAMIAN
STEVEN TINGAY

As matter falls onto a black hole via a process known as accretion, powerful jets are often launched, which can travel away from the black hole at close to the speed of light. X-ray binaries within our own Galaxy, which are systems consisting of a black hole accreting matter from a companion star, are known to exhibit bright outbursts, during which such transient jets are launched. By imaging these jets with radio telescopes, we can track their motion and thus determine their precise ejection time, allowing us to identify the physical processes occurring in the inner accretion flow that are responsible for the launching of jets.

In order to image these jets, we use a radio astronomy technique called very long baseline interferometry (VLBI), by which the signals measured by multiple telescopes separated by thousands of kilometres are combined together to create a virtual telescope with enough resolving power to make out a two dollar coin in Sydney from Perth. However, imaging radio jets from X-ray binary black holes with VLBI is a challenging task due to their highly variable nature. These jets exhibit rapid variability in both intensity and morphology, making it difficult to reconstruct a high fidelity image during a typical few-hour observation, and thus precisely determine their position.

To address these challenges, we have developed a new technique where instead of directly imaging the observations, we fit simple models to the underlying data, where the models are allowed to vary with time. An example of a model is a small circular Gaussian emission region that has constant size, moves with constant velocity, and changes in brightness linearly with time. This technique allows us to track and measure the motion and brightness variability of jets within a single observation. An example of this technique is shown in Fig. 1, where we show two images of the X-ray Binary MAXI J1803-298. The images, with the colours and contours denoting brightness, show two different observations separated by a day. Between the two days there is some evolution of a component which moves to the south-east. With our modelling we were able to show that the component seen in epoch A was most likely stationary, and that the component in epoch B was moving during the observation. We were thus able to infer that in epoch A we detected the core of the system prior to the launching of a transient jet, which we observed in epoch B.

The development of new VLBI analysis techniques will be crucial for analysing the observations of future instruments like the SKA and the next generation Event Horizon Telescope (ngEHT). The ngEHT will have much higher sensitivity and angular resolution than the current generation of telescopes, and will observe at much higher frequencies, enabling us to study transient jets earlier in their evolution. By combining these observations with our modelling techniques, we will be able to better connect the ejection of transient jets to the changes in the inner accretion flow responsible for their launching.

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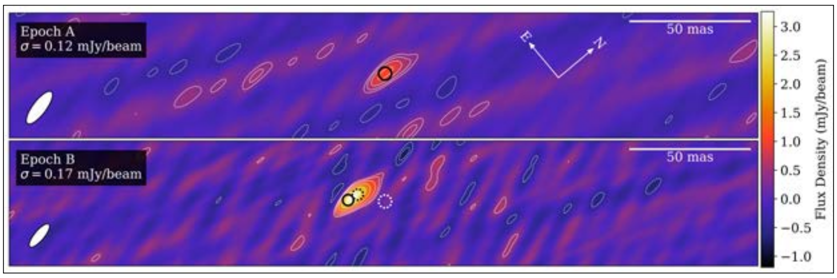


Figure 1
Images of MAXI J1803-298 from 13th May 2021 (Epoch A) and 14th May 2021 (Epoch B). The images have been rotated 50° clockwise (see arrows in the first panel), and all share the same colour scale as marked by the colour bar on the right. The black circle in the first panel marks the position of the circular Gaussian model component that was fit to the visibility data in this observation. Our modelling suggested that this component was stationary. This component is not present in epoch B, but its position is marked by the dotted white circle. In epoch B, our modelling revealed that the component was moving during the observation. The dotted black circle marks its fitted position at the beginning of the observation, and the solid black circle marks its position approximately 3.5 hours later, at the end of the observation. Without modelling, we would be unable to determine if either of the emission regions were showing intra-observational motion.

A new view of the Epoch of Reionisation: application of a Multifrequency Angular Power Spectrum to extract cosmological information

CATHRYN TROTT

Exploration of the first billion years of the Universe's history remains an ongoing challenge for observational astronomy, with neutral hydrogen gas obscuring much of the information about early galaxies, and the mapping of the hydrogen gas itself with radio telescopes technically difficult. Witnessing the formation of the first generations of stars and galaxies in the Universe, the Cosmic Dawn and Epoch of Reionisation within the first billion years remains a key period in piecing together the full evolution of the Universe.

In order to image these jets, we use Low-frequency radio telescopes that allow us to observe the cosmologically-redshifted emission from hydrogen gas in its neutral form. Prior to its "reionisation" by high energy light from the first generations of stars, the hydrogen gas fills the cosmos, tracing the physical and radiative properties of the environment and providing the signatures of the early Universe's evolution. This hydrogen signal, however, is extremely weak, and contaminated by other signals at the same frequencies, making direct detection only possible with the next-generation of telescopes. Instead, the Murchison Widefield Array (MWA) experiment combines data together in such a way to extract the properties of the hydrogen gas, rather than directly attempting to measure it.

In this work we used a different approach to extracting the signal statistics, employing an estimator that had been developed by a research group in India, but never applied to real experimental data. The Multi-Frequency Angular Power Spectrum estimator, MAPS, developed by Rajesh Mondal and colleagues, avoids some of the shortcomings of the typical power spectrum estimator for band-limited data, but suffers from the effects of dominant contaminant foreground galaxy signals. This was the first attempt to apply this well-developed estimator to real data, with some potential benefits being identified. One such benefit is that it avoids the problems of signal evolution, providing local information about the brightness temperature distribution evolution, rather than mixing information from different lookback times in the Universe where the physical conditions have changed.

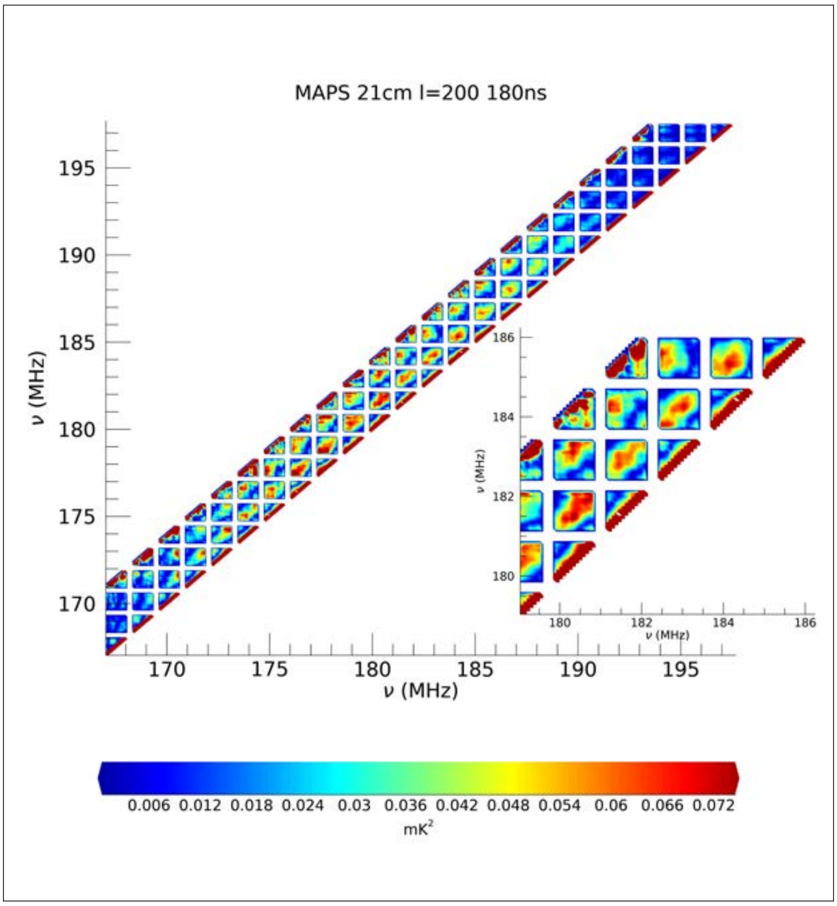


Figure 1

Figure 1 shows the MAPS as a function of different frequency channels for 110 hours of MWA high-band data, where the frequency channels map to different lookback times in the Universe. The colours denote different temperatures of the hydrogen gas, with the inset showing increased resolution for clarity. The MAPS extracts cosmological information across independent frequency channels, highlighting frequency correlations in the signal as a way of separating early Universe signal from contamination by other radio galaxies.

Ionospheric subtraction with *hyperdrive*

CHRIS JORDAN
DEV NULL

hyperdrive is the next generation of MWA calibration software, developed by CIRA's Chris Jordan and Dev Null. It takes the best aspects of *mwa-reduce*'s *calibrate* and the *Real-Time System (RTS)*, forming an efficient, accurate and easy-to-use software suite. To date, *hyperdrive* has focused on direction-independent calibration, which has already improved the state of calibration within the MWA Epoch of Reionisation (EoR) team. However, to make further progress, the EoR team needs to be able to accurately "remove" bright foreground objects from their observations. A crude subtraction method has been available in *hyperdrive* for a long time, but recently "ionospheric subtraction" has been implemented.

The MWA is a low-frequency radio telescope, which means that its data can be corrupted by the presence of the ionosphere. "Ionospheric subtraction" is the term we're giving to one of the techniques used to help mitigate this corruption. The positions of sources are found in visibility space, and subtracted there rather than where we expect the source to be. This results in cleaner data, ultimately helping us to detect the elusive EoR signal.

The *RTS* is also able to perform ionospheric subtraction, and was used by the EoR team in the past. However, a number of considerations make usage of the *RTS* untenable:

- The *RTS* requires simultaneous use of 25 GPUs, whereas hyperdrive only needs one;
- The *RTS* is extremely difficult to use correctly; and
- *RTS* output files are much more difficult to interface with.

The next steps for *hyperdrive* are to further test and improve ionospheric subtraction, as well as implementing peeling. All of these efforts will help the EoR team to improve their understanding of MWA data and publish more limits papers over shorter time scales.

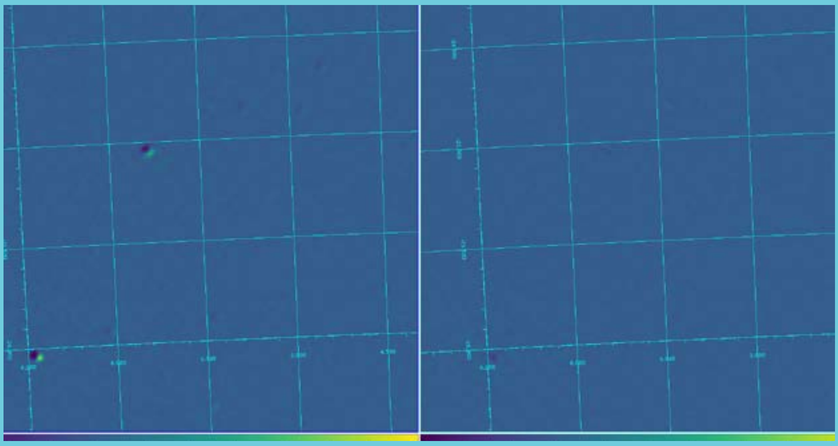


Figure 1
A comparison of a single observation with (left) direct subtraction and (right) "ionospheric subtraction". We see that the residuals of normal subtraction are dramatically mitigated when the ionosphere is taken into account.

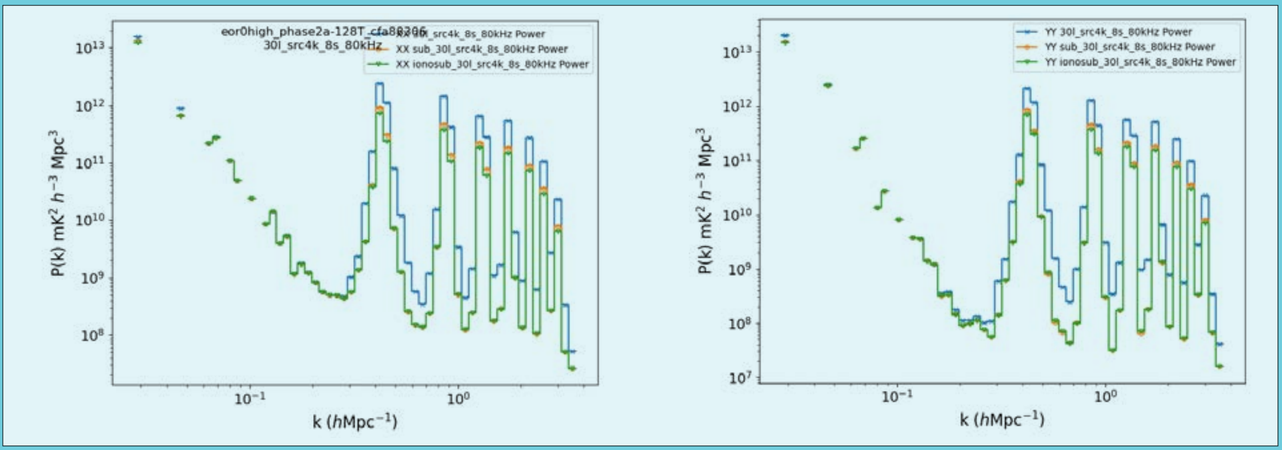


Figure 2
1D-average EoR power spectra of (blue) calibrated visibilities, (orange) subtracted visibilities, and (green) "ionospherically subtracted" visibilities. We see that ionosub removes the most power, bringing us closer to an EoR detection. All processing was performed with hyperdrive.

The Most Distant Fast Radio Burst

CLANCY JAMES

The Commensal Realtime ASKAP Fast Transients (CRAFT) project with the Australian Square Kilometre Array Pathfinder (ASKAP) continues to make astounding discoveries. 2022 saw the detection of seven new fast radio bursts (FRBs), chief among them FRB 20220610A. This burst was localised using the 'CELEBI' analysis pipeline developed by Curtin PhD student Danica Scott, with the aid of Dr Marcin Glowacki and other CRAFT members, with optical follow-up observations as the Very Large Telescope in Chile revealing the host galaxy (see Figure 1). This galaxy is the most distant FRB host yet identified, at a redshift of 1.016 – meaning that FRB 20220610A had been travelling for seven and a half billion years to reach us! This is turn makes this FRB the most powerful burst ever detected that has a reliable energy estimate.

The observation of FRB 20220610A posed a dilemma however. Its dispersion measure – a measure of amount of cosmic gas between us and it – was even larger than expected for its redshift, at 1458 pc cm^{-3}. Analysis by PhD student Mawson Sammons, Dr Clancy James, and other CRAFT researchers showed it was difficult to attribute this large dispersion measure to any one source: neither the FRB progenitor itself, the host galaxy, nor the intergalactic medium could alone account for it. Resolving this mystery is an ongoing topic of research within the CRAFT collaboration.

2022 also welcomed a new researcher, Dr Apurba Bera, to the CRAFT team at Curtin. His expertise will be needed: the CRAFT coherent upgrade (CRACO) on ASKAP is due to be commissioned this year, and enable a ten-fold increase in the number of FRBs detected. We expect this new data sample to resolve cosmological questions, such as how fast our Universe is expanding.

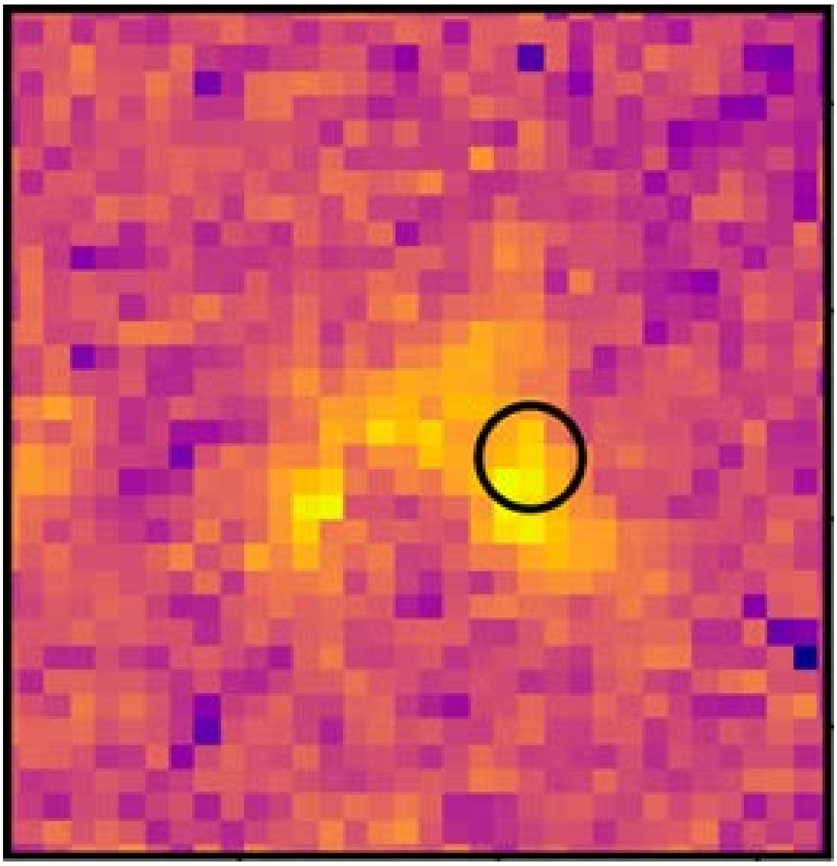


Figure 1
The host galaxy of FRB20220610A. At 7.8 billion light years away, this galaxy – or galaxy group - appears as a smudge even when viewed with the Very Large Telescope. The FRB location is indicated by the black circle.
IMAGE: S. Ryder et al., arXiv:2210.04680v1 [astro-ph.HE] 10 Oct 2022

WALLABY Pre-Pilot Survey: Radio Continuum Properties of the Eridanus Supergroup

JOE GRUNDY

The WALLABY pre-pilot survey observed the Eridanus supergroup and we performed the first in-depth radio continuum science using WALLABY early science data. We looked to examine the relationships between HI and continuum observations on a population of galaxies known to be undergoing environmental pre-processing. Radio continuum emission is produced in star-forming galaxies by massive young stars as they ionise their surrounding neutral hydrogen (HI) gas envelopes and then explode as supernova, producing shocks that emit synchrotron radiation. These massive young stars also heat the surrounding dust and molecular clouds which re-radiate in the infrared (IR). Hence both the radio continuum emission and the IR emission are linked to star formation resulting in the widely corroborated infrared-radio correlation (IRRC). Understanding how the radio continuum and IRRC are related to the physical properties of star-forming galaxies (SFGs) will be key to understanding future survey data that will be produced by the SKA and its pathfinders.

We examined the star-formation properties of these galaxies using a number of different methods and find that they are primarily passive disks that are not significantly starbursting. We then created resolved IRRC maps for each galaxy to investigate whether we can observe the group environment pre-processing effects which are visible in the WALLABY HI observations. Whilst the low SFR's of our sample limit our ability to observe the radio continuum throughout the galactic disks of our sample, we find that the resolved IRRC can be used to easily discriminate between active galactic nuclei (AGN) and SFGs as well as identify background radio sources. We find evidence for environmental pre-processing in NGC 1385 due to the coincidence between the IRRC gradient and HI disturbance. The gradient in the IRRC is postulated to be caused by cosmic ray (CR) electron streaming due to tidal reacceleration or ram-pressure. Resolved studies like this will be important for future surveys as understanding how the radio continuum and IRRC within galaxies can be modified by environmental effects will allow us to explain what causes discrepancies in these properties when measured as part of large-scale population analyses.

FOR FURTHER INFORMATION

If you want to read more, please check out my paper accepted for publication in PASA or the ArXiv and at the DOI: **https://doi.org/10.25919/8ga8-0n09**.

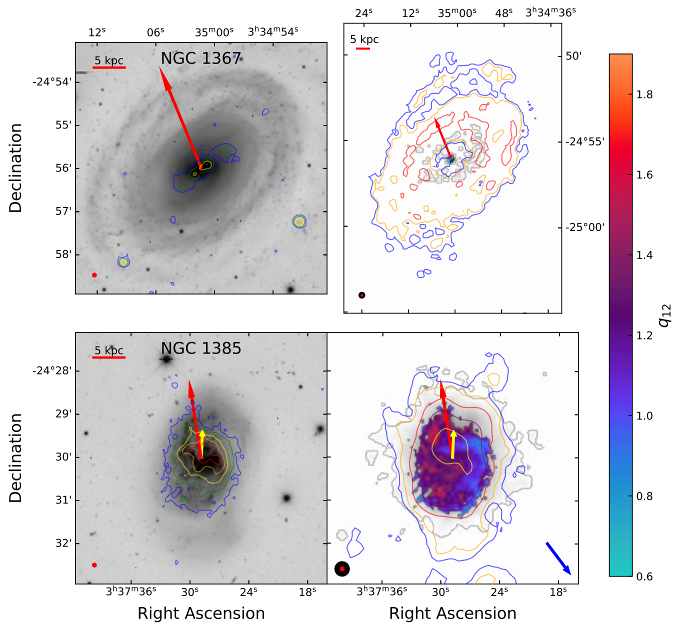


Figure 1

The left column shows the 1.37 GHz WC contours overlaid on the SDSS g-band image. The right column shows the q12 map with colours ranging from 0.6 (cyan - radio excess) to 1.9 (orange - radio deficient) overlaid on *WISE* W3PAH with HI contours from For et al. 2021. The WC clearly shows the AGN jets and lack of star formation in NGC 1367. NGC 1385 has star formation throughout the disk and a radio deficit region on the leading edge as well as radio excess in the direction indicated by the blue arrow. This along with the HI disturbance is indicative of pre-processing effects such as tidal interactions causing CR electron streaming in this direction. IMAGE: Grundy et al. (2023)

New techniques toward detecting Cosmic Dawn

DANNY C. PRICE

The first stars and galaxies formed during a period known as the 'Cosmic Dawn'. When the light from these first stars pierced the infinite darkness, their radiation quickly heated and ionised their surroundings. This rapid ionisation process should give rise to a global (i.e. isotropic across the sky) signal that a radio telescope can measure. The physics of the early Universe are imprinted upon this signal, so if we detect it, we will be able to unravel the history of the early Universe.

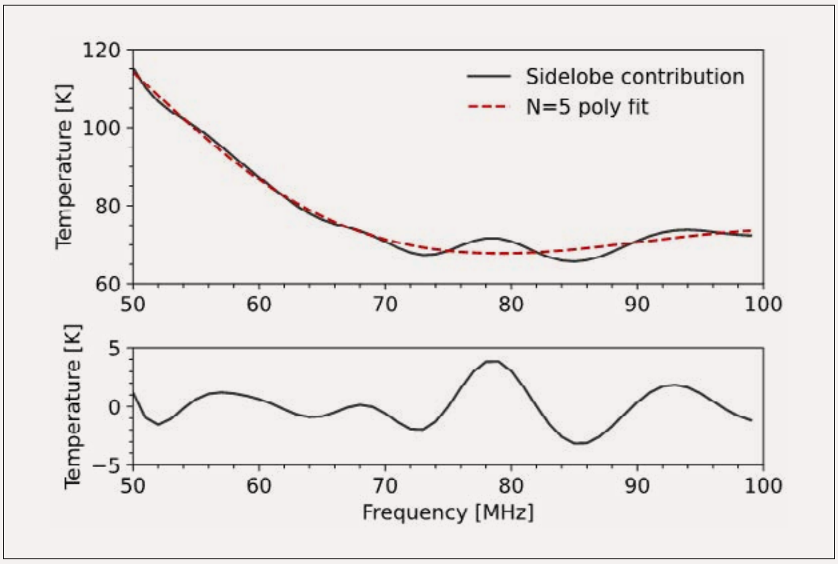
Detecting this signal has, however, proven fiendishly difficult. This last year, I investigated new approaches that could help detect the global Cosmic Dawn signal [1,2]. The first is a new approach for characterising noise generated by amplifiers. Self-noise from amplifiers is a key systematic that must be accounted for in global signal experiments. The approach expands on previous CIRA research on measuring noise parameters [3]. The new approach is ideal for global signal experiments as it works at low radio frequencies and does not require expensive equipment.

The second approach I investigated is whether a beamformed radio telescope can detect the global signal. A beamformed telescope has a complex beam pattern that changes across frequency; previous studies argued that the global signal cannot be detected if a telescope has a frequency-dependent beam. I ran simulations which showed that the width of the beam can vary without impeding signal detection, but the complex behaviour outside the main beam (called 'sidelobes') can be problematic. But if sidelobes can be sufficiently suppressed, the global signal could indeed be detected with a beamformed telescope.

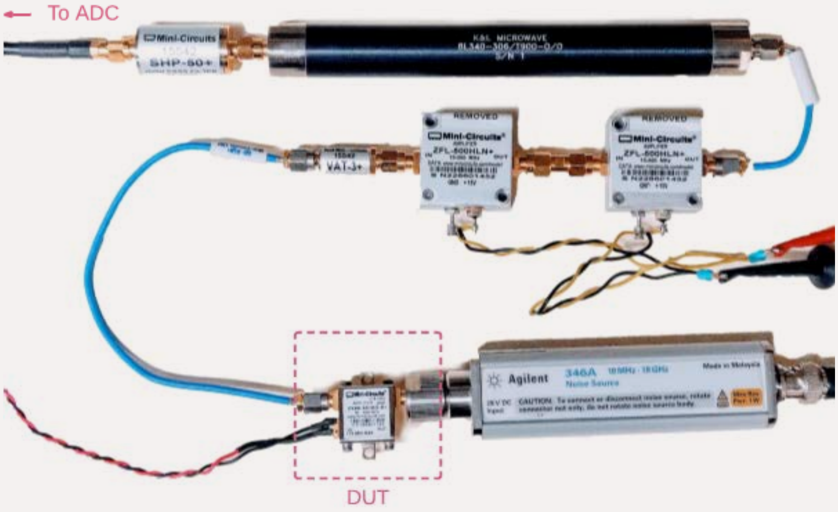
Nevertheless, it would be difficult for existing beamformed telescopes to suppress their sidelobes enough to detect the global signal. However, radio arrays have other tricks up their sleeves that could help, such as forming multiple beams, or imaging the diffuse Galactic foregrounds that are the main confounding issue.

There are other approaches to detecting the global signal, such as the CIRA-based SITARA experiment

[4], that could detect the global signal. And of course, many of us at CIRA are busy working on power spectrum experiments with the MWA. I am optimistic that the light from the Cosmic Dawn will not stay hidden forever.



↗ **Figure 1**
For a beamformed telescope, the contribution of sidelobes to the measured sky temperature (top panel, simulated data) will confound detection of the global Cosmic Dawn signal. The bottom panel shows the systematic residual after subtracting a log-polynomial fit. Reproduced from [2].



↗ **Figure 2**
A simple experimental setup for measuring the noise parameters of a device under test (DUT). More details can be found in [1].

ENDNOTES

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Commercial Supercomputing comes to Radio Astronomy

IAN KEMP (PRIMARY AUTHOR)
STEVEN TINGAY (CIRA EXECUTIVE DIRECTOR)
STUART MIDGLEY (DUG TECHNOLOGY)
DANIEL MITCHELL (CSIRO SPACE & ASTRONOMY)

Modern radio astronomy is critically dependent on the availability of high performance computing (HPC). As our telescopes get larger, and generate vastly more data, it might be expected that computing will become a bottleneck on the realisation of science from new instruments such as the SKA.

My research suggests the opposite: that we face a future of cheap and plentiful computing which will enable new science and new forms of investigation. In my PhD research I am using case studies to investigate new approaches to astronomy which may open up with such a future.

'Moore's Law' – the exponential growth of computing power – was expected to come to an end in the 2000's as we hit the dual limits of quantum mechanics (minimum component size) and the speed of light (maximum chip size). But the industry responded by developing architectures based around parallelisation: all new supercomputers have thousands of chips networked together and orchestrated centrally.

Another industry trend is that large commercial operators are emerging. Within 10 years, we expect to see a number of commercially available computing platforms, in the region of 40,000 times more powerful than today's largest national computing facilities.

One of my first case studies has been a scale-up of an image-based search for Fast Radio Bursts in MWA data, inspired by a study published by Professor Tingay in 2015, using the DUG commercial system in Perth. To fully harness modern HPC architecture it is essential to use code which can take full advantage of parallel processing, and to maximise the number of computations which can be packed onto each core and onto each node.

Tingay's approach in 2015 was based around the extraction of dynamic spectra of pixels in cleaned radio snapshot images. It was quickly apparent that the 2015 approach would not scale well as it was not conducive to parallel processing. For example, construction of dynamic spectra of pixels dispersed at 500 pc.cm-3 normally require measurement sets to be assembled in their time sequence of observation, which does not lend itself to parallel processing.

My first task was to reformulate and 'parallelise' the problem. This was done by making the basic unit of computation a 24-channel 1MP image cube of a 2-second snapshot. Typically 60 snapshots can be created from each 2-minute measurement set, and then processed by difference imaging and de-dispersion entirely in memory. Allocation of one supercomputer node (with 64 cores and 128GB of memory) to each measurement set allows all snapshots to be processed simultaneously. The end point is the extraction of Gaussian statistics on pixels in the dispersed images to identify candidate FRBs with an intensity greater than 7 sigma.

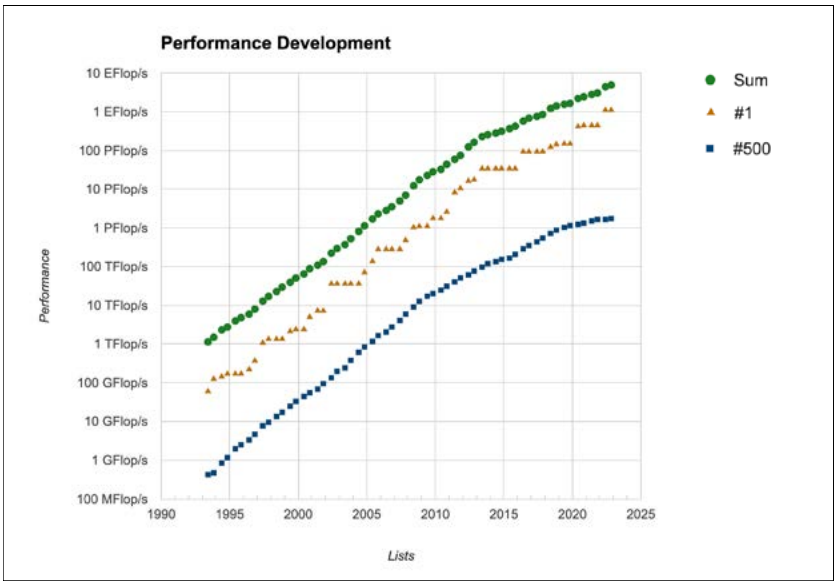


Figure 1
Continuing exponential growth in supercomputing: IMAGE: top500.org

This approach, together with the use of 'RAM drive' to ensure that data is maintained on the node at all times, results in a run time of around 15 minutes. With thousands of nodes available, 10 hours of observation time (334 measurement sets) were processed in 25 minutes, which compares well with a test run of around 72 hours per measurement set using 'serial' file based computing.

For 2023 this case study is continuing, with a similar search of ~100 hours of observations of the EOR0 field, which was recently re-calibrated by the EOR team using *hyperdrive*. This data is currently being prepped for processing at DUG, with an expected total run time of one hour, using 1500 KNL nodes.

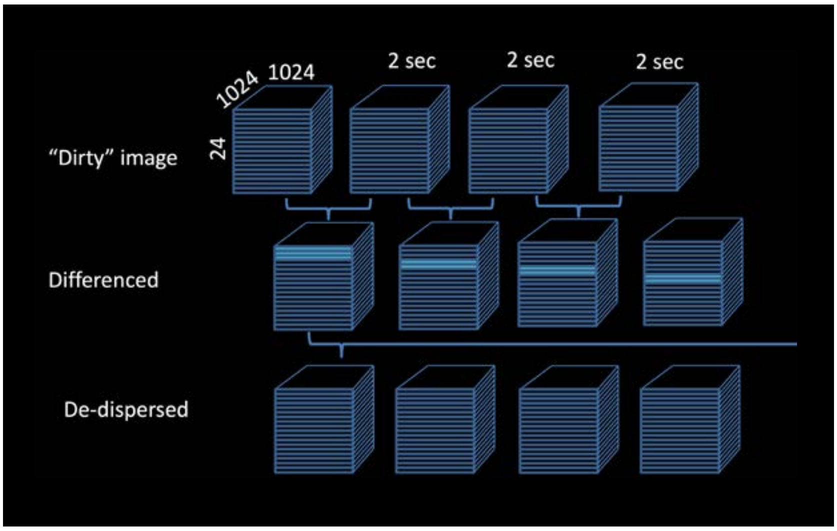


Figure 2
Parallel processing approach for image-based FRB search.

With a brand new supercomputer being planned at DUG, there is the possibility of processing the entire 44 Petabyte MWA archive before the end of my PhD.

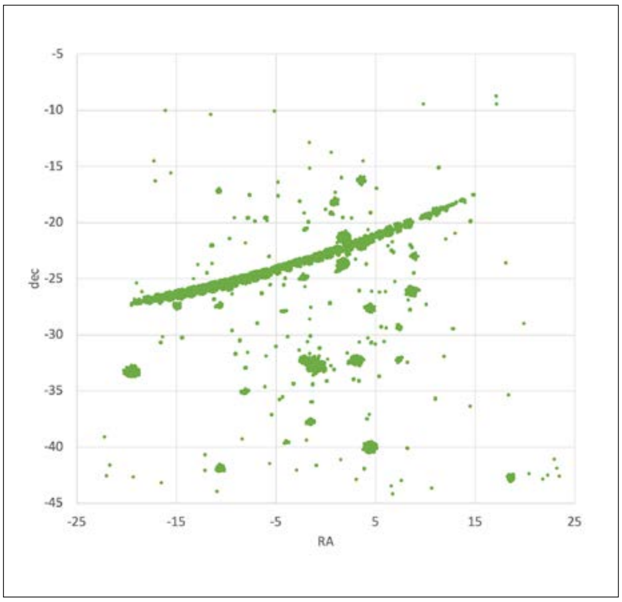


Figure 3
Some of the issues in processing are scintillation of bright radio sources (dots) and intereference from satellites (large curved track).

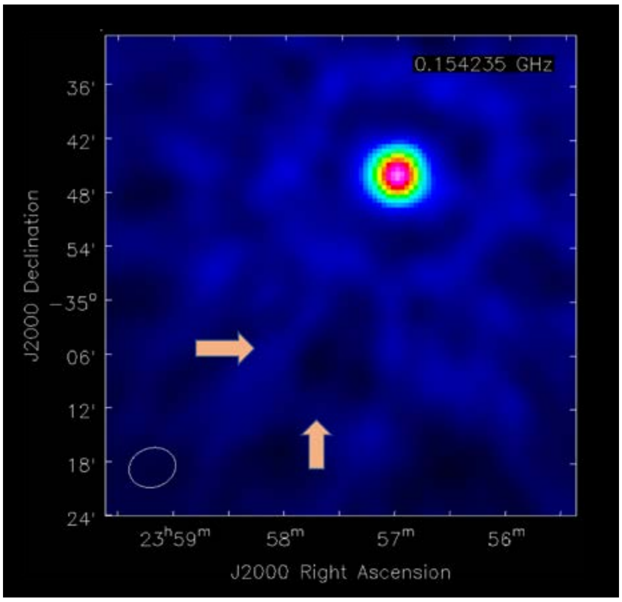


Figure 4
The only 7-sigma candidate in our first 10-hour search was proven to be an imaging artefact.

Twinkle Twinkle Little Radio Galaxy

KAT ROSS

Adult radio galaxies can often extend to millions of light years across, but the pathway of radio galaxies from birth to adulthood is still largely unknown. In order to try to watch this cosmic life cycle, we need to first find the baby galaxies. Thankfully, the baby radio galaxies appear blue in colour and slowly turn red as they age. Using the GaLactic and Extragalactic All-sky MWA (GLEAM) survey, a population of blue radio galaxies, known as peaked-spectrum sources, were found and over the last few years I've been closely watching them to catch any misbehaving little radio galaxies.

While these tiny radio galaxies are small compared to the incredible scales of typical adult galaxies, they still often extend to scales of tens of thousands of light years across. As such, they shouldn't be showing any changes unless we watch them carefully over tens of thousands of years. Unexpectedly, in 2020, we found hundreds of these peaked-spectrum sources changing their brightness over the course of a year.

In 2022, we continued to watch these particularly odd small radio galaxies using the Long Baseline Array (LBA) to try and understand why they were behaving so uncharacteristically. By combining 10 radio telescopes across Australia, New Zealand and South Africa, we produced high resolution images of a handful of the little radio galaxies. These images caught the cosmic burp coming from the supermassive black hole at the centre of the galaxy MRC 0225-065 unleashed into the Universe around 400 years ago. The remnants of this cosmic burp have created bright mushroom shaped clouds over 1,000 light years away from the burping black hole.

As the light from these cosmic burps travels across the Universe, a journey of millions of light years, the dust and gas within our own Milky Way galaxy bends and shifts the light, just like twinkling stars in the night sky. And so the mystery of this oddly behaving baby radio galaxy was solved! We were lucky enough to catch the twinkling of cosmic black hole burps!

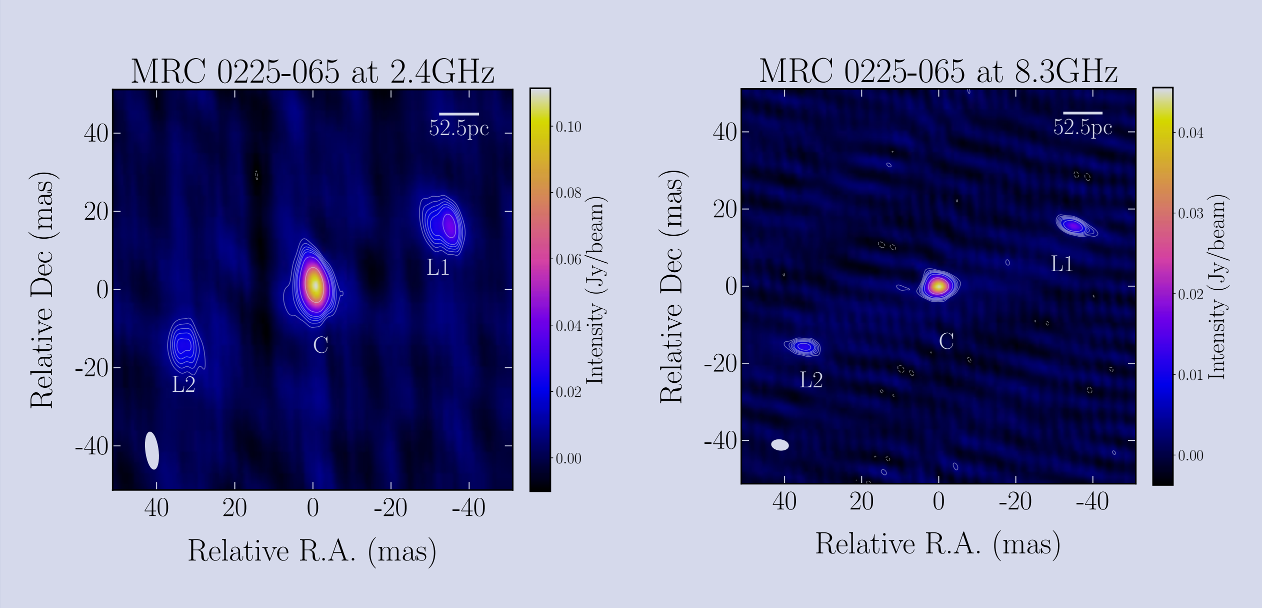


Figure 1
MRC 0225-065 as seen by the LBA at a) 2.4GHz and b) 8.3GHz. The bright region in the centre is the core, corresponding to the burping black hole, and the two fainter regions on either side are the leftovers of the cosmic burp ejected into the Universe around 400 years ago. IMAGE: Ross et al. 2023

Deleting the Milky Way

NICHOLE BARRY
JACK LINE

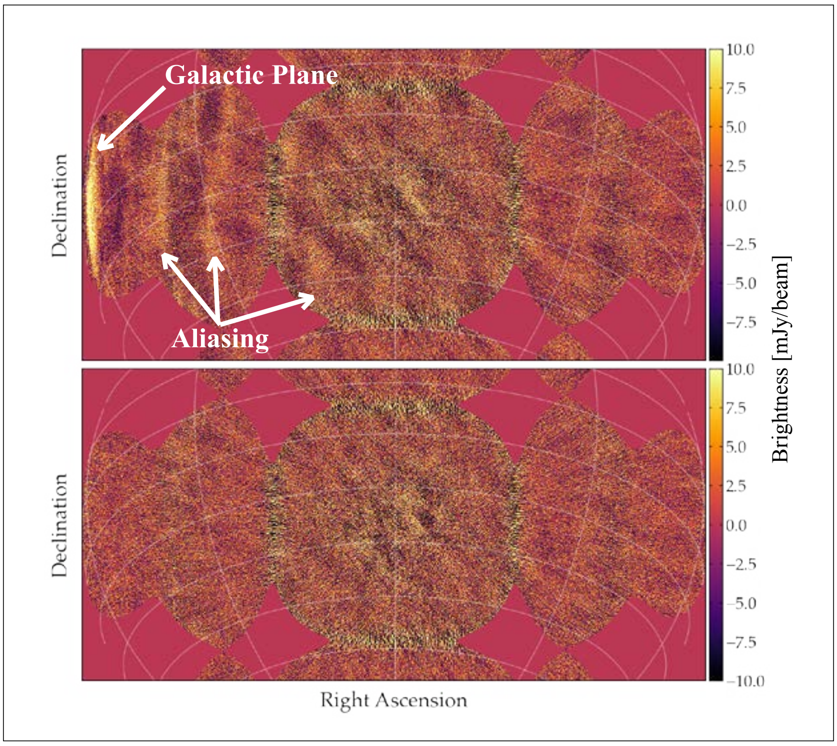


Figure 1
The top panel is a horizon-to-horizon observation from the MWA. All other sources have been removed in this image, and the galactic plane can be seen on the far left. In the bottom panel, the same observation has now had the galactic diffuse emission removed.

The last global change of the Universe is called the Epoch of Reionisation (EoR) – when the first stars and galaxies burned away the last remaining primordial hydrogen – and it holds a wealth of information about astrophysics and cosmology. Systematics and foregrounds cloud the EoR measurement, and thus the EoR team focuses on building and developing mitigation methods. Recent effort into decreasing these systematics has revealed a fascinating artifact, and its discovery was only possible with the teamwork exhibited by researchers at CIRA.

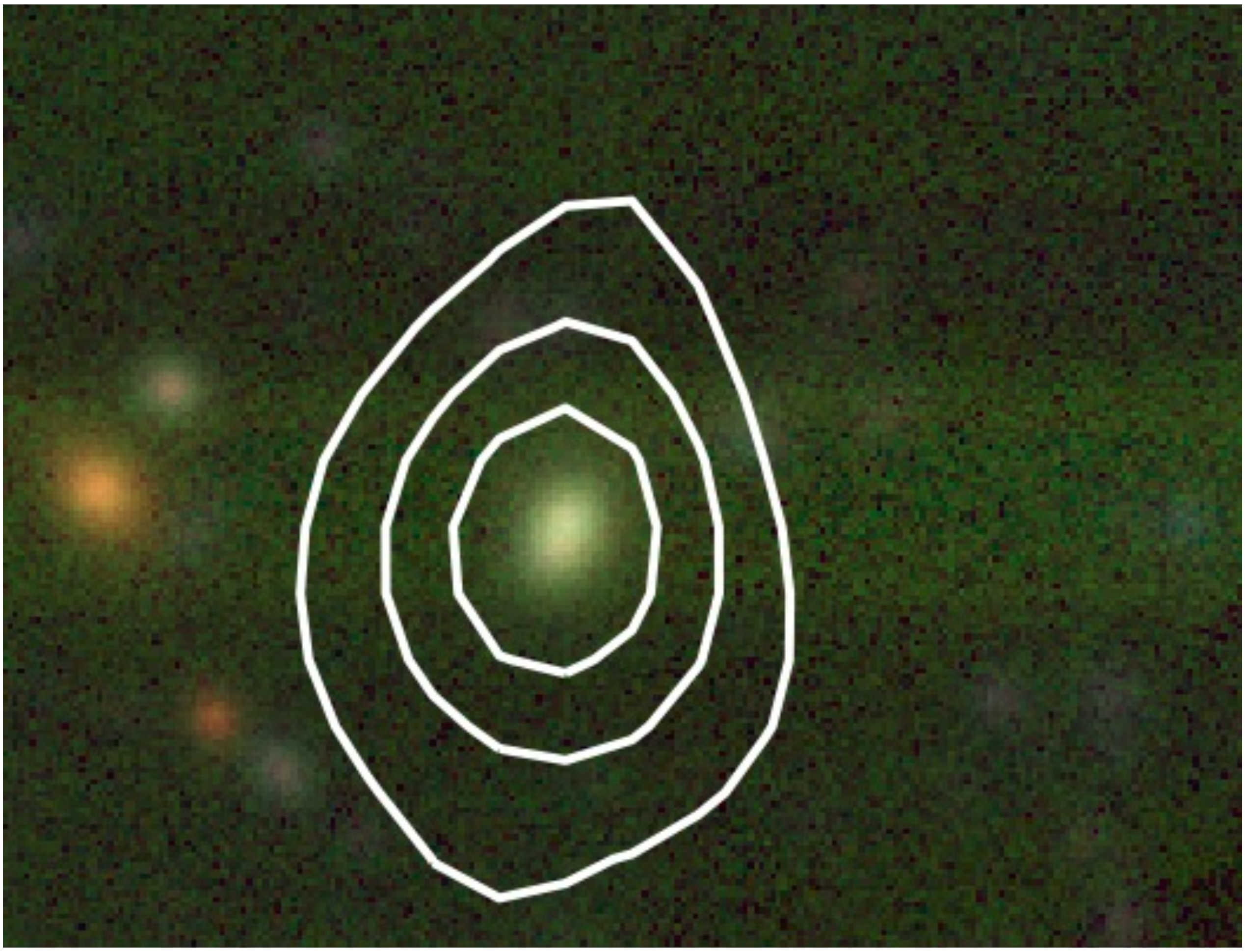
The Murchison Widefield Array (MWA), a radio interferometer used to search for the EoR, has a wide field-of-view. This allows for more of the sky to be measured by the instrument. However, Barry et al. 2022 revealed that small levels of beam sensitivity at the horizon, levels reaching only 0.3% of the maximum sensitivity, caused a contamination in the analysis. By reducing this systematic, images that were large enough to include the horizon improved drastically. This allowed for a very clear view of the galactic plane along the horizon in the field typically used for EoR observations.

Even though the galactic plane is at 0.3% beam sensitivity, it remains the brightest source in the image once all other sources in the LoBES catalogue (Lynch et al. 2021) of 80,000+ radio sources are removed. Given that it is located on the horizon, it is difficult to remove due to projection-based assumptions. The software package WODEN (Line et al. 2022) avoids these assumptions by utilising the speed of GPUs, and thus can recreate the galactic plane on the horizon given an input model.

Kriele et al. 2022 created a map of the galactic diffuse emission at low frequencies using the Engineering Development Array 2 (EDA2). This model represents the galactic diffuse emission seen by the MWA better than other models due to the frequency of the measurement. By using a galactic input from Kriele et al. 2022, in addition to extragalactic input from Lynch et al. 2021, a more complete theoretical sky can be created with WODEN via Line et al. 2022 to match the emission in data seen via improvements from Barry et al. 2022. Four separate projects enabled this outcome.

The Figure above reveals an interesting secondary systematic of the galactic plane: *aliasing* of the galactic plane. There is a drastic, sharp cut-off in brightness as the galactic plane sets below the horizon. These sharp edges cause aliasing in Fourier space, which is the native space of the measurement, and thus inherent to the measurement itself. Looking closely at the Figure, one can see that this aliasing ripples throughout the entirety of the image! How removing the galactic plane will affect the power spectrum measurement of the EoR is an active area of research.

Meet “Nkalakatha”, the new big boss discovered by the MeerKAT radio telescope



Above
Colour image of the host galaxy of the OH megamaser in visible light, obtained with the Hyper Suprime-Cam (HSC) on the 8.2m diameter Subaru Telescope, overlaid with white contours representing MeerKAT’s detection of the OH emission “peak”. IMAGE: Glowacki et al. 2022

MARCIN GLOWACKI

An international team of astronomers, led by Marcin Glowacki, detected a powerful radio-wave laser, or “megamaser”, with the MeerKAT radio telescope in South Africa. Masers (a laser in the radio regime) can be created by hydroxyl molecules (one atom of oxygen and one atom of hydrogen) within a gas cloud in galaxies. A megamaser is born from the collision and merger of two galaxies, in which the gas content of the resulting galaxy is concentrated. It is this ensemble of dense gas, including hydroxyl, that creates the giant megamaser signal.

The discovery came from the first night of observation of the LADUMA (Looking At the Distant Universe with the Meerkat Array) survey. This major science experiment will search for atomic hydrogen gas, the star forming fuel of galaxies. This gas will be detected in very distant galaxies, using the powerful new MeerKAT radio telescope in the Karoo of South Africa, for over 3,000 hours on one area of the sky to probe deeper than ever before. While atomic hydrogen gas is the focus for LADUMA, hydroxyl emission from megamasers can also be detected by the survey.

What makes this new discovery special is the fact this is the most distant megamaser of its kind to be seen by any telescope to date. While previously just over 100 hydroxyl megamasers had been detected, all have been relatively close to us, while this newly discovered megamaser is over 5 billion light years away. New radio telescopes such as MeerKAT will greatly improve statistical studies of megamasers, with the LADUMA survey predicted to almost double the number of known hydroxyl megamasers by itself. By detecting more megamasers including in the distant past, astronomers will be able to test the hypothesis that galaxies merged more often earlier in the Universe's history and better understand how galaxies have evolved over time.

It is one of the most luminous hydroxyl megamasers ever discovered as well, earning it the nickname of "Nkalakatha". Nkalakatha is a Zulu word meaning "big boss", suggested by a South African student in a naming competition for the new megamaser. It has also been discovered that some of the gas in the host galaxy may be outflowing – being pushed out of the system, perhaps by winds created by star formation processes.

It is Nkalakatha's luminosity, combined with the excellent sensitivity of the MeerKAT telescope, that made it the first scientific discovery of the LADUMA survey. Follow-up observations of the galaxy with other telescopes are underway, which will help inform us on the potential outflow. Meanwhile, several more observations for LADUMA continue to be taken and analysed, which will lead to many more discoveries like Nkalakatha.

REFERENCES

Glowacki et al. (2022), LADUMA: Discovery of a Luminous OH Megamaser at z > 0.5, *The Astrophysical Journal Letters*, 931 L7. **https://iopscience.iop.org/article/10.3847/2041-8213/ac63b0**
See also: **https://www.icrar.org/megamaser/**

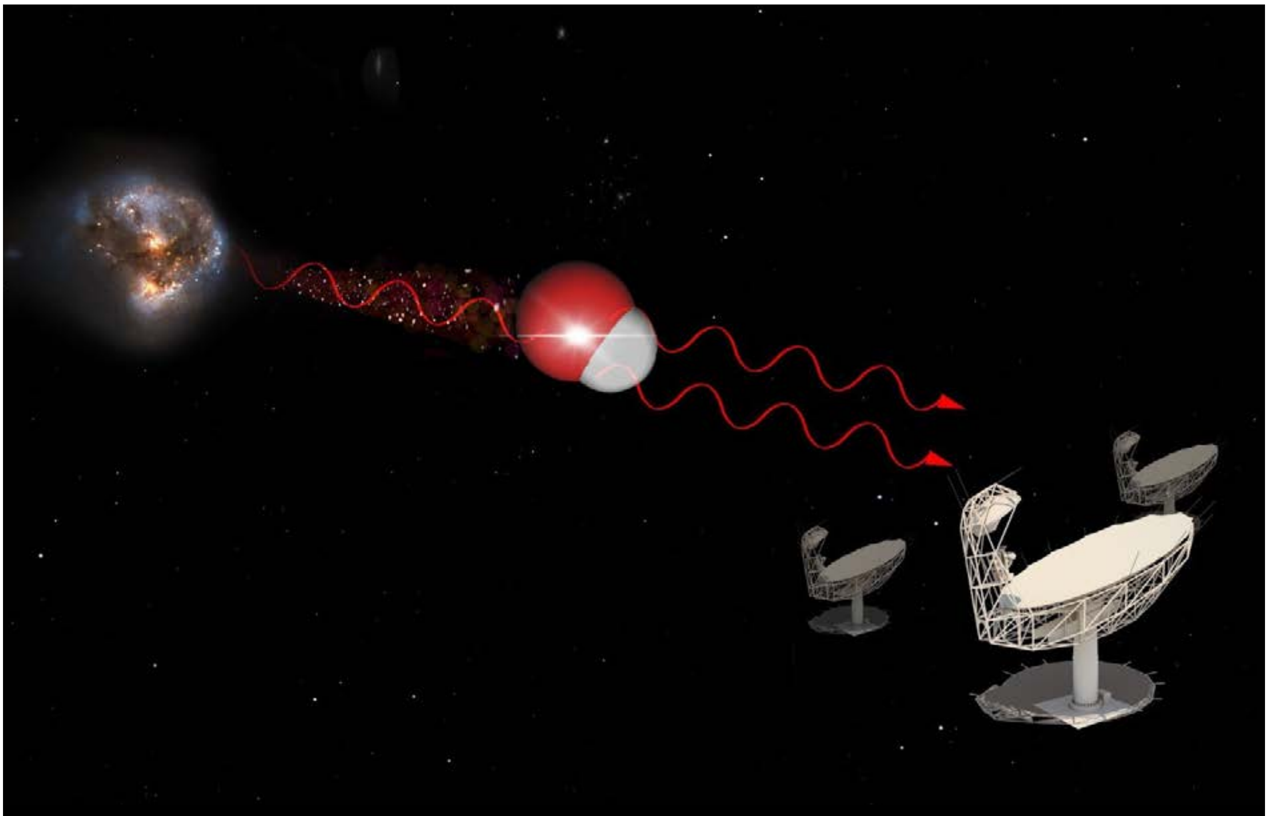


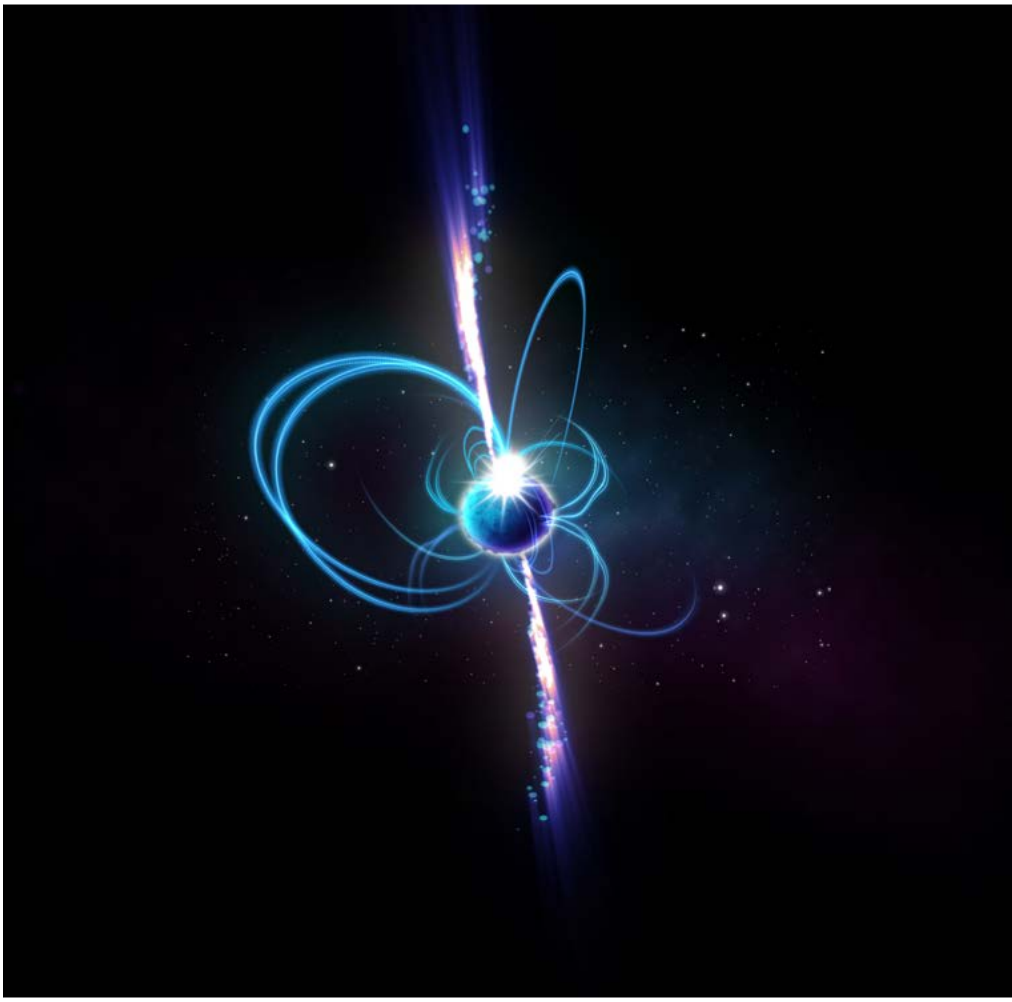
Image
Artist's impression of a hydroxyl maser. Inside a galaxy merger are hydroxyl molecules, composed of one atom of hydrogen and one atom of oxygen. When one molecule absorbs a photon at 18cm wavelength, it emits two photons of the same wavelength. When molecular gas is very dense, typically when two galaxies merge, this emission gets very bright and can be detected by radio telescopes such as the MeerKAT. © IDIA/LADUMA using data from NASA/StSci/SKAO/MolView

A long-lived repeating radio transient

NATASHA HURLEY-WALKER

In 2022, we published the discovery of a new kind of radio transient, GLEAM-X J162759.5-523504.3 (Hurley-Walker et al. 2022a, Nature). Discovered in the GaLactic and Extragalactic All-sky MWA eXtended (GLEAM-X) survey (page 28) by the Murchison Widefield Array, it produced radio waves that repeated every 18 minutes for several months in early 2018. Pulsars, a type of magnetic neutron star (page 36) can also produce repeated radio bursts, and slow down as they age. However, once their rotation rate is slower than about one minute, they are not expected to produce radio waves. So, what could this strange source be? Potentially: an ultra-long period magnetar, a theorised type of neutron star with a very strong magnetic field.

This cosmic mystery provoked an enormous storm of public enthusiasm across the world. More than 3,000 articles across over 100 countries were published, reaching at least 13 million people. The discovery also created a stir in the scientific community, with theorists offering new ideas as to the origin of the radio emission, and observers across the world creating new programmes to search for this new class of objects. Unfortunately, we could not do more with GLEAM-X J1627, as all our follow-up showed that the source was no longer producing radio waves. Therefore, the key to unlocking the mystery is to find such a source and then follow it up with many telescopes across as many wavelengths as possible, while it is still active.



↗ **Image**
An artist's impression of a magnetar. Magnetars are extremely magnetic neutron stars, some of which sometimes produce radio emission. Known magnetars rotate every few seconds, but theoretically "ultra-long period magnetars" could rotate much more slowly, perhaps explaining the pulses seen from GLEAM-X J1627 and GPM J1839-10. IMAGE: ICRAR

To accomplish this goal, I created a new programme to monitor the Galaxy with the MWA (the Galactic Plane Monitor; GPM). Over July to September in 2022, we observed 4,000 square degrees of the Milky Way over 30 times, each area observed for at least half an hour, twice a week. I worked with Tim Galvin (now at CSIRO) and Csanad Horvath, a talented 3rd-year undergraduate student, and the ADACS team to create a pipeline that would, in near real-time, reduce the data, search for transients, and report results in an online viewer. A week after starting observing, we were successful, finding a new long-period radio transient!

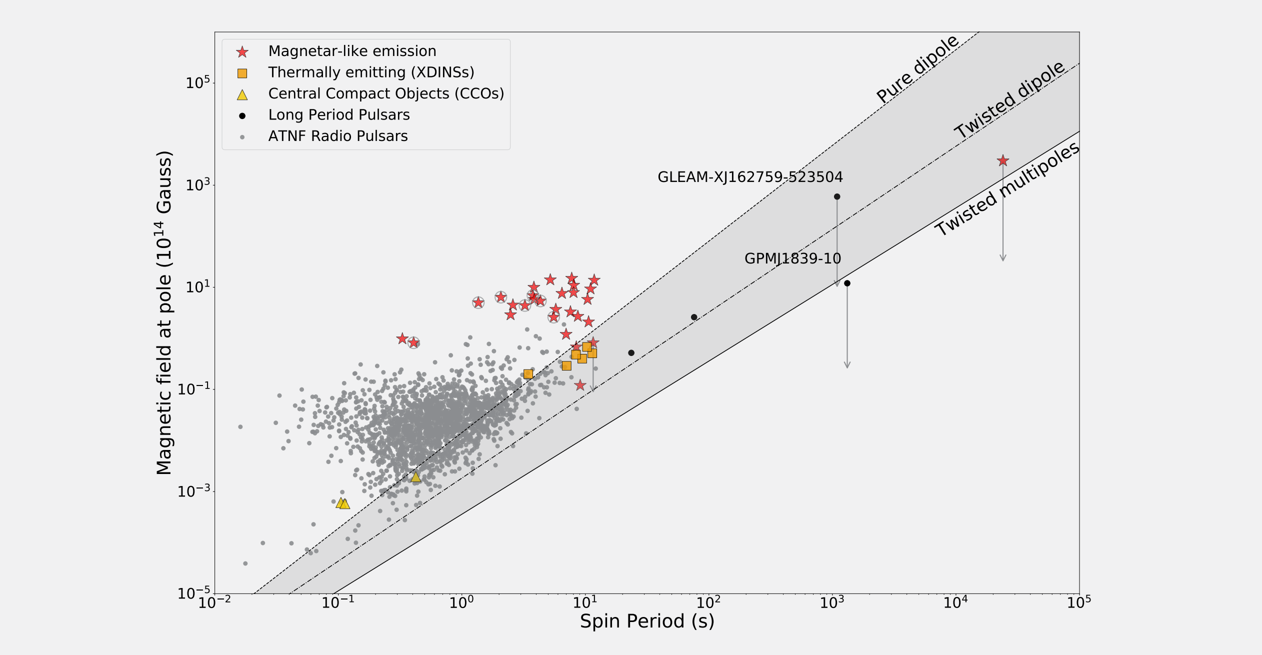


Figure 1
The long-period source periods and magnetic fields, in context with the known pulsars and magnetars. GPMJ1839-10 lies beyond the “death lines” for producing radio emission in neutron stars. IMAGE: Hurley-Walker et al. (2023, submitted to *Nature*)

Named GPM J1839-10, this radio source repeats every 21 minutes, and lies three times further away than GLEAM-X J1627. Thanks to our rapid detection of the source, we were able to follow it up quickly with a slew of radio telescopes: the Australia Telescope Compact Array, Parkes/Murriyang, the Australian Square Kilometre Array Pathfinder, MeerKAT, and of course more observations with the MWA. We also used the Swift and Chandra X-ray telescopes, and the Gran Canaria Telescope, one of the largest optical telescopes in the world. By piecing together the observations over a wide frequency range, we figured out the spectrum of the source, allowing us to better understand its energy and luminosity. The highly sensitive MeerKAT polarisation measurements yield excellent insights into the strange magnetic fields that must be generating the emission.

However, this wasn’t the most surprising part of this discovery. I worked with colleagues in the United States who are experts in looking through the archives of one of the oldest digital radio interferometers in the world, the Very Large Array, in New Mexico. To our surprise, we detected pulses from GPM J1839-10 as far back in time as *1988*. This source has been under astronomers' noses for over three decades, but if it was ever noticed before, was probably dismissed as a strange artefact. Measurements over such a long length of time have empowered us to measure the timing of the object’s rotation incredibly precisely, to better than one part in a billion. These timing measurements put very strong constraints on the physical mechanism underpinning the emission: neutron stars with almost any configuration of magnetic field cannot generate the radio waves. At the time of writing, this discovery is in review with Nature, and will likely provoke a similarly large storm when published.

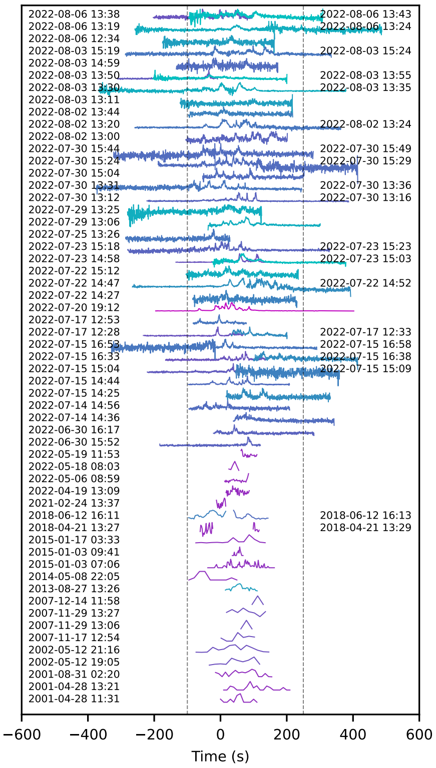


Figure 2
Pulses of GPMJ1839-10 lined up by its measured period over 34 years. The pulses were observed by the Murchison Widefield Array, Very Large Array, MeerKAT, and the Giant Metrewave Radio Telescope, spanning 72 MHz to 1 GHz.

A New Population of Radio Galaxies with Ultra-faint Hosts: Update from the High-z Radio Galaxy Group

NICK SEYMOUR
JESS BRODERICK
TIM GALVIN

> *"The radio galaxy was a fierce and mighty beast; its jets stretching for thousands of light years, roaring through the void of space with an unyielding fury. Its black hole heart, a devourer of stars and planets, fueled the power that drove the monster forward in its endless journey through the cosmos. Its presence, felt from countless light years away, served as a reminder of the vastness and unforgiving nature of the universe. Yet, for all its might, the radio galaxy remained a mystery, a cosmic enigma that humbled even the most learned astronomers and scientists who dared to gaze upon its awesomeness."*
>
> **Ernest Hemingway** (via ChatGPT)

One of the key aims of the HzRG group is to determine the origin of super-massive black holes in the early Universe. With billion-solar-mass black holes now regularly found within 800 Myr of the Big Bang, there is now considerable tension between observations and theory concerning their formation. Finding the immediate ancestors to these black holes is a key goal in astronomy. These black holes are likely to be accreting rapidly, but the luminosity from this accretion could be obscured by dust or the interstellar medium of the host galaxy, or from the extreme accretion rates via 'photon-trapping'. However, many black holes emit powerful jets when they accrete which produce highly luminous radio emission, i.e. radio galaxies. This radio emission can be so luminous that radio galaxies within the first billion years of the Universe can easily be detected in current all-sky radio surveys, e.g. with the Murchison Widefield Array (MWA).

Our successful pilot study used the GaLactic and Extra-galactic All-sky MWA (GLEAM) survey to select four high-redshift candidates via a novel selection based on the curvature of the 70–230 MHz spectrum. Follow-up of these sources with deep near-infrared *K*-band imaging and with the Atacama Large Millimetre/sub-millimetre Array (ALMA) revealed

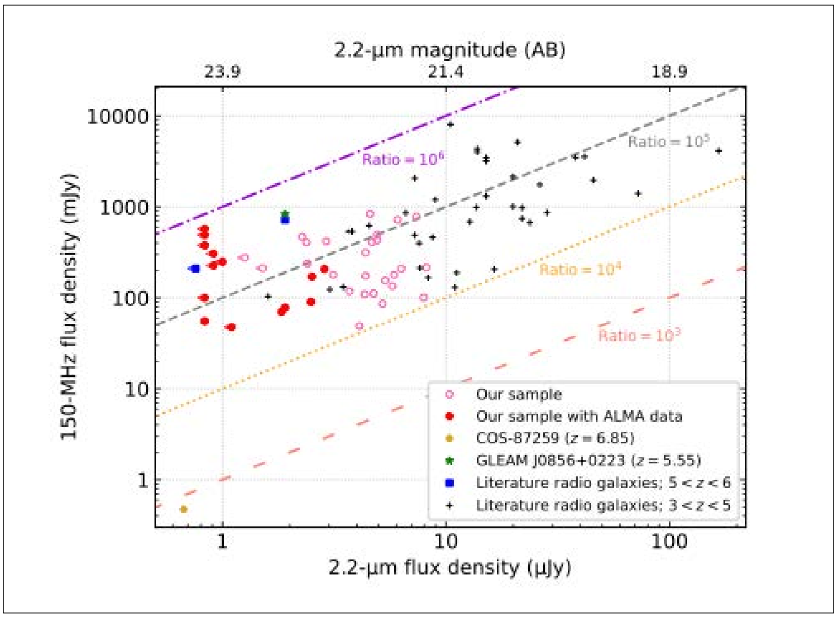
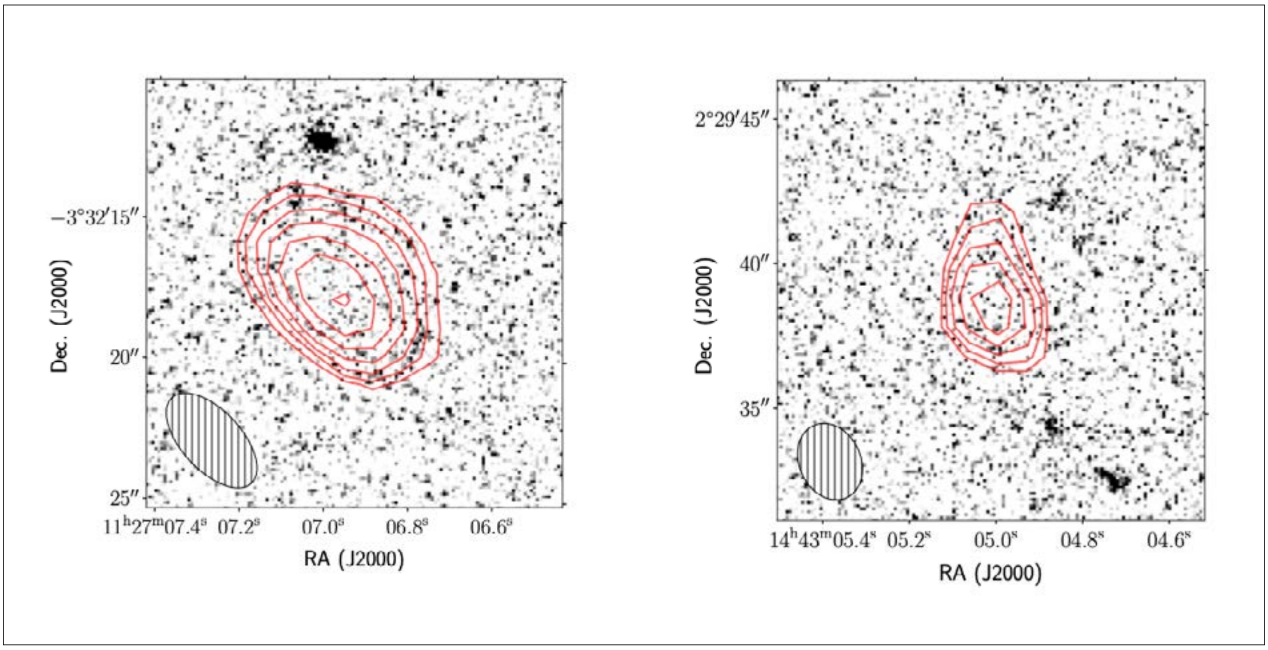


Figure 1
Radio (150 MHz) v. *K*-band (2.2 μm) flux densities of our sample (Broderick et al., 2022) compared to known high-redshift radio galaxies, including our pilot source, GLEAM J0856. Note that arrows indicate 2.2μm flux density upper limits. Our sample has high radio to near-infrared flux ratios (104–106), similar to known high-z radio galaxies, but extending to fainter flux densities. A total of 14 candidates have ALMA data (red), with some of these sources having K-band flux densities comparable to TGSS J1530 (at z = 5.72) and COS-87259, a recently discovered, weakly radio-loud, but obscured super-massive black hole at z = 6.85. If our candidates are not at similar redshifts then they must be hosted by unusually low-mass galaxies (i.e. be an unprecedented population). IMAGE: Adapted from Broderick et al. (submitted).



↗ **Figure 2**
Two of our candidate ultra-high redshift radio galaxies (GLEAM J1127-0332 left and GLEAM J1443+0229 right) which are very bright in the radio, 150 MHz flux densities > 0.1 Jy, but very faint in K-band, < 1 µJy. In each panel the greyscale is the VLT *K*-band image, while the radio contours are 3-GHz images from the VLA Sky Survey (VLASS). Both radio sources clearly have no host galaxy. Where are the 'invisible' back holes powering these radio sources? Images from Broderick et al. (submitted).

two low-redshift interlopers, one at an unknown redshift and one at z = 5.55 (Drouart et al., 2020). This latter source is found just one billion years after the Big Bang and likely has a comparable black hole mass and accretion rate to the known population of QSOs at z > 6. The source at an unknown redshift has remained elusive despite further follow-up with ALMA, the Very Large Array and Hubble (Drouart et al., 2021, Seymour et al., 2022, annual reports passim). Further Hubble grism data on this source will be analysed in 2023.

Following the success of our pilot, we curated a sample of 51 new candidate ultra-high-redshift (z>6) radio galaxies from a much larger area (selected on the basis of radio spectral curvature, radio compactness and faintness in wide-area near-infrared surveys). We presented this sample along with follow-up radio data and broadband radio spectral modelling in Broderick et al. (2022). Furthermore, over the course of 2022, we obtained deep *K*-band imaging from the Very Large Telescope (VLT; leveraging Australia's partnership with the European Southern Observatory) of 37/51 radio galaxies. Of this sample, 78% (29) were detected with magnitudes 21.6 ≤ K ≤ 24.1 and eight were not detected to a limit of K ≈ 24. In Fig. 1 we plot their *K*-band flux densities against MWA flux densities.

This undetected sample of 'invisible' black holes have similar radio to *K*-band flux ratios as lower-redshift powerful radio galaxies (i.e. 3 < z < 6), but fainter K-band fluxes which are consistent with the radio galaxy TGSS J1530 at z = 5.72 and COS-87259, a weakly radio-loud, but obscured black hole at z = 6.85. Hence, our faintest sources are prime candidates for being radio galaxies at z > 6 (see Fig. 2). If not, they would represent a new population of radio-loud black holes at lower redshifts with host galaxies which are surprisingly quiescent and/or low mass for hosting such powerful jets.

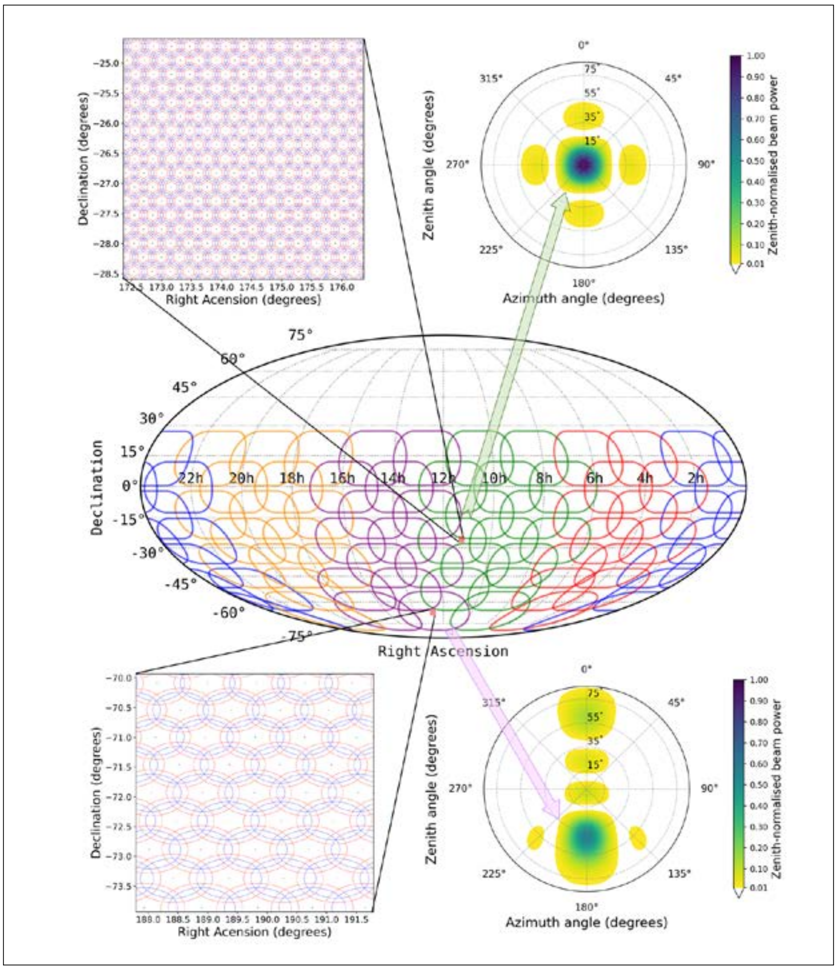
How can we determine the nature of this new population? We need to know their redshifts and for that we need spectroscopy. Last year we had an ALMA proposal accepted for spectroscopic follow-up of the 14 including the K-band faintest most extreme sources (see Fig. 1). These data will arrive in early 2023 and will also provide a continuum flux density measurement at 100 GHz, helping with the broadband modelling of the synchrotron emission. We also plan to apply for JWST spectra of these sources in 2023 as well. These data should reveal the nature of these mysterious sources.

The SMART pulsar survey takes off

RAMESH BHAT
NICHOLAS SWAINSTON
SAMUEL MCSWEENEY
BRADLEY MEYERS

Pulsars – city-sized, super-dense, very fast-spinning stars that harbour extreme physical conditions – have continued to fascinate astronomers since their discovery five decades ago. These exotic objects emit beams of electromagnetic radiation from their magnetic poles, resulting in their signals observed as a regular train of pulses by telescopes. This "cosmic lighthouse" behaviour also captivates the attention and interest of the general public. They are premier laboratories for physics, with applications including probing the nature of ultra-dense matter, extreme magnetism, and testing strong-field gravity. There are hardly any areas of physics or astrophysics where these exotic objects haven't had an impact. Unsurprisingly, pulsar astronomy is a headline science theme for the Square Kilometre Array (SKA) telescope project.

Yet, despite its distinct status of being Australia's official precursor for the SKA low-frequency telescope, the Murchison Widefield Array (MWA) was not originally geared up for pulsar science; the related capabilities had to be developed within the constraints of a pre-designed system architecture, dictating the choice of non-traditional (and often suboptimal) paths, which necessitate processing several tens of Terabytes of data on supercomputers, and developing high-performance software subsystems that will form the backbone of the MWA pulsar system. Notwithstanding the challenges, the pulsar team pushed ahead with their effort, developing a series of important capabilities over the time; notably, the ability for coherent combination of signals from 128 tiles of the array for maximum sensitivity (Ord et al. 2019), and an ability to reprocess the recorded (raw voltage) data to reconstruct microsecond resolution time series (McSweeney et al. 2020). These initial milestones enabled a range of pulsar science including investigating pulsar emission physics and studying millisecond pulsars that are important for high-profile pulsar timing-array experiments. Along with the advent of a compact array layout that became possible with the MWA following its upgrade, this led to the conception of the Southern-sky MWA Rapid Two-metre (SMART) survey project – an ambitious project to explore the vast southern skies for pulsar discoveries and science.



↗ **Figure 1**

The central concept underpinning the SMART pulsar survey project, which exploits some unique strengths of the MWA upgrade and the advanced software instrumentation developed for pulsar science with the MWA (see Bhat et al. 2023a for details). With a field-of-view of ~600 square degrees (at 155 MHz), the entire visible sky of the MWA can be covered in just 70 pointings, and hence the full survey can be completed in 100 hours of telescope time. The survey speed is ~1000 times larger than all previous-generation southern pulsar surveys of similar sensitivity.

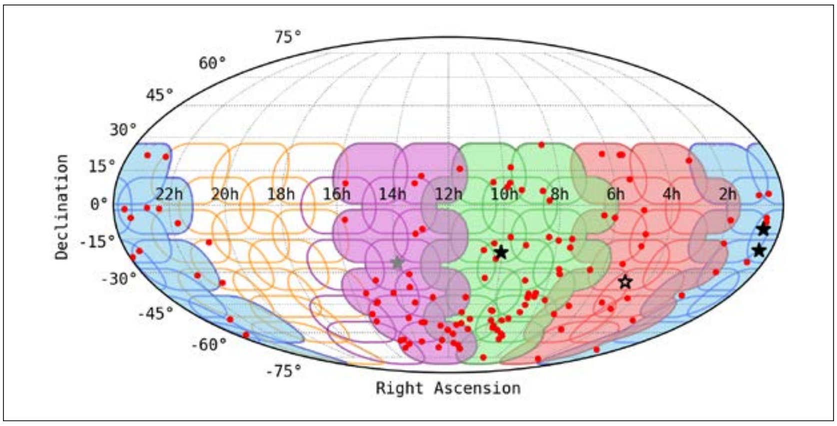


Figure 2
Current status of the SMART survey that covers the entire sky south of declination +30 degree in 70 pointings. The coloured contours represent the half-power points of the main lobe of the primary beam (at 155 MHz). The blue, red, green and purple pointings are already completed through four dedicated observing campaigns in 2018-2021. The red dots are the known pulsar detections (120 so far) from initial analysis for data quality checks, and the black stars are the new pulsar discoveries, from a “shallow search” of ~5% of the data analysed (figure adapted from Bhat et al. 2023b).

The SMART pulsar survey exploits several unique strengths of the MWA. While the combination of a large field of view and ability to record raw (i.e. unprocessed) data from 128 elements (tiles) provides an astonishingly large survey speed (~450 square degrees per hour), thereby allowing instantaneous sampling of a very large patch of the sky – several hundred times larger than the size of the Moon – it also poses numerous challenges owing to a large data rate (28 Terabytes per hour). The survey will accrue over 3 Petabytes of data over its lifetime, which will need to be systematically processed to form on the order of a million sensitive tied-array beams that will tessellate the sky, each of which is searched in the extensive parameter space to discover new pulsars. Recognising the computationally daunting task ahead, the team adopted a practical approach, starting with a first-pass of processing to effectively conduct a “shallow survey” where only a small fraction (10%) of data are processed. In parallel, they initiated the effort to develop an extensive database infrastructure, both to manage the processing and analysis challenges, and also as a pathway to fulfil their outreach aspirations to develop a citizen science project for facilitating public engagement. Over the past years, by taking advantage of a small number of “windows of opportunity" when the array was configured in a compact layout, the SMART team successfully advanced the data collection effort to 70% completion.

The hard work and perseverance over the years is now beginning to pay off; in 2021, the team announced their first pulsar discovery (Swainston et al. 2021) – PSR J0036-1033, an object that belongs to the rare class of low-luminosity object that is also brighter at low frequencies. The second pulsar discovered (also an independent discovery), PSR J0026-1955, turns out to be a fascinating object as it exhibits a remarkable phenomenon where the emission structure moves progressively in pulse phase as the pulsar rotates (McSweeney et al. 2022). Of the two further discoveries, one appears to be a low-luminosity object and the other exhibits intriguing emission phenomenology – all from the analysis/scrutiny of only a small fraction of the data, processed to reach only a third of the sensitivity that the full search processing will attain. A bonus outcome from this ongoing first-pass processing has been the low-frequency detection of more than 100 already known pulsars in the southern sky; the 120 detections from SMART data brings the MWA-detected pulsar tally to 180, thereby tripling the number of pulsars from the early days (Xue et al. 2017). With our processing ecosystem in place, the data can now be reprocessed for high fidelity and polarimetry to extract a range of new science.

This marks an important project milestone, but it is also the beginning of a new era for MWA pulsar astronomy. As the team steadily ramps up the efforts to transition to the "second-pass" processing stage to undertake a “deep survey”, exciting years are ahead but not without a fair share of challenges. This will be a significant step forward: not only will it provide a three-fold boost in sensitivity to long-period (i.e. slow-spinning) pulsars, but it will also extend the search parameter space to target short-period (millisecond) pulsars and those with companion stars (i.e. in binary systems). Notwithstanding the challenges ahead, especially the daunting task of managing, processing and analysing large volumes of data, the team is determined to forge ahead, to chase the scientific dividends awaiting, as well as to leverage opportunities for public engagement through citizen science projects.

PUBLICATIONS

1. Bhat, N. D. R., Swainston, N. A., McSweeney, S. J., Xue, M., Meyers, B. W. et al. 2023a, PASA, In Press, arXiv:2302.11911. doi:10.48550/arXiv.2302.11911
2. Bhat, N. D. R., Swainston, N. A., McSweeney, S. J., Xue, M., Meyers, B. W. et al. 2023b, PASA, In Press, arXiv:2302.11920. doi:10.48550/arXiv.2302.11920

First pulsar science using SKA-Low prototyping stations

CHRISTOPHER LEE
RAMESH BHAT
MARCIN SOKOLOWSKI

Pulsars are rapidly-rotating, highly-magnetised cores of dead stars which periodically emit electromagnetic radiation that can be observed at radio frequencies. Despite their discovery in 1967 at very low frequencies (81.5 MHz), much of pulsar astronomy later moved to higher radio frequencies (>400 MHz) due to a range of signal degradation effects that are more pronounced at lower frequencies. Studying how the radio intensity (known as 'flux density') of pulsar emission evolves as a function of frequency can give unique insights into physical processes that govern the pulsar radio emission mechanism – an outstanding problem even after more than five decades of research. Pulsar radio spectra are typically described by a steep power-law model, with the flux density increasing rapidly towards lower radio frequencies. However, some pulsars show interesting deviations from this behaviour at frequencies below or around 150 MHz, in the form of a spectral flattening or 'turnover'. Despite this, below 300 MHz remains a poorly explored frequency band for pulsar astronomy.

Fortunately, the low-frequency Square Kilometre Array (SKA-Low) is planned to operate between 50-350 MHz, which will offer an unparalleled tool for performing low-frequency pulsar science. The SKA-Low will comprise 512 field nodes called 'stations', each with 256 dual-polarisation antennas. The signals from each of the antennas in a station are coherently combined to form an electronically-steerable beam, which allows the station to effectively function as a single-dish telescope. In preparation for the SKA-Low, two prototype stations have been deployed at Inyarrimanha Ilgari Bundara, the CSIRO Murchison Radio-astronomy Observatory. These are the Aperture Array Verification System 2 (AAVS2) and the Engineering Development Array 2 (EDA2). The stations differ by the types of antennas used, with the EDA2 using the well-characterised MWA bowtie dipoles and the AAVS2 using SKALA-4.1 'Christmas tree' antennas.

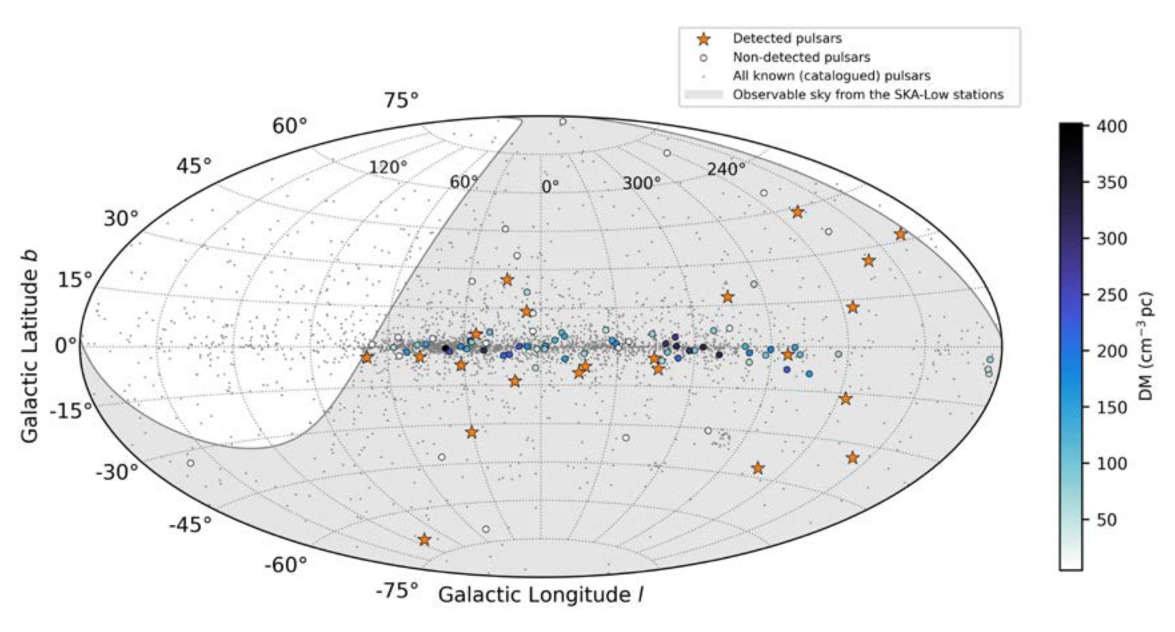


Figure 1
Sky map showing the locations of the pulsars observed in the southern-sky census with the SKA-Low prototyping stations. The detected pulsars are indicated by orange stars; non-detections are indicated by colour-filled circles, where the colour scale indicates the dispersion measure (DM; a measure of the number of free electrons along the line-of-sight towards the pulsar, and a proxy for the pulsar distance). The shaded area is the observable sky with the SKA-Low stations (declinations less than +30 degrees). Figure taken from Lee et al. (2022).

The initial capabilities of the prototype SKA-Low stations allowed for observations to be made over an only ~1 MHz bandwidth, which translates to less than 5% of the sensitivity obtainable with the Murchison Widefield Array (MWA) – Australia's precursor for the SKA-Low. However, despite such a modest sensitivity, the SKA-Low stations have a unique advantage over the MWA – they record the beamformed data in real-time instead of recording the signals from each of the antennas individually. This reduces the data volumes by three orders of magnitude, making data processing and analysis significantly faster. Furthermore, with far reduced data storage requirements, it is feasible to observe a large number of targets, or even to perform regular observations of interesting targets, without having to deal with the prohibitively large data volumes of the MWA's Voltage Capture System.

Motivated by this, and to ascertain the early science prospects of SKA-Low stations, we performed observations of 100 southern-sky pulsars (see Figure 1). Our analysis yielded successful detections of 22 pulsars; non-detections can be reconciled by accounting for an overestimation of the expected flux densities, or signal degradation due to propagation effects such as interstellar scattering. A subsample of these pulsars were observed at multiple frequencies across the SKA-Low band (50-350 MHz) in an effort to better constrain the spectral behaviour, such as a flattening or a turnover (see Figure 2). Six of our pulsar detections were at the lowest frequencies ever published. We presented these results and spectral modelling for the 22 detected pulsars in a peer-reviewed publication (Lee et al., 2022). The software that we created to model the pulsar spectra is presented in a separate publication (Swainston et al., 2022). Importantly, our analysis warranted a spectral revision for a large majority of the pulsars (17 out of 22) we studied, hinting at the important role the low radio frequencies will have for advancing pulsar astronomy.

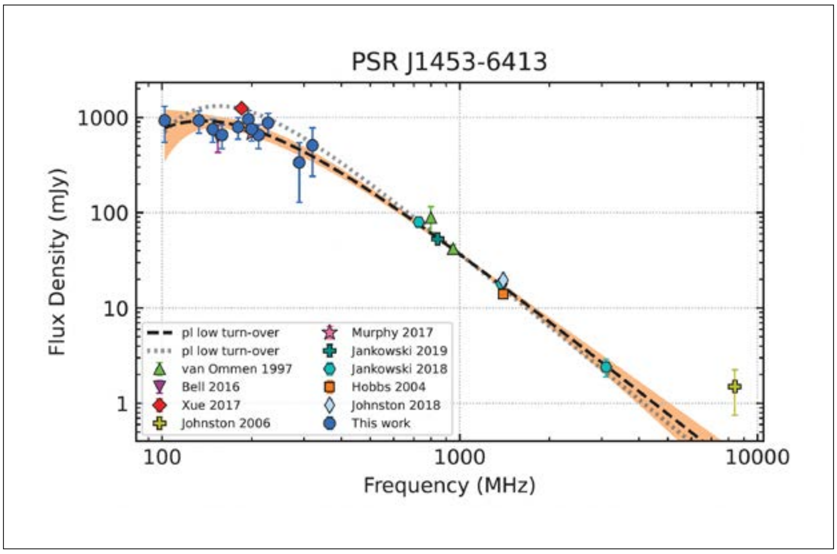


Figure 2
Example of a flux-density spectrum hinting at a turnover at low frequencies. The blue data points are flux densities we measured using the SKA-Low stations, providing the strongest constraints on the model at these uncommonly observed frequencies. The black dashed line is the best-fit model to the data. The grey dotted line is the best-fit model when flux densities calculated from interferometric continuum images are excluded. For further details, see Lee et al. (2022).

Remarkably, this early science accomplishment was made using the modest sensitivity of the initial systems. Improved spectral modelling of a larger sample at the low frequencies can help to inform studies of the Galactic pulsar population and make improved predictions of the expected yields of large pulsar surveys, such as those planned for the SKA-Low. With a five-fold increase in sensitivity enabled by the upgraded systems (~25 MHz bandwidth), it is now possible to do this, which will also serve as an important preparatory step for pulsar science and survey planning with the SKA-Low.

REFERENCES

Lee, Bhat, Sokolowski, Swainston, Ung et al., 2022, PASA, 39, e042

Swainston, Lee, McSweeney, Bhat et al., 2022, PASA, 39, e056

Modelling pulsar flux density spectra made easy

NICHOLAS SWAINSTON
CHRISTOPHER LEE
SAMUEL MCSWEENEY
RAMESH BHAT

Pulsars, the collapsed cores of once-massive stars, have proven themselves as powerful tools for a variety of physics and astrophysics, with applications including probing ultra-dense matter and performing exquisite tests of general relativity. Despite this amazing success, details on the physical processes that make these compact objects shine remain poorly understood. Among the numerous ways to investigate pulsar emission physics is obtaining reliable measurements of their flux densities, which are useful indicators of brightness as observed by a telescope, and accurately modelling the functional form that describes the frequency dependence. This can potentially provide useful insights into understanding the radiation processes at work in the complex magnetospheres of these compact, dense stars.

While it may seem rather a straightforward exercise, in practice, this can often prove tedious, particularly for a large sample of pulsars. For one, unlike many other areas of radio astronomy (e.g. continuum radio imaging surveys), measuring and recording accurate flux densities has not been a routine in pulsar observations. Secondly, pulsar flux densities vary substantially, on both short (~minutes to hours) and long (~weeks to months) timescales, as a result of interstellar scintillation phenomena (a radio analogue to the twinkling of stars at optical wavelengths). The problem is further compounded by numerous technical issues relating to telescopes and systems (e.g. limited knowledge of system sensitivity, beam models in the case of aperture arrays, and the lack of a reliable calibration scheme in some cases). As a result, there is no reliable catalogue for pulsar flux-density measurements. The closest, and a popular, resource is the Australia Telescope National Facility (ATNF) pulsar catalogue, which provides only limited information on flux densities, with measurements often recorded at a small number of spot frequencies.

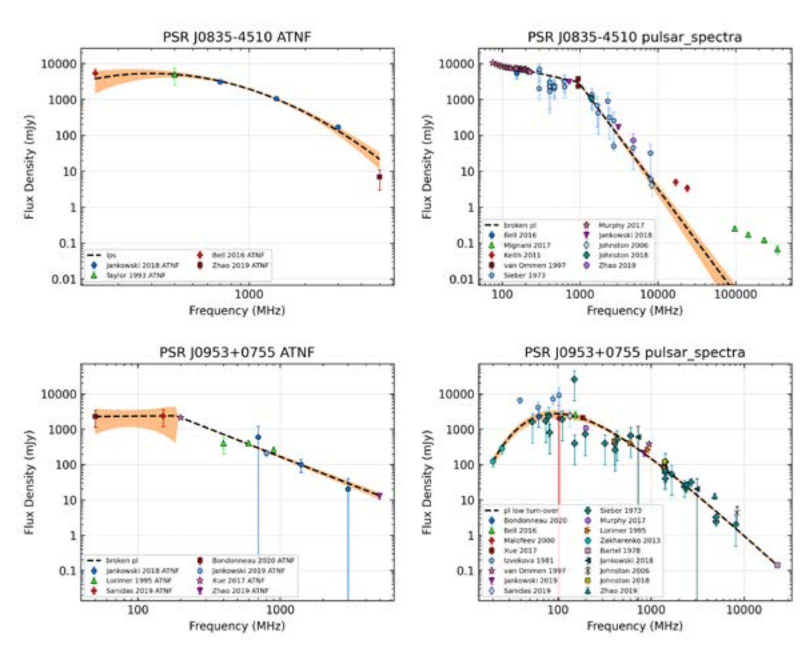
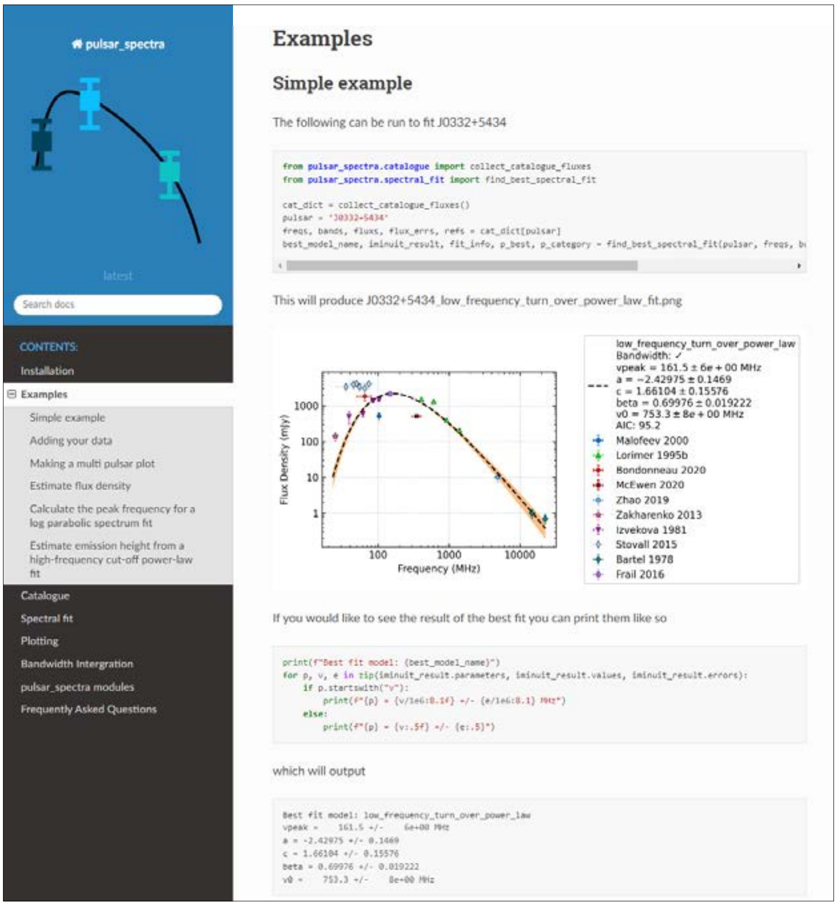


Figure 1
Left panels: Examples of spectral fits using only the flux density values from the ATNF pulsar catalogue.
Right panels: Spectral fits using all available flux density values from the *pulsar_spectra* catalogue. As evident through these examples, *pulsar_spectra* can yield more accurate spectral fits.

Modelling the functional forms that describe the frequency dependence of pulsar flux densities is also less straightforward. There are no theoretical predictions, and so observers often resort to empirical modelling, to best describe the available measurements. Further, as with any other observable emission properties of pulsars, the spectral form tends to vary; ranging from a simple power-law to a broken power-law, or the ones that exhibit a turnover or flattening at low frequencies (below ~300 MHz), which is also the frequency band where SKA-Low will operate. Building improved models for pulsar spectra is therefore vital not just for understanding pulsar radiation processes, but also to plan pulsar science with the SKA telescope, and for performing related population analysis or modelling to make meaningful forecasts on the expected survey yields.

pulsar_spectra has been developed as a prospective solution to this problem; it is intended to be a dedicated flux-density catalogue of pulsars, as well as a software repository for performing reliable spectral fits to determine the best-fit empirical models. It is an implementation of the method developed by Jankowski et al. (2018) that relies on Akaike information criterion (AIC) to determine the best-fit spectral model, but extended to account for the bandwidth over which flux density measurements are made. It makes use of the Huber loss function and is therefore far less susceptible to the influence of outlier measurements. The algorithm was tested extensively by Jankowski et al. for a large body of pulsar measurements.



Examples

Simple example

The following can be run to fit J0332+5434

```
from pulsar_spectra.catalogue import collect_catalogue_fluxes
from pulsar_spectra.spectral_fit import find_best_spectral_fit

cat_dict = collect_catalogue_fluxes()
pulsar = 'J0332+5434'
freqs, bands, fluxs, flux_errs, refs = cat_dict[pulsar]
best_model_name, iminuit_result, fit_info, p_best, p_category = find_best_spectral_fit(pulsar, freqs, b
```

This will produce J0332+5434_low_frequency_turn_over_power_law_fit.png

If you would like to see the result of the best fit you can print them like so

```
print(f"Best fit model: {best_model_name}")
for p, v, e in zip(iminuit_result.parameters, iminuit_result.values, iminuit_result.errors):
    if p.startswith("v"):
        print(f"{p} = {v/1e6:8.1f} +/- {e/1e6:8.1} MHz")
    else:
        print(f"{p} = {v:.5f} +/- {e:.5}")
```

which will output

```
Best fit model: low_frequency_turn_over_power_law
vpeak =    161.5 +/-    6e+00 MHz
a = -2.42975 +/- 0.1469
c = 1.66104 +/- 0.15576
beta = 0.69976 +/- 0.019222
v0 =    753.3 +/-    8e+00 MHz
```

↗ **Figure 2**
A screenshot of the *pulsar_spectra* repository. In an effort to encourage its wider use by the scientific community, *pulsar_spectra* has been extensively documented, by describing details of installation, common uses, methods, and how to contribute to the repository.

pulsar_spectra is an open source repository and has a user-friendly interface (**https://pulsar-spectra.readthedocs.io/en/latest/index.html**) that allows uploading new measurements, customising and performing spectral fits to produce publication-quality plots. It is meant to be complementary to the ATNF pulsar catalogue, which has been a valuable resource for the most reliable pulsar ephemerides. It has already been utilised for research in multiple publications, e.g., Lee et al. (2022), Janagal et al. (2023), Bhat et al. (2023), etc. The database repository is also used to perform a spectral analysis of a very large sample of pulsars (~900), the results from which will be reported in a future publication. The database is expected to grow over the course of time as astronomers add more flux density measurements and refine the methods, which will make it a valuable resource for the wider community.

PUBLICATIONS
Swainston, N. A., Lee, C. P., McSweeney, S. J., Bhat, N. D. R. 2022, PASA, 39, e056

Hunting for pulsar candidates in MWA images

SUSMITA SETT (PRIMARY AUTHOR)
MARCIN SOKOLOWSKI
RAMESH BHAT

Pulsars are spinning neutron stars that emit beams of radiation from their magnetic poles. Since the discovery of pulsars, they have been studied extensively and have played a crucial role in exploring various physical concepts such as precise tests of general relativity. To enhance our understanding of spectral properties and emission mechanisms, it is necessary to discover more pulsars emitting at low radio frequencies. The Murchison Widefield Array (MWA) Voltage Capture System (VCS) has been used regularly to study known pulsars at low frequencies and even discover new ones. The MWA VCS can record complex voltages from all individual antennas, which can be beamformed or correlated/imaged offline at millisecond time resolution. The greatest advantage of MWA VCS is that the same data can be processed in multiple ways, i.e. the candidates found in image based search can be verified using the same data by checking for pulsations.

For many years, pulsar searches have relied on time domain search methods that are highly effective at detecting periodic pulses, and led to the discovery of the majority of known pulsars. However, the sensitivity of these traditional techniques may be compromised by orbital motion, binary eclipses, and scattering, especially at low radio frequencies where dispersion measure (DM), smearing, and multipath scattering become dominant factors, leading to fewer detections of potentially interesting or exotic systems. At the MWA frequencies (70 – 300 MHz), traditional pulsar searches are also more time-consuming and computationally expensive due to the large number of DM trials required. Additionally, discovering pulsars in tight binaries requires performing acceleration searches, which increases processing time. An alternative approach is to use the high time resolution data of interferometers like the MWA to create continuum images, identify pulsar candidates in the image domain, and verify them using high-time resolution time-series data from the same dataset. Not only can this reduce compute time, but it can also lead to discoveries of pulsars missed by high-frequency searches.

Motivated by the idea, this part of my PhD focused on developing and applying novel methodologies to hunt for pulsar candidates in images from MWA VCS data. The first show-stopper was the lack of an end-to-end pipeline that would process high-time resolution MWA VCS data and produce good quality images ready for further analysis. A good part of the last year was spent working along with my supervisor, to prepare, test and optimise one

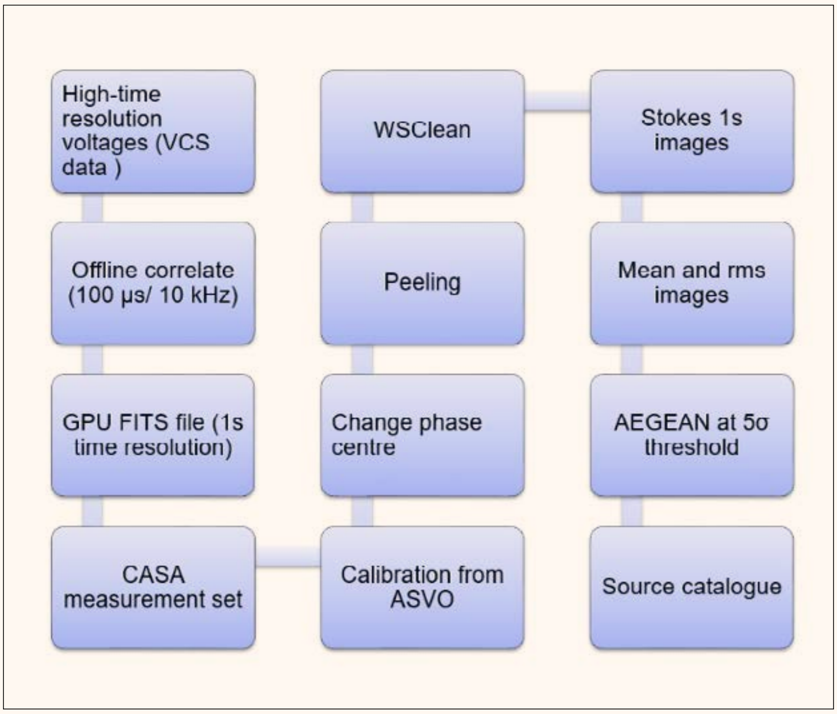
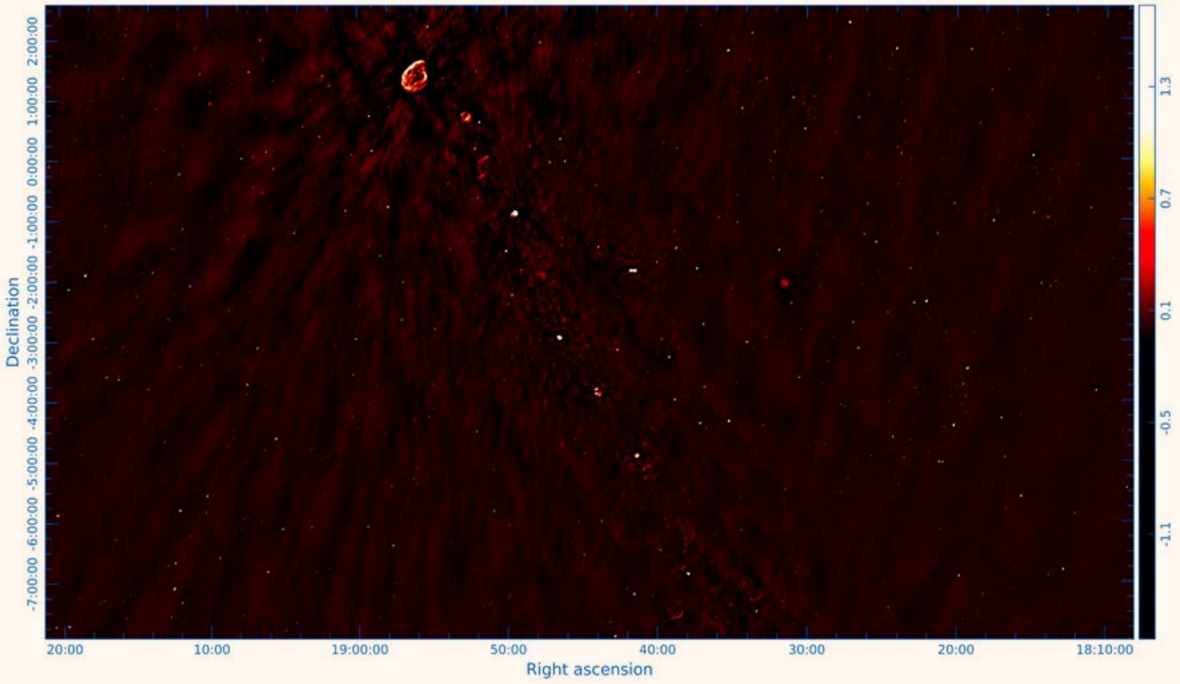


Figure 1
Block diagram of the imaging pipeline, which produces all Stokes images in 1-second time resolution from MWA VCS data, performs initial pre-processing of these images and identifies radio sources, which are used in further analysis.



↗ **Figure 2**
Cutout of Stokes I image. We can see a variety of extended sources, such as supernova remnants, as well as point sources including known pulsars. We verified that typically ~50 % of known pulsars can be detected in our images.

such pipeline that would produce images in all Stokes polarisations from MWA VCS data. After much toil the pipeline was developed, and is shown in the flowchart in Figure 1.

Once the pipeline was ready, it was tested on four observations. The very first and one of the best MWA VCS data Stokes I images to date is shown in Figure 2. It shows a region of the Galactic Plane passing through the centre of the image along with a supernova remnant which causes significant increase in the noise in that region. The source-finding software identified almost 9000 radio sources in this image, and the standard deviation of the noise in the center is about 5 mJy / beam.

These radio sources are then matched against three criteria developed based on pulsar properties to identify pulsar candidates. The first criterion selects sources with steep spectrums, where spectral index was calculated using flux density measured in our MWA images and RACS catalogue created from ASKAP data. The second verifiction is fractional circular polarisation, as pulsars tend to have to have at least a small degree of circular polarisation. Finally, we check time variability of the sources, as pulsars vary in short timescales. The details of the processing and results can be found in the recently published paper, Sett et al 2023. The candidates are then verified by forming a time series from the very same MWA VCS data. The best ranked candidates are then followed up with the Parkes (Murriyang) Telescope or the Giant Metre-Wave Radio Telescope (GMRT).

We are in the process of applying these developed image-based methodologies to MWA VCS observations covering the whole Galactic Plane to find pulsar candidates and discover new pulsars. The hunt is on! Stay tuned!

A new outreach tool to explore the Andromeda galaxy

Image 3
The Andromeda galaxy represented in Minecraft, with the differently coloured blocks representing stars of varying colours and luminosities. The star-forming spiral arm can be distinguished as the blue region. IMAGE: Ravi Jaiswar

RAVI JAISWAR

The prototype of a new interactive outreach tool made its debut at the 2022 Innovator's Expo, with an audience of forty Year 9-10 students. It allows students to explore our neighboring Andromeda galaxy in the familiar world of Minecraft, a game that combines creativity and logic in an unimposing, pixelated setting. The coloured blocks represent the actual physical positions of stellar mass clusters taken from the astrometric device upon the Gaia satellite orbiting Earth, and their colours reflect the photometric data, which represent the real colours and temperatures of the stars. Gaia is a European Space Agency space observatory that is charting the positional and velocity properties of one billion stars in our Galaxy and nearby galaxies, providing a rich and complete dataset for exploration by students. The Minecraft game allows users to fly around and see the galaxy model from a perspective not offered by other means, even revealing the spiral arm structure.

At the Expo, the students played with the model and even helped improve upon certain aspects of the tool through their interactions and feedback.

The tool will be further developed to allow students to explore our own and other galaxies accurately, through gaming, with the potential for other datasets to be used in this Minecraft environment.

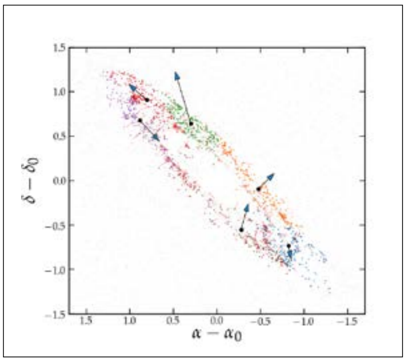


Image 1
The Andromeda galaxy spiral arms with the arrows representing the net motion of the stars in the coloured region. IMAGE: Ravi Jaiswar

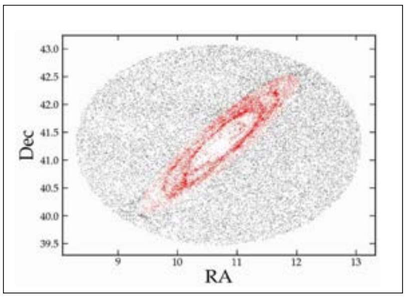


Image 2
The Andromeda galaxy position in our sky.
IMAGE: Ravi Jaiswar

Mitigating systematics from our observations

RIDHIMA NUNHOKEE

Understanding the evolution of our Universe implies unveiling the mysteries behind the different transitions undergone by our Universe, one of which includes the Epoch of Reionisation (EoR). About 400 million years after the Big Bang, our Universe went from being completely neutral, to reionised, through the emergence of the very first massive stars. This period is termed the EoR, and it enables us to study the formation and evolution of these early light sources.

We use the 21 cm hydrogen line at low frequencies as a probe to measure the statistical fluctuations of the intergalactic medium during the EoR. However, the 21 cm signal is few orders of magnitude weaker than our astrophysical foregrounds including Galactic and extragalactic emission. MWA applies the ‘foreground subtraction’ method whereby a known model of these astrophysical foregrounds is subtracted from our observations. This technique is sensitive to both the inaccuracies in our known sky model and instrumental systematics.

We used statistical metrics as a diagnosis tool to investigate systematics, including badly-behaving antennas and observations dominated by RFI or other radio transmissions. Figure 1 illustrates the effect of removing bad antennas from our data prior to foreground subtraction. We illustrate an observation where our diagnosis tool identified four misbehaving antennas. It can be seen from the left panels of the image that if the behaviour of these antennas is omitted, fringe-like structures are produced, that could be mistaken for Galactic diffuse emission, and they propagate to the subtraction step. This in turn induces a bias in our final 21 cm power spectra measurements. The right panels show the same observation after discarding these four antennas. The structures observed in the left plots are no longer visible and the foreground subtracted data are cleaner. It is therefore imperative to identify systematics arising from the observing instrument to avoid any bias in our final measurement.

In addition, the derived metrics are used as a clustering tool to classify the two-minute observations spanning the latest EoR measurements into several groups. Assuming these groups have at least one property in common, we evaluate the power spectra averaged over measurements from each group. Our aim is to find the group of observations that contribute towards the optimal 21 cm measurement.

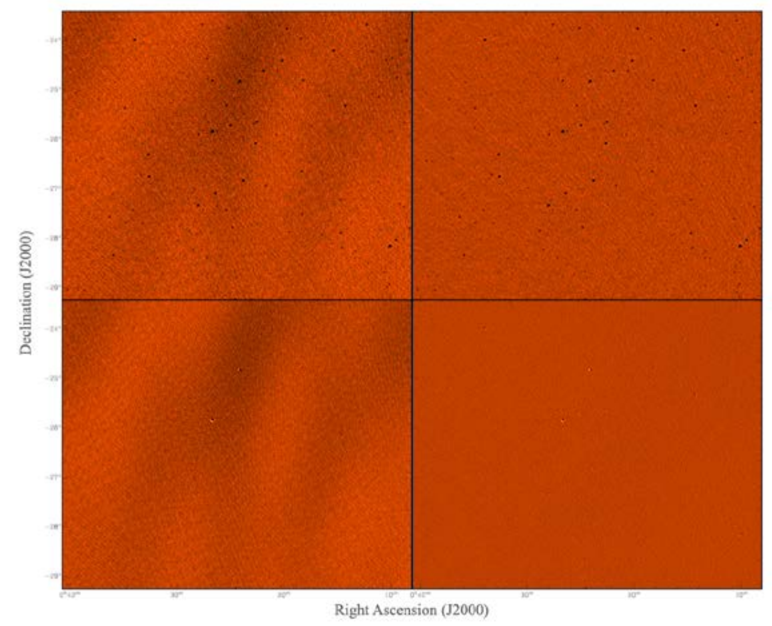


Figure 1
Images constructed from an MWA observation, focused at the EoR. The top panel illustrates the sky, comprising both the foregrounds and 21 cm signal, while the bottom panel shows the sky after subtracting the foregrounds. The misbehaving antennas present in the observation are excluded in the right-hand plots.

A Near-Field imaging capability using the MWA

STEVE PRABU
STEVEN TINGAY

Using three basic assumptions, conventionally used radio astronomy imaging techniques use a 2D Fourier transform to create images of the observed radio sky. The conventional method assumes the instrument to observe the sky with a narrow bandwidth (assumption 1), observing a far-field source whose radiation can be approximated to planar wave-fronts (assumption 2), and the instrument is assumed to have a narrow Field of View (FOV) (assumption 3). Whilst much work has been developed in the literature to overcome the bandwidth and FOV assumptions (such as Multi-Frequency Synthesis and W-Stacking) which enable us to perform the majority of the science cases accurately, not much progress has been done in developing techniques/tools to observe sources in the near-field whose radiation wavefront cannot be approximated to be planar. In this work, we demonstrate near-field imaging techniques using the extended configuration of the Murchison Widefield Array (MWA), whose long (6 km) baselines see events within the atmosphere in the near-field (for frequencies that the MWA is capable of observing in).

To focus the array (i.e., the MWA) to any desired near-field distance, we apply phase corrections to each baseline so that the curved radiation wavefront from the near-field event falls coherently on the array. The applied phase corrections can be thought of as adding additional delays in order to ‘curve’ the array to match the curvature of the wavefront. The process is illustrated in the four panels of Figure 1, where we present the absolute delay corrections performed on approx. 8000 instantaneous baselines of the MWA for four different focal distances (10,000 km, 1,000 km, 500 km, and 50 km). In contrast, the long baselines require larger phase corrections (delay) to be applied as they see more curvature in the near-field radiation wavefront.

We generate near-field images at various focal distances using a single time-step during which the ISS was detected through FM reflection. We focus the array over a broad range of distances (10,000 km, 1,000 km, 500 km, and 50 km) and create images. The corresponding images are presented in the four panels of Figure 2. When the array is focused at 10,000 km, which is in the far-

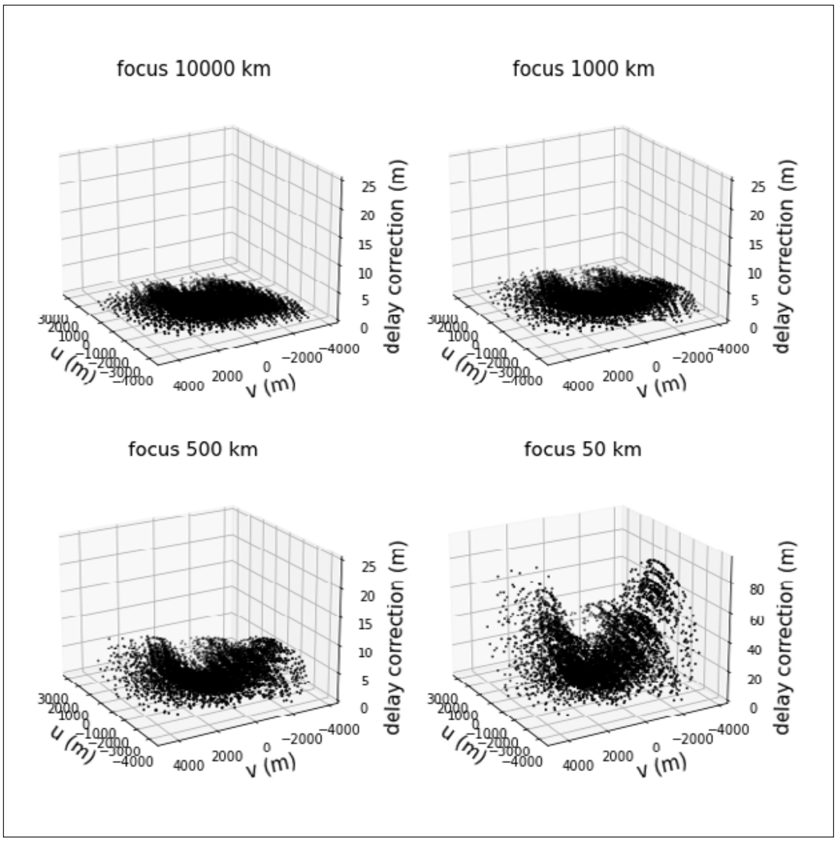


Figure 1
The absolute delay corrections performed to bring the MWA into focus for four different focal distances.

field of the instrument, the resulting image is similar to the image obtained without any near-field correction. However, at around 500 km, we observe a streak-like signal from the ISS that was previously de-correlated when the array was focused to infinity. The ISS signal once again gets de-correlated as we bring the focal distance to much shorter distances, such as 50 km.

In Figure 2, the 10,000 km image also reveals a point source, which is a background radio galaxy. The white arrow indicates the location of the point source in the sky. As we bring the focal distance to much smaller distances, the point source becomes de-correlated, which is expected. Because the source is unresolved, all baselines respond uniformly to the point source. However, the Phase 3 MWA has predominantly long baselines that undergo significant phase correction as we vary the focal distance, leading to the de-correlation of the point source. Conversely, the overall phase structure of an extended source in the observation is expected to remain intact for a wider range of focal distances since the shorter baselines that do not undergo significant phase corrections sample the overall phase structure of an extended source.

In the Future, we will incorporate our techniques to develop tools to perform near-field peeling of RFI from interferometer data. We will also use our methods to search for events in near-field of the MWA, such as intrinsic emissions from meteors, satellites, and aircraft.

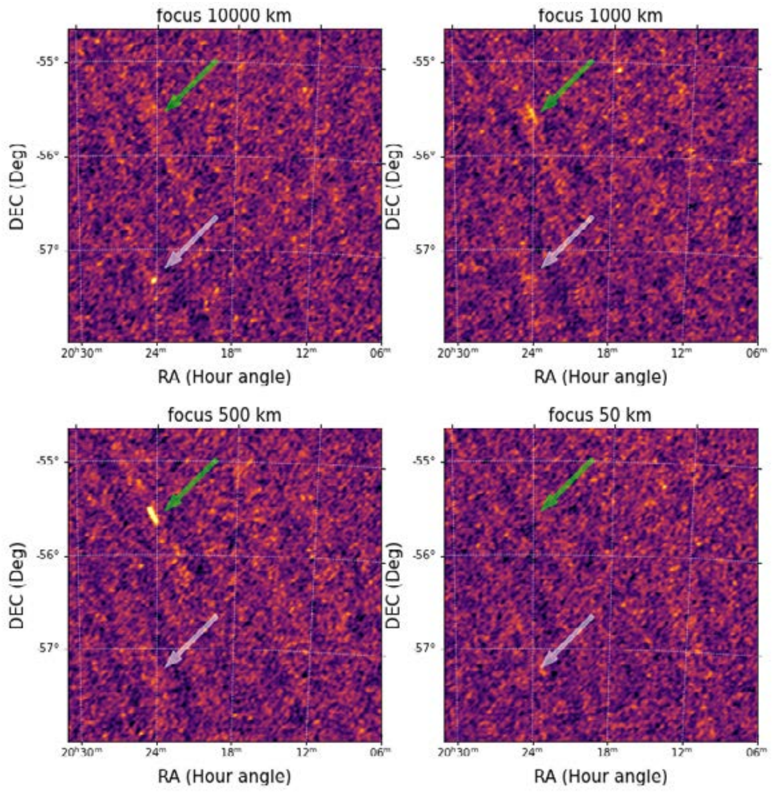


Figure 2
MWA images for four different focal distances. The green arrow shows the location of the ISS signal and the white arrow shows the location of the background point source.

Calibration of next generation radio telescopes; how can small satellites help?

FERRY LANTER

With the calibration of current radio telescopes already presenting some problems and having limitations [1], finding ways to improve or aid in calibration for the significantly more complex next generation of radio telescopes is crucial to realise their full potential. The Ionosphere imposes several unwanted effects on radio astronomy observations because of its refractive index and therefore must be calibrated for. The longer baselines of the most recent iteration of the Murchison Widefield Array, and in particular, next generation radio telescopes such as the future Square Kilometre Array means that a completely different Ionospheric condition may be observed by each antenna station that comprises a baseline. Ideally, absolute Ionospheric measurement data, which is currently not available, is needed to calibrate for such a condition [1].

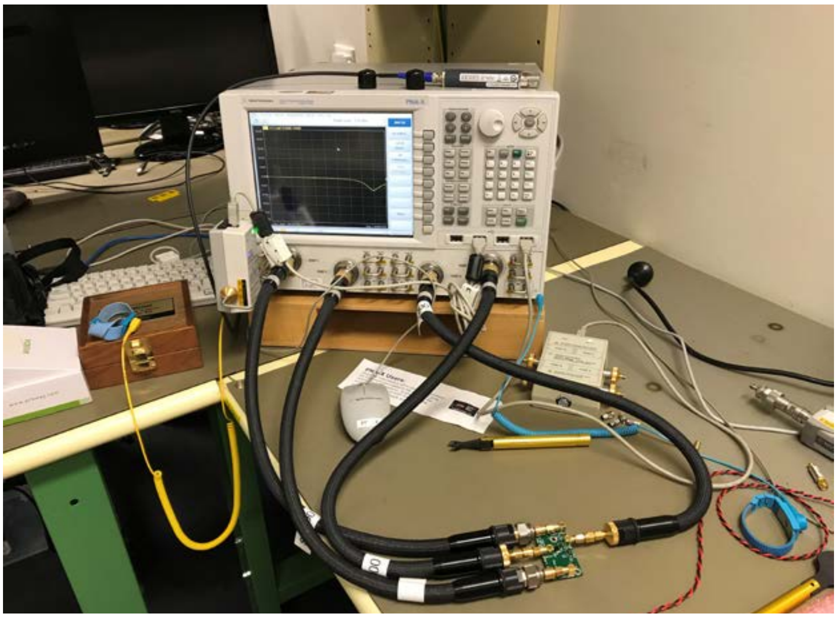
Small satellites present a cost-feasible opportunity to address this challenge. By placing a small satellite in a low Earth orbit above the Ionosphere (at around 1000 kilometres), absolute measurements of the Ionosphere can be made. Furthermore, because of the high orbital velocity, each pass over the relevant observational sky occurs on a timescale where the Ionosphere may be considered constant which provides a ‘cut’ of the observational sky. However, the current state-of-the-art small satellites are unable to provide the functionality to enable this solution. A number of key engineering challenges must be overcome.

Figure 1
3U CubeSat tri-band antenna prototype for Ionospheric measurement.

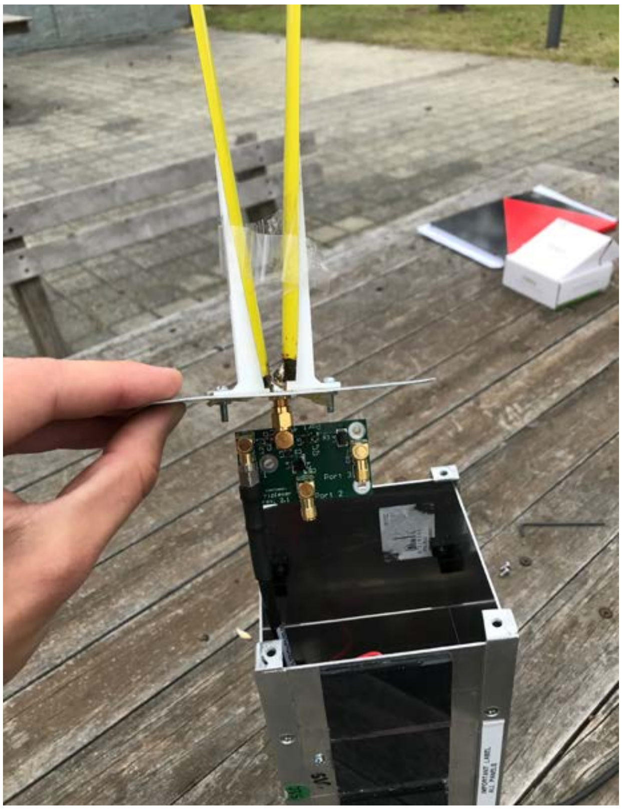
In order to determine the key small satellite requirements that enable such a solution, a new Ionospheric measurement technique suitable for small satellites was developed [2]. Unlike conventional Ionospheric measurement techniques that require four or more transmitting frequencies, absolute Ionospheric measurement can be achieved with only three transmitting frequencies. From this, we obtained practical and comprehensive RF payload requirements (for the antenna and transmitter), which triggered further work on a small satellite antenna leading to the development of a tri-band 3U CubeSat antenna [3].

From the conclusion of the antenna work, we found the mechanical constraints of small satellites resulted in some unique antenna characteristics that present a number of novel challenges that must be overcome to integrate it with three RF transmitters (one for each frequency). Most notably, the small size of CubeSat satellites meant that the antenna had to be small. However, a small antenna means that the antenna’s radiating resistance also becomes small, and its capacitance becomes large. To radiate out of the antenna as desired, power must be delivered to the antenna’s radiating resistance. Any power delivered to the capacitance gets reflected back to the transmitter which can cause it to be destroyed. To address this, we developed a new multiplexer design technique that not only isolates each of the three transmitters from one another, but also simultaneously ensures that each transmitter is delivering all its power to the antenna resistance [4].

The work done thus far represents a starting point in the realisation of this small satellite solution, providing the necessary contributions to assemble a suitable RF payload. This starting point also presents a plethora of opportunities for interesting and novel future work, including power supply design and mechanical structure design, to name a few.



↗ **Figure 2**
Measurement verification of the multiplexer that enables the integration of three transmitters to the single tri-band antenna.



↗ **Figure 3**
The triplexer circuit being tested with the prototype antenna.

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The MWAX Correlator goes live

Figure 1
The final day of the two-week site trip to install MWAX. Left to right: Greg Sleap, Mia Walker, Harrison Barlow. Not pictured: Andy McPhail. IMAGE: Mia Walker

Figure 2
New MWAX hardware arrives at CIRA. IMAGE: Greg Sleap

GREG SLEAP
IAN MORRISON

Since its commissioning in mid-2013, the MWA's correlator (aka the legacy correlator) was a solid workhorse, correlating up to 128 tiles and later incorporating a voltage capture system (VCS) that enabled capture and storage of fine-channelised voltage data.

As MWA entered "Phase II" in 2017, priority was given to planning the expansion up to correlating all of the 256 tiles now deployed. The legacy fine channeliser and correlator was limited to 128 tiles and a single frequency resolution option. The VCS also did not allow for capturing of voltages at the full coarse channel time resolution. There was also a directive from MWA management to reduce the reliance on bespoke equipment in the signal chain, and instead prioritise utilisation of commercial off-the-shelf (COTS) hardware and software where possible.

During Phase II, the high-level requirements for a replacement correlator and VCS which could take MWA from 128 to 256 tiles started to become clear. The new system, named "MWAX", would:

- Be flexible enough to correlate any number of tiles up to 256, as it was likely new tiles would be added gradually over time, rather than all additional 128 tiles (and their required receiver hardware) being deployed at once.
- Be able to correlate data from the existing 16 receivers as well as any new/future receivers.

- Be able to expand instantaneous bandwidth by simply adding more servers (1 server for each coarse channel).
- Be able to correlate with many more frequency resolution and time averaging options.
- Be able to provide full coarse channel time resolution voltage capture.
- Be able to support real-time fringe-stopping as a future enhancement.
- Be more robust to failures and Pawsey/archiving outages.
- Be able to support any number of external instruments commensally tapping into the high time resolution voltage stream (for example a future FRB search or Breakthrough Listen pipeline).

During 2018-2020, the MWAX team developed an architecture that would reuse the existing receivers, network switches, storage servers and some of the VCS servers. Twenty-six new “MWAX Servers” would be procured, and each would combine the functions of the fine channeliser, correlator and VCS in software, and use the 100 Gbps link to the Curtin data centre to buffer data from MWAX in the event that the archive at Pawsey is temporarily unavailable. MWAX’s software stack would be based on well-known and supported technologies: multicast UDP for sending receiver data to any number of MWAX servers, the NVIDIA cuFFT library for the F-stage of correlation, a customised version of the xGPU library for the X-stage of correlation, PSRDADA for ring buffers, xrootd for data transfer, and the FITS format for visibility files.

In the second half of 2020, a comprehensive and independent critical design review (CDR) was undertaken to ensure the MWAX design was suitable for taking MWA to a 256-tile system. The CDR milestone was passed successfully and by late 2020 CIRA was awarded an AUD $1M Federal Government grant to purchase new MWAX hardware components.

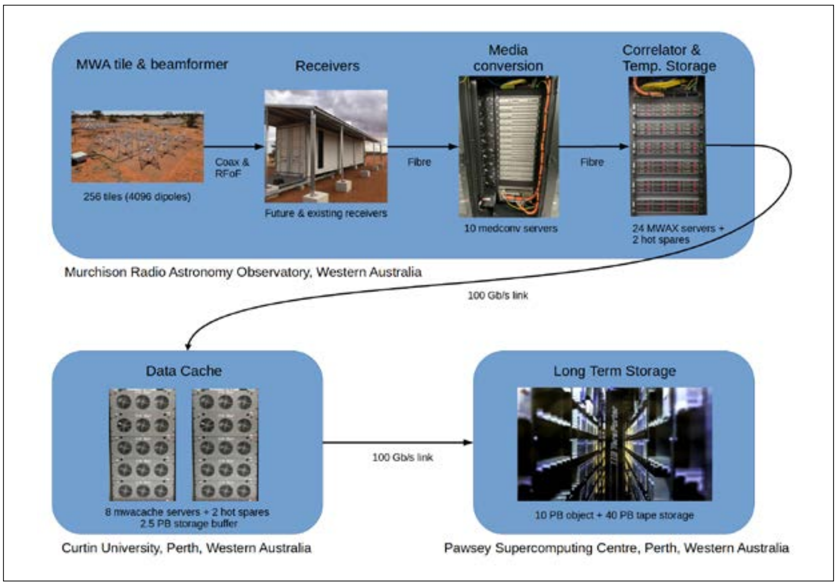
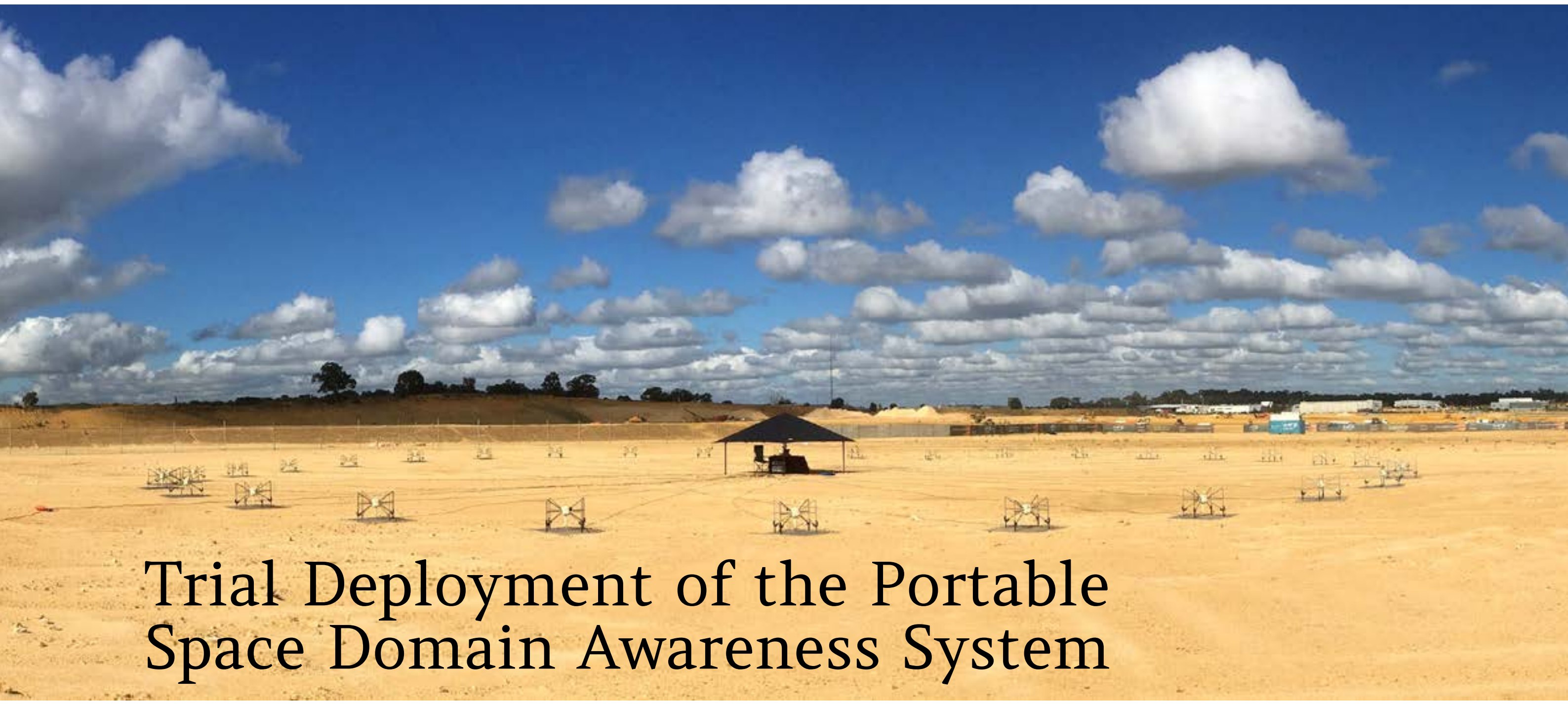


Figure 3
The high-level signal path for MWAX. IMAGE: Greg Sleap

After a rigorous request for quotation (RFQ) process, 26 HPe MWAX Servers were procured and delivered to CIRA in mid-2021 for pre-site configuration. Around September 2021, over two weeks, the legacy correlator and VCS were removed and replaced with the new MWAX system. Then began the engineering commissioning process where the MWAX team refined and tested the software and hardware configuration, fixing any bugs and establishing baseline performance benchmarks to allow science commissioning to commence.

By late December 2021 a successful, several month-long, science commissioning phase for MWAX was wrapping up. This paved the way for MWAX to “go live” in March 2022 with the first observations of the 2022A semester. Over the course of the year the 2022A season was completed, with over 9 PB of data collected from ~1,400 hours of observing.

During the 2022A semester, the MWAX team continued to work on new features such as fringe-stopping (allowing the telescope to track a point in the sky allowing for smaller data sets with the same quality) and the ability to quickly change the number of correlated tiles in MWAX as new receivers and tiles come off- and on-line. To cap off a successful year, MWAX was chosen as a WA State Finalist for the Engineers Australia’s 2022 Excellence Awards, recognising the successful design and implementation of the MWA’s new correlator and VCS system, a crucial step in taking the telescope to a more capable, 256-tile system as Phase III progresses.



Trial Deployment of the Portable Space Domain Awareness System

Figure 1
The Portable SDA system deployed at the AARP next to the custom built trailer used for transportation.

JAKE JONES
SDA TEAM

The Portable Space Domain Awareness (SDA) system, designed and developed by the team at CIRA, is a passive radar demonstration system with a purpose to detect and monitor objects in space. As a passive radar, it does not transmit, but rather it detects reflections of existing commercial broadcast signals such as FM radio or Digital TV. It consists of an array of 32 MWA dipoles, a coherent receiver system based on Airspy R2 software defined radios, a timing distribution system and a server for signal processing.

The system is also intended to be portable so that it can potentially be deployed to remote locations. When the system is deployed, the 32 dipoles are arranged in a 35m diameter circle with the receiving equipment located in the centre, and when packed, all parts are self-contained within a custom built trailer. Figure 1 shows the deployed array alongside the trailer it packs into. Trial deployments have shown the system is capable of being deployed by 4 people within a couple of hours.

While the system is intended to track objects in space using broadcast transmitters several hundred kilometres away, it can also be used to track aircraft where the transmitter can be much closer. Therefore, as part of the test campaign, we deployed the system to the AARP (Australian Automation and Robotics Precinct), about 47 km from Perth's main broadcast antenna which is an ideal configuration to observe aircraft. During the test, we recorded several hours of data at different frequencies and at one point a small aircraft flew overhead in a circular holding pattern making for an ideal target to track.

The collected data was subsequently processed offline, implementing a coherent bi-static passive radar. Firstly, a copy of the transmitted reference signal was obtained by digitally beamforming the array towards the horizon in the direction of the transmitter. Since reflections from moving objects experience a doppler shift, several frequency shifted copies of the reference signal are also computed. Next, the reference signals are lag-correlated with each antenna before a grid of beams are computed across the visible sky. This effectively produces a power-like quantity over a 4 dimensional search space of signal delay, doppler shift and two dimensions for direction. The target object appears as a peak within this search space.

The results of the test are presented in Figure 2 which shows a clear detection of the target aircraft using digital TV as a non-cooperative source. At the bottom

of the figure is a delay-doppler map; it shows a strong peak corresponding to the aircraft along with some extra clutter. In the top-right of the figure is a view of the detected power vs direction for the entire visible sky, clearly showing the direction that the reflected signal came from. Finally the delay information, combined with the direction information was used to compute the flight path of the aircraft which is plotted in the top-left of the figure. It can be seen that the detected flight path (green dots) matches closely with the publicly available flight track data (in blue).

Overall, we have demonstrated the systems capability to function as a passive radar to detect aircraft. The next logical step for the project is to conduct another deployment with the goal to detect an object in orbit.

This research was supported by the Defence Science Centre, an initiative of the Australian Government and State Government of Western Australia.

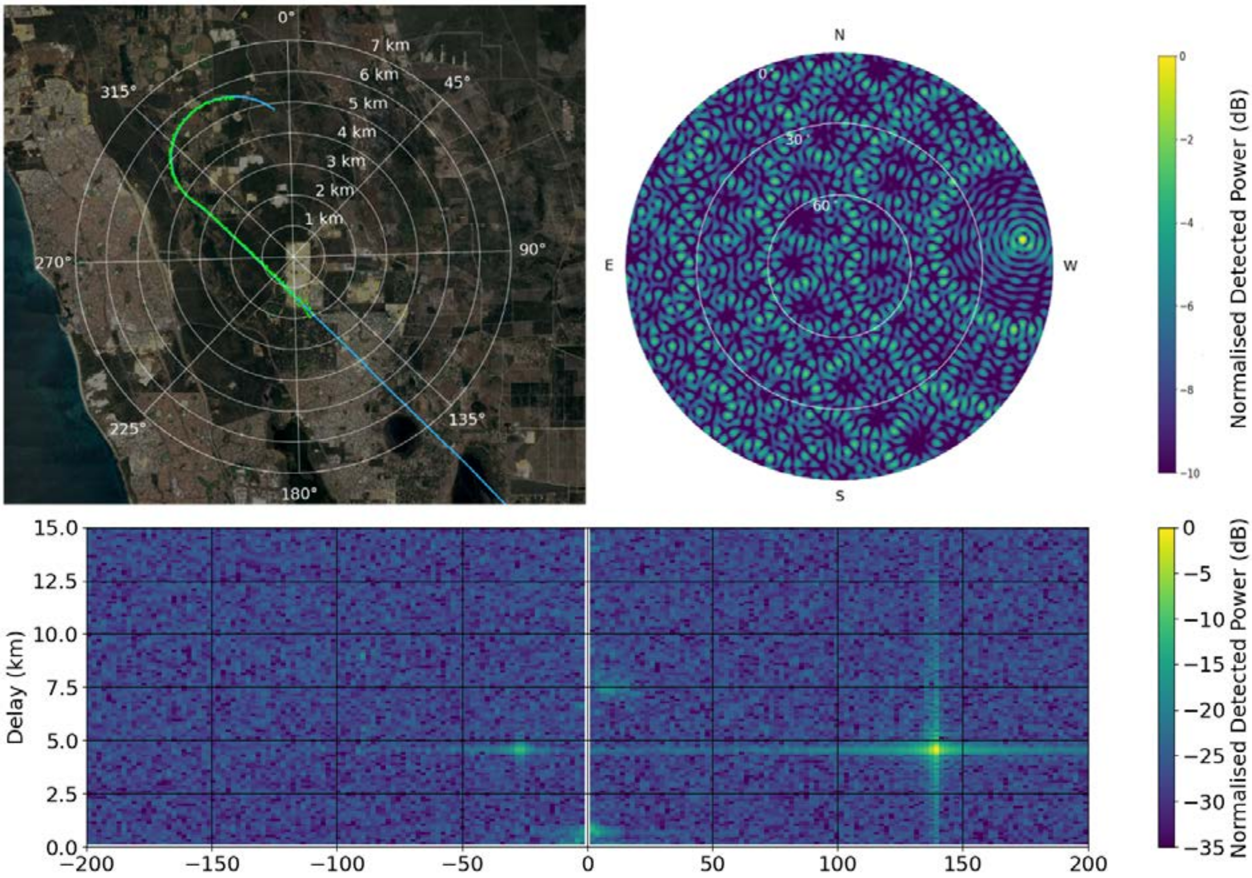


Figure 2
The result from the trial deployment demonstrating a detection of the target aircraft and its flight path. Top-Left: The detected flight path (green) and the actual flight path (blue). Top-Right: All-sky view of the detected power. Bottom: A delay-doppler map showing a strong peak corresponding to the aircraft.

High-time resolution GPU imager for the MWA and SKA-Low stations

MARCIN SOKOLOWSKI
GAYATRI ANIRUDDHA
DANNY PRICE
CRISTIAN DI PIETRANTONIO (PAWSEY)

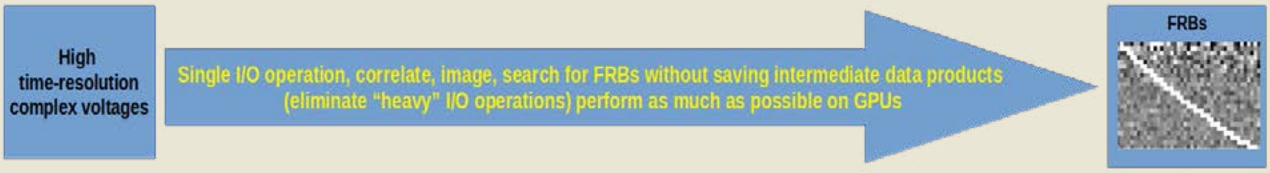
Fast Radio Bursts (FRBs) are one of the most exciting and mysterious phenomena discovered only 15 years ago in archive data from the Australian Murriyang (Parkes) radio telescope. They are short (typically millisecond) duration radio pulses originating from even the very distant Universe (redshifts reaching 1). Although we still do not fully understand the underlying emission mechanisms and FRB progenitors, FRBs have already been successfully used to probe and better understand the composition of the Universe, as radio waves can precisely measure the amount of electrons (and consequently other matter) between their source and observers on Earth.

Initially discovered at GHz frequencies, in the last five years hundreds of FRBs have been detected down to 400 MHz by the CHIME telescope. So far, only a handful of FRBs have been detected at frequencies below 350 MHz. However, the FRB daily rates measured by CHIME at 400 - 800 MHz, the rates measured by higher frequency telescopes extrapolated to lower frequencies, and especially the recent FRB detections by the LOFAR telescope indicate that there are a couple of bright low-frequency FRBs per day over the entire sky. Nevertheless, no FRB has yet been detected in the Southern Hemisphere at frequencies below 400 MHz.

The main difficulty in detecting these FRBs is the lack of all-sky and wide-field monitoring instruments and suitable software which can process data efficiently and search for them (ideally in real-time). Therefore, one of the main goals of the PaCER BLINK project is to develop this kind of software utilising Graphical Processing Units (GPUs), which are becoming more powerful and widely used in both radio astronomy backends and supercomputers. Their energy efficiency (shown to be up to ten times better than CPUs for complex problems) makes them a good alternative to traditional CPUs to reduce the carbon footprint of HPC centres and other computing infrastructure for astronomy.

The main goal of the PaCER BLINK project is to develop a very efficient, GPU-based software pipeline, which will read complex voltages from a hard-drive or receive them from the backend of a telescope, correlate them, form high-time resolution images and search for FRBs or other transient phenomena as close to real-time as possible. The main requirement is to keep the data in the GPU memory from the very beginning of the processing, through correlation, imaging and FRB searches. Hence, very slow I/O and data conversion operations limiting the efficiency of low-frequency FRB searches using standard radio astronomy software packages and data formats (like CASA measurement set or MIRIAD uv FITS files), will be eliminated (Figure 1). Furthermore, keeping the data inside GPU memory will minimise memory copy operations between GPU and standard CPU (Host) memory, which can also be time consuming.

The realisation of these goals is supported by the Pawsey PaCER initiative, which enabled a close collaboration of CIRA researchers and Pawsey staff, and funds a student to develop the software and perform FRB searches on data samples from low-frequency instruments such as the MWA and SKA-Low stations. Over the last



↗ **Figure 1**
Diagram of the BLINK GPU processing pipeline with the main paradigm to minimise I/O operations, and keep the data processing from the start to FRB search inside the GPU memory.

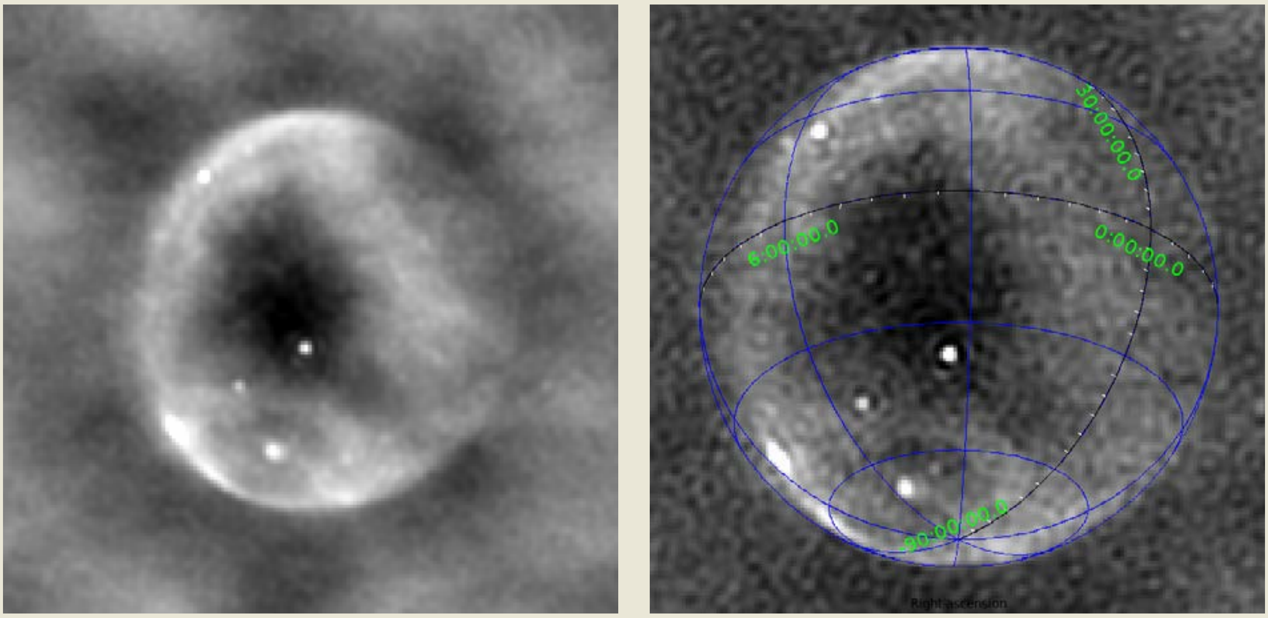


Figure 2
Image of the entire visible hemisphere created using complex voltages from the Engineering Development Array 2 (EDA2) at 160 MHz. Left : "dirty image" created using software developed by PaCER BLINK team (takes about 15ms). Right : a corresponding image created with standard radio astronomy software MIRIAD applied to the same data and using settings replicating the BLINK imager (takes about 300ms). The blue lines mark the horizon and equatorial sky coordinates.

two years the group have achieved significant progress, and developed a GPU imaging software, which was verified and tested on simulated and real data from the MWA and EDA2 telescopes. An example image from the “BLINK” imager is shown in Figure 2 where it is compared to an image produced by MIRIAD software applied to the same data using very similar imaging options (the so-called “dirty image”). The initial benchmarking showed that producing a 180 x 180 image from EDA2 complex voltages took about 16ms, which is much less than MIRIAD (300ms) and CASA (3000ms), where all execution times were measured including reading the input data (I/O) to make the comparison as fair as possible.

The group has also developed the first version of a pipeline which reads the input high-time resolution data from files, performs correlation, gridding and imaging (both steps on GPU) without intermediate I/O operations. We are currently developing a production version of the software, which will enable processing of longer portions of data (minutes up to an hour) in multiple frequency channels. In the next step, de-dispersion and FRB search algorithms will be included into the pipeline. This will enable processing of many hours of MWA VCS data stored in the Pawsey archive, and also the development of a near real-time FRB search pipeline to be deployed on SKA-Low stations.

Besides FRB searches, high-time resolution imaging software developed in the course of this project can be applied to any data from low-frequency radio telescopes to look for transients, spatial monitoring of radio-frequency interference (RFI) and potentially other applications as we intend to make the software publicly available for research purposes.

Fulbright Future Scholarship

MARIA KOVALEVA

My four-month Fulbright program spanned from the 1st of August until the 30th of November 2022 at Brigham Young University (BYU), Utah, where my host supervisor Prof Karl Warnick is the director of Radio Astronomy Systems Research Group. My project titled "Analysis and Optimization of Wideband Phased Array Receiving Antennas for Radio Astronomy" aimed to advance numerical techniques used in radio astronomy engineering, to extract information about mutual coupling between neighbouring antennas in an array of telescopes from the existing measured data on radiation patterns. Since digital signal processing is the top research strength of Radio Astronomy Systems Research Group, my other goal was to learn about the digital signal processing part of radio astronomy engineering, and especially about CASPER, which stands for the Collaboration for Astronomy Signal Processing and Electronics Research, and radio frequency system on chip (RFSoC). As a result of collaboration with Prof Warnick, I have published a conference paper M. Kovaleva, K. Warnick, "Effect of Noise in Embedded Element Pattern Measurements on Mutual Impedance Matrix Extraction", at the European Conference on Antennas and Propagation, and worked on a draft of a journal paper. I gave a short talk and a colloquium about the SKA-Low (see Fig. 1), attended a Utah Wireless and RF Day and presented a guest lecture at BYU, but also spread the word about the future largest radio telescope in the world when meeting new people. It was great to see the fascination about the Square Kilometre Array. The scale of the project and its aims sparked a lot of interest, and I felt very privileged to spread the word about it in the USA.

Figure 1
With Dr Mitch Burnett, a research engineer at the BYU Radio Astronomy Systems research group. After the colloquium about SKA-Low, there was a 60-min "Meet a researcher" session where students could ask their questions. IMAGE: Dr Maria Kovaleva, 2022

Figure 2
With Professor Cynthia Furse of the Department of Electrical and Computer Engineering at University of Utah next to the famous Smith Chart quilt that she made. All the signatures are of her graduated students. IMAGE: Dr Maria Kovaleva, 2022

WHAT DID THIS EXPERIENCE MEAN TO YOU AND HOW HAS IT IMPACTED YOUR LIFE?

I had an incredible experience while on my Fulbright Future Scholarship. The environment of Utah presented itself as very generous, warm and welcoming, and I enjoyed seeing the change of seasons from August to November, which you cannot see that strongly in Western Australia. Working with my host Prof Karl Warnck, I acquired new skills that will propel my future research in Australia, and I finally understood some concepts that I could not understand before just by reading the manuscripts. Being there in person made such a difference! I am also much more confident about my research now; it feels like I broke the glass ceiling by trying myself in an absolutely new place. The feedback and questions I received during my presentations at Brigham Young University allowed me to see my research from a different perspective and gave me the ideas on how to become a better presenter. Thanks to my host professor who introduced me to his academic collaborators in Europe, I expanded my professional network and learned about the details of antenna measurements. I also had an incredible chance to meet Prof Cynthia Furse (see Fig. 2) from the University of Utah, who has been my role model in electromagnetic research and education for the last 10 years due to the popularity of her lectures about electronics and electromagnetics on YouTube. Not all the benefits of the Fulbright Future Scholarship are related to research. While in the US, I saw the places that are visited by people from all over the world and learnt about what matters to me. I understood that meeting people is the part of travelling I like the most. I loved finding the differences and similarities between people of different nationalities, and my conclusion is that we all have so much in common that it is humbling and eye-opening. I truly enjoyed solo travelling because it was so much easier to make new friends. Living in Provo was my first time living in the mountains, and I could not stop admiring their majestic appearance. It was unforgettable to see the Arches National Park, dinosaur footprints, petroglyphs and pictographs and to learn about the history of Utah, as well as visiting San Jose in California and going to Stanford University, Silicon Valley and driving to Carmel-by-the-Sea.

ERA – The Educational Radio Array

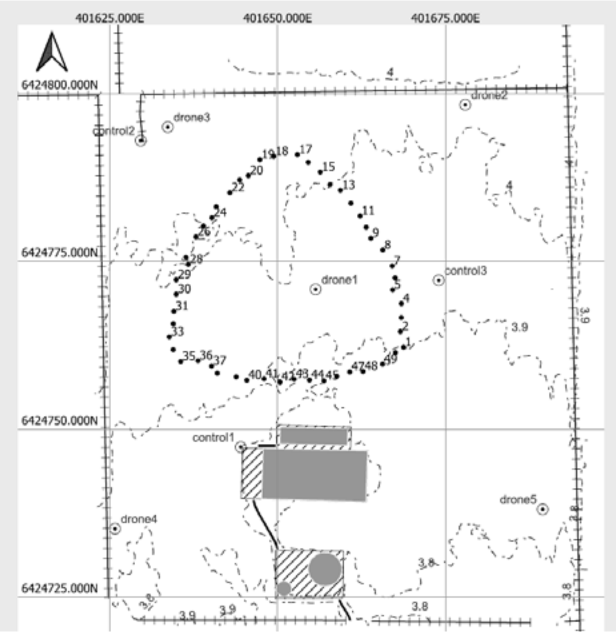
RANDALL WAYTH

Historically, demonstrating radio astronomy for the purpose of education and outreach has been challenging. While a modest optical telescope pointed at the Moon, Jupiter or Saturn can be an extraordinary experience for many, a similarly sized radio telescope simply can't generate the same "wow" factor. Many small-scale radio telescope systems exist for education/outreach, but these are typically limited to single dish/antenna systems that have very poor spatial resolution and do not perform interferometry, which is at the heart of most radio astronomy. ICRAR's "Tiny Radio Telescope" system is a notable exception, which uses two satellite dish antennas to form a simple two-element interferometer.

In the SKA era, it is more important that ever to have meaningful and inspiring demonstrations of radio astronomy as well as systems that can be used by students to learn the fundamentals of radio interferometry. That implies having an education/outreach array with a large number of antennas that can perform interferometry and make inspiring images of the radio sky.

An essential requirement of a radio array is to have coherent radio receivers. Coherent has specific meaning in radio astronomy: it means the receivers are in synchronised lockstep so that the electromagnetic waves received by the antennas can be combined electronically to form images. One of the technical challenges of building radio arrays with antennas separated large distances is maintaining coherence in the array. Over several years I have been developing inexpensive coherent receivers through a series of student projects, culminating in a successful demonstration of a 5-input system in 2019 which was scalable to very large numbers of inputs. This development allowed building an inexpensive radio interferometer array with many antennas. In collaboration with the ICRAR outreach team based at The University of Western Australia (UWA), the concept of ERA (pronounced like the word 'era') was developed as part of the Translation and Impact program.

ERA was envisioned as a low-frequency remotely-controlled radio telescope suitable for Secondary and Tertiary educational use.



↗ **Figure 1**
The ERA Site Plan of surveyed antenna locations in a perturbed Reauleaux triangle, by Curtin University student Andrew Meumann and supervisor Dr David Belton, March 2022. Map scale is 1:500.

↗ **Figure 2**
Surveying the Educational Radio Array.

↗ **Figure 3**
Installing ERA antennas.

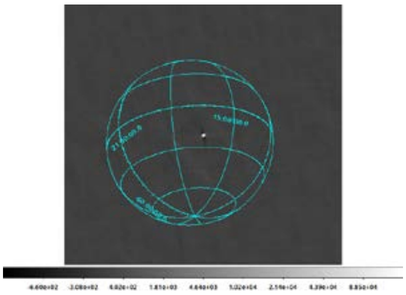


Figure 4
“First light” of the ERA system, with the Sun clearly visible.

Figure 5
The finished instrument at the Mardella observatory.

ERA’s purpose is:

- A tool for undergraduate education that will assist in teaching of fundamental radio astronomy principles through practical experience.
- To increase awareness of the Square Kilometre Array project and ICRAR’s (and WA’s) involvement amongst secondary and tertiary student audiences.
- To increase awareness of the opportunities radio astronomy and the SKA present within Western Australia for a broad spectrum of STEM fields and training levels.

During 2020 and 2021, the concept and details of ERA were fleshed out and a successful grant application by our colleagues at ICRAR/UWA meant that the array could be realised. An array the size of an SKA-Low station (approx 35 metre diameter) with 50 antennas was chosen as a system that has good imaging performance, is relevant to SKA-Low, and was practical within the constraints of site and budget. The ERA was also chosen to reside at the newly designated Mardella observatory alongside the suite of optical telescopes housed at the site. Mardella is in a semi-rural area approximately 45 minutes drive south of Perth.

The radio environment at Mardella was measured in late 2020 as part of the initial investigations into potential sites.

The final design of ERA is a perturbed Reauleaux triangle using COTS antennas that are sensitive to the 320-330 MHz frequency range (see Figure 1).

The array uses a modular receiver system using modified RTL-SDR USB receiver dongles packaged into units of 10. The receiver modules incorporate a custom designed clock distribution system designed at CIRA. The full array is comprised of 5 modules, each servicing 10 antennas. The antennas are connected to custom-built low-noise amplifiers which amplify the signal for transmission over coaxial cables to the receivers and signal processing system.

In semester 1, 2022 the site surveying for antenna deployment was assigned to final year Curtin Surveying student Andrew Meumann (Figure 2). The antenna mounting poles were placed based on an initial round of surveying followed by a second round to confirm the as-built configuration. The result was a successful student project and professional-grade survey of the site to mm accuracy.

Following the survey and placement of antenna mounts, the remaining infrastructure was built out over the remainder of the year with the Curtin technical and operations teams, and ICRAR/UWA outreach team. This included mounting all antennas and LNAs (Figure 3), placing the cable trays and associated mounts, laying and terminating the long coaxial cables and installing a custom built “gland plate” that allows managed and weather proof cable ingress into the building. In addition, work to build an archive and user interface system was commenced by our colleagues at UWA.

The full system was connected and an initial short test in December was a successful “first light” of the system, generating a clear signal from the Sun from all 50 antennas (Figure 4).

The ERA (Figure 5) was completed on schedule and under budget and the initial results look promising. Looking forward, the next goals for ERA are to produce observing programs suitable for high school and undergraduate students and to flesh out the data archive and user interface. To our knowledge, there is no comparable radio array anywhere in the world with as many antennas that is dedicated to education and outreach in radio astronomy.

PaSD Software Development

ANDREW WILLIAMS

CIRA has been working on designing and building prototypes for the SKA-LOW 'Power and Signal Distribution' (PaSD) system for a few years now, and is about to hand over the completed designs and documentation to industry for mass production. My job has been to write the software to monitor and control them – in MWA-speak, this would be 'M&C', but in the SKA-world, it's 'MCCS' software.

The PaSD system needs to:

- Provide power (around 5V DC) to each of the 256 antennas in a station.
- Measure the current drawn by each antenna around 1000 times per second and turn an output off fast enough to protect the hardware if there is a short (for example, if an animal chews a cable).
- Accept the RF signals from each of those antennae via coaxial cables.
- Convert the RF signals into analogue optical signals over fibres.
- Aggregate the hundreds of fibres from the station into a single 576-fibre cable to go back to the control building.

The PaSD system made up of a controller for each station (the 'Field Node Distribution Hub', or FNDH), which converts mains power into 48V DC, and distributes it via 28 switchable outlets, each using a single coaxial cable, like the way power is distributed to MWA beamformers. The FNDH is controlled by a couple of microcontrollers running custom firmware, talking to the outside world via a single network link, using a common industrial communications standard called 'ModBus'.

The FNDH sits just outside the station, and coaxial cables from the FNDH outputs run to 24 'smartboxes', sitting amongst the antennas on the station mesh. Each SMARTbox converts the 48V DC to ~5V DC, distributes it to 12 antennas, and converts the signals from those antennae to fibre. The fibres then run from each smartbox back to a fibre connection/aggregation box near the FNDH. Each smartbox has an internal microcontroller which communicates with the M&C software via a low-speed serial link over the 48V coaxial cable, also via ModBus.

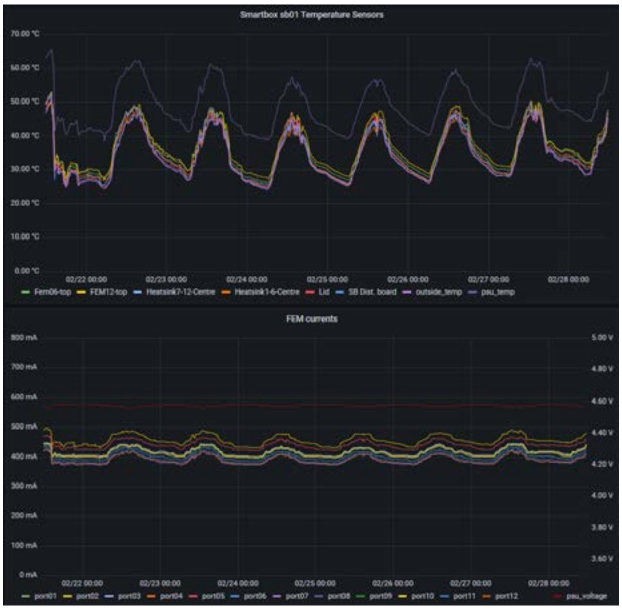


Figure 1
SMARTbox currents.

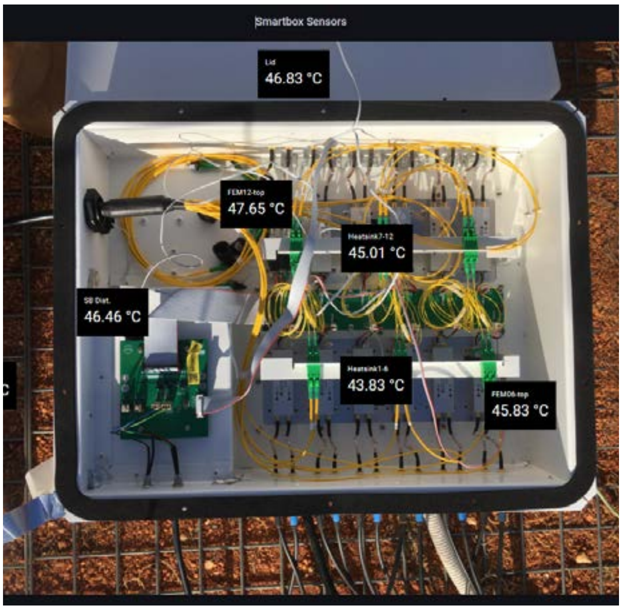


Figure 2
SMARTbox temperatures.

Having 24 SMARTboxes, each with 12 inputs, provides extra capacity to handle hardware failures, by swapping an antenna over to another box. In the same way, the 28 outputs on each FNDH that connect to only 24 SMARTboxes which allows for a few ports to fail before repair is needed.

The ModBus protocol is simple – each device has an address (1-255), and a set of 'registers', numbered from 0-65535, each holding a 16-bit number. You control a device by sending a special packet over the serial link, addressed to the device you want to talk to, to write new values to one or more of those registers. The device replies with another packet indicating success or failure. You get information from a device by sending another packet asking to read one or more of those registers and get a packet in reply with the data.

We settled on what registers we were going to use, for the FNDH and SMARTboxes, and how we were going to use them, long before any actual hardware existed. That let me start working on the software in time to have it ready for testing when the first boards were ready. I did that by writing SMARTbox and FNDH simulator code – it listened for packets via ModBus (over a real serial cable, or a network connection), emulated reads and writes to the set of registers we had decided on, and generated fake voltage and current data, simulated faults, etc, in those registers, ready for the outside world to read.

Then I used commercial ModBus software, running on my laptop, to read and write these simulated registers, inside my simulated FNDH and SMARTboxes – that let me verify that the simulator code was obeying all the rules that defined the official ModBus specification.

Once I was happy that the simulated boxes behaved the way that we wanted the real ones to work, I could start writing the code to control them. It needed to configure them on startup (provide the temperature, current and voltage limits above which the box would shut down to protect itself), and tell them what outputs to turn on. It then needed to monitor those values, to provide environmental data that we needed to validate the design – the best voltage to drive the antennae, whether we needed better heatsinks or insulation, etc. Eventually, I had a simulated FNDH connected to 24 simulated SMARTboxes, all running on one computer, talking to the monitor and control code running on another computer, via an old-school serial cable to give the same slow speed as the real hardware (1920 bytes per second).

The development involved a lot of iteration, as the hardware evolved to fix issues that developed, and the firmware changed (to support new hardware, or add new features). To allow for these changes, we added the ability to push new firmware to the FNDH or SMARTbox over the network, via ModBus. We also included firmware and 'API version' registers, always at the same addresses – by reading these registers, the M&C software can tell what version of the firmware is on any device, and use that to communicate with it in the right way.

The current version of the M&C software can control an entire station, of FNDH and 24 SMARTboxes, although at the moment, the prototype on site only has four SMARTboxes connected, all connected to AAVS2 antennae. It detects when SMARTboxed are unplugged, or new ones plugged in (and automatically configures them when they are), and allows every port (FNDH and SMARTbox) to be turned on or off, individually, or en-masse, with a separate command line client, using a PostgreSQL database for communication. It also pushes all the telemetry data to a separate 'round robin database' (RRD) so that we can visualise it using a tool called Grafana. Figures 1 and 2 show real-time temperatures in a SMARTbox, superimposed on a picture showing where the sensors are, and the connection between temperatures and currents inside a smartbox, over 7 days.

Data Archaeology: Mining MWA's Download Logs

HARRISON BARLOW
NAHAL RASTI
GREG SLEAP

The MWA telescope generates many petabytes of data every year and that data is stored at the Pawsey Supercomputer Research Centre's Long-Term Storage (LTS) system. Until recently and with the support of Pawsey, the capacity at the LTS has kept mostly in lockstep with data generated by the MWA, and the only data that has been deleted so far has been bad/unusable, or redundant data. Storage is expensive and Pawsey cannot keep up with the huge volume demands of the telescope. As a result, we have developed and are in the process of implementing a Data Retention Policy which can be found at https://www.mwatelescope.org/wp-content/uploads/2022/09/MWA_DATA_RETENTION_POLICY_V2.0.pdf. This policy provides a mechanism for routinely deleting data prior to each observing semester, should there not be sufficient capacity in the LTS during the observing semester. The MWA Principal Scientist is responsible for identifying the oldest and least useful data to MWA members (and radio astronomers in general).

To assist the Principal Scientist in deciding the relative utility of MWA observations, the Data team, consisting of Greg Sleap and Harrison Barlow, wanted to make the number of downloads of an observation available. This was a challenging task as over the lifespan of MWA providing data to astronomers, we had collected over a terabyte of logs stored in tens of thousands of log files of our various archiving systems and in several different formats.

As part of this project, we recruited a Curtin student, Nahal Rasti (currently working on her Masters in Predictive Analytics) as part of the "Earn While You Learn" programme. Nahal joined the Data team in October 2022 and worked with Harrison until the end of 2022 to determine the different sources of logs, what information they contained and how we could extract the key attributes of each downloaded observation. They very quickly encountered some challenges with this mammoth task.

Harrison and Nahal developed a python library which can be used to perform data mining of a large amount of heterogenous log data, and uploading the results back to a database so that useful metrics can be queried back. The library provided a fast, robust, repeatable way to process the different log formats for the various source systems, especially as each log type required different processing steps to extract the download information. Figure 1 shows the distribution across time of which source system we used logs from to create our database. Now that we had an almost complete repository of download information for each observation, we then made it available to the Principal Scientist via the MWA's virtual observatory table access protocol (TAP) service. The Principal Scientist can now run queries such as: how many downloads were there over a specific date range for all the observations in a particular MWA project? Which projects have not had observations downloaded recently? Many more queries of this data are now possible now that we have it in a format that it can be easily queried back. Although the download information is only one small part of the many factors which the Principal Scientist must consider when determining old, valueless data to remove from the archive, it is also a valuable and interesting resource when exploring the history of the MWA archive and its usage. We have only just scratched the surface at what potential insights this database will provide us and the MWA collaboration.

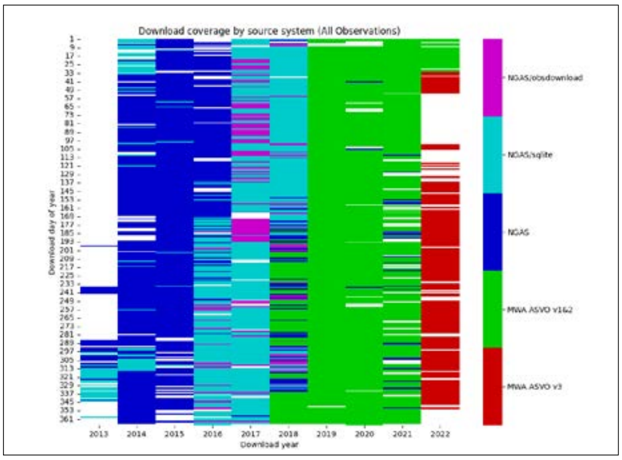


Figure 1
IMAGE: Greg Sleap

Long-term Archive Upgrade at Pawsey

HARRISON BARLOW
GREG SLEAP

As part of the Pawsey Supercomputing Centre's $70m Capital Refresh, they have made several big changes to how researchers manage data. This had a number of implications for the MWA archive which is stored at Pawsey.

One such change was the introduction of a new storage system called Acacia – a 60PB disk-based object storage system. Pawsey have allocated 10PB of storage to the MWA, and we have used this space as both an extension of the archive, as well as to support the functionality of the MWA ASVO. Acacia was designed to be highly extensible, meaning that Pawsey could easily expand our allocation by simply adding more storage hardware (with future funding). This has already been achieved as part of the ARDC data retention project, which has allowed us to add almost 3PB to our Acacia allocation and ensure that several important MWA datasets are exempt from being considered for deletion by the MWA's Data Retention Policy.

Pawsey have also introduced Banksia, which is a total overhaul of the way that we interact with the 40PB tape library where the bulk of the raw MWA archive is kept. Pawsey engaged Xenon – a Melbourne based high-performance computing (HPC) company to deliver the new system, which was provided by Versity, a San Francisco based company specialising in storage technology. As part of the transition to Banksia, we also had to develop a service to interact with and stage data from Banksia.

We worked closely with all stakeholders for both projects to help inform the requirements for the project and both were successfully delivered between Q1 and Q2 of 2022. These systems provide a significant upgrade to the MWA archiving systems and we have been extremely pleased with their performance.

Several changes were also required to the MWA ASVO to integrate it with the new systems. The new architecture is much more performant and extensible, allowing us to more easily develop new features and improvements for the MWA ASVO into the future.

Users of MWA data have benefitted enormously from these changes, as they now have more options for how their data is processed and delivered. For example, they can now opt to have their data delivered directly to the /astro filesystem at Pawsey which allows many MWA researchers to simplify and optimise their own processing pipelines by skipping the download and extraction steps. Users also benefit from much reduced processing times compared to the old infrastructure.

The RFI Emissions Whack-A-Mole

DAVID EMRICH
PHILLIP GIERSCH
LUKE VERDUYN
MIHAELA SAFTA

If you are occasionally experiencing interference with your mobile phone, radio, TV or garage door opener, you are most likely experiencing Radio Frequency Interference (RFI). Some primary natural sources of RFI include electrical storms, solar radiation, and cosmic noise from beyond the earth's atmosphere. Common human-made sources of RFI include any electrical, electro-mechanical or electronic equipment. Uncommon human-made sources include the Power and Signal Distribution (PaSD) system for SKA-Low.

The SKA-Low radio telescope will operate at frequencies between 50 and 350 MHz, similar to FM radio and TV broadcasts. The SKA-Low antennas will be able to search for radio emission from neutral hydrogen in the very early universe before the gas was ionised by the light of the first stars, galaxies and quasars, and the cosmic dark ages came to an end. This emission is at 1420 MHz, but as the universe expands this emission is stretched to lower frequencies. The aim is to use SKA-Low to try and detect the end of the so-called 'Epoch of Reionisation' at a theorised frequency of 200 MHz.

This signal has been travelling for so long (over 13 billion years) that when it arrives it appears “behind” almost every other object in the universe, and so it is “buried” in the much louder radio foreground, possibly by a factor of 10000 or more.

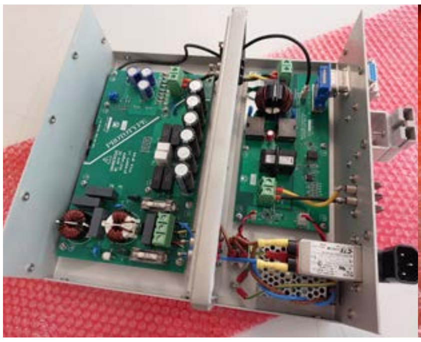


Figure 1
Power Module with internal shielding wall.

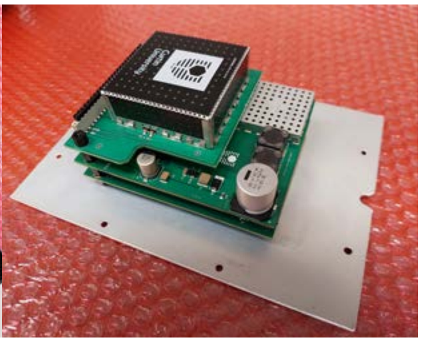


Figure 2
SMART Box Electronics Package Circuit Boards stack.

To detect it, the SKA-Low has to be extremely sensitive, very well calibrated, and operate in a very radio-quiet environment (including self-generated RFI) so that the radio foreground can be accurately measured, and subtracted, leaving “only” the EoR signal.

The PaSD system consists of several electronic and electrical products, in close proximity to the SKA-Low antennas and the Low Nose Amplifiers (LNAs) fitted to the antennas, that must generate very low to no RFI emissions that could interfere with the RF signal chain.

The PaSD design team have used system-level EMC design methods and multiple RFI control techniques, to develop an effective and cost-effective system, and to make the PaSD system products as “quiet” as possible. The design process has been iterative, selecting components for their low RFI emissions, including RFI control devices, and continuously making improvements to the design as quieter and quieter RFI emissions sources were identified during radiated RFI emissions tests.

PaSD prototypes that are the culmination of the last 12 months of EMC design work have already been delivered to Houwteq EMC Test Facility in South Africa. The Houwteq test facility is one of only three SKAO approved EMC test facilities in the world, where ultra-sensitive RFI emissions testing can be carried out. In March 2023, members of the PaSD design team will join members of the SKAO RFI team to measure the RFI performance of the prototypes and find out how quiet they are. This is the first RFI pre-qualification testing for SKA-Low and everyone in SKAO and CIRA will be waiting for the results with bated breath. Shhh, quiet please!

Space Domain Awareness Sensor

ROB HOWES

My exciting role as the Engineering Project Manager engaged in the delivery of the Space Domain Awareness (SDA) sensor was rewarded when the first antenna cluster was turned on in October 2022 providing a wealth of data that verified the future success of the project.

SDA is a project to detect and monitor space-based objects, typically in the Low Earth Orbit (LEO). These objects may be active satellites, or Resident Space Objects (RSO) from previous space activities. Australia's involvement in cataloguing RSOs is actively encouraged by government and space agencies.

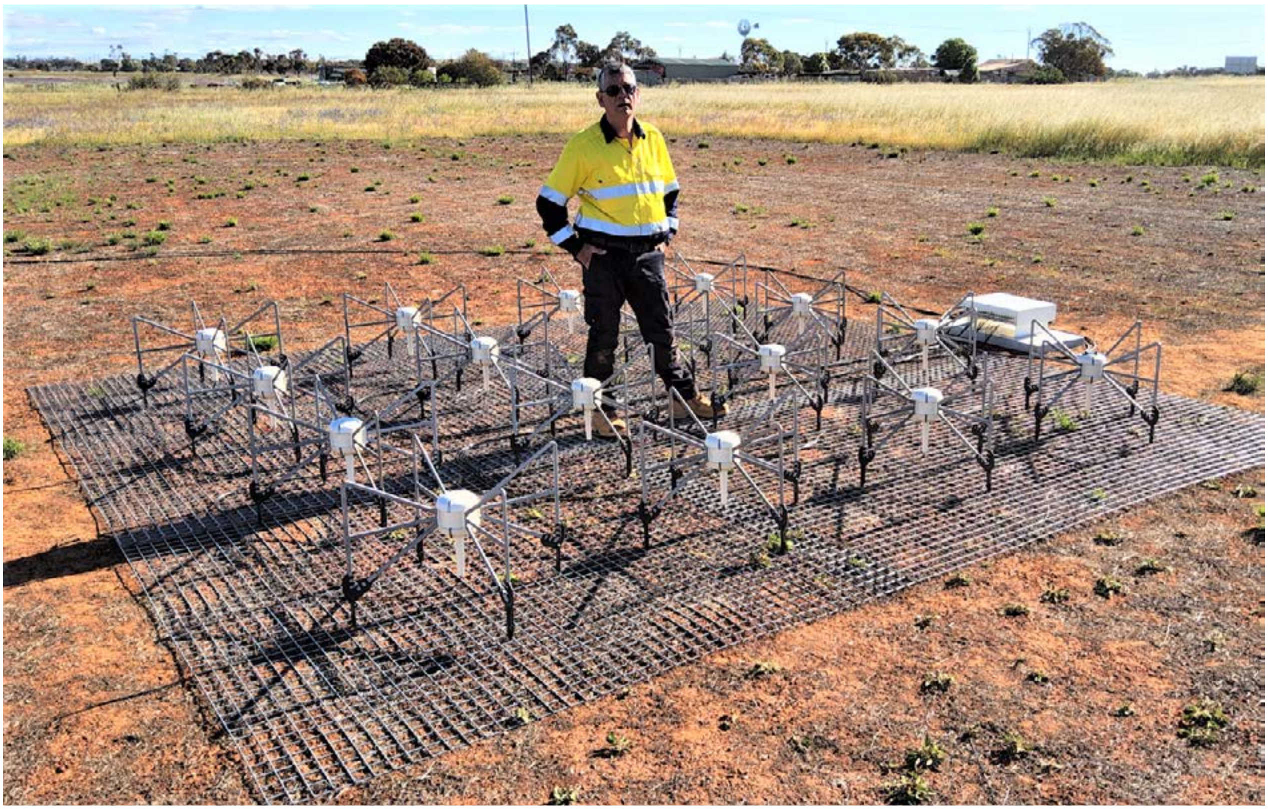
The technology behind the sensor is derived from an observation that impacts on radio astronomy observations, where signals from terrestrial transmitters such as radio and television stations are reflected from RSOs and detected by sensitive radio astronomy instruments interfering with the desired radio signal from outer space. For radio astronomers this is an undesirable outcome, but an opportunity for the space industry.

Since man's ability to launch objects into space, we have been littering the heavens with debris that puts future space objects at risk of collisions, a concern that was raised back in 1978, by NASA scientist Don Kessler (known as the Kessler Syndrome) who proposed that the probability of collisions between objects in space is high enough that space activities would need to be curtailed.

The sensor is being constructed in Peterborough, South Australia, in collaboration with Nova Defence Systems, and will verify that the technologies of Passive Radar and Passive RF are a viable scientific tool to monitor the space precinct.

The CIRA SDA project has brought a team together, working collaboratively with academics, engineering, software developers and technical staff, as well as external engagement from local industries who are locally manufacturing the antennas, amplifier boards, specialised cabling and providing High-performance Computing services.

In 2023 we will see the project expand to a total of 256 antennas allowing the sensor to detect low level signals, improving its sensitivity to track smaller objects.



Translation & Impact

AOIFE STAPLETON
EMMALINE YEARSLEY

The Translation and Impact (T&I) team welcomed some new faces in 2022. Project Lead, Aoife Stapleton, joined in January, with Manager, Emmaline Yearsley starting in April. The T&I effort was supported by the critical technical and organisational know-how of Mia Walker, who very patiently guided (read: 'sense-checked') our understanding of the technical and cultural landscape at CIRA!

Our objectives for 2022 were:

1) to continue to support and develop the great projects that Andrew Burton had developed during his time as the previous T&I Manager, and

2) to identify T&I opportunities by:
   - engaging with CIRA staff and students;
   - building visibility for radio astronomy more widely with Curtin University; and
   - stewarding external relationships with industry and government stakeholders.

Thanks to the engagement of CIRA staff and students who were keen to share their ideas, we quickly got to work leveraging our combined skillsets and contacts to see where we could bring impact.

Some of the more visible activities that we undertook in 2022 are included here.

ENGINEERS AUSTRALIA CHAPTER VISIT

In October, members from the Engineers Australia Mechatronics and Mechanical Engineering Chapter visited CIRA for an expo-style showcase of relevant Curtin Engineering capabilities.

With special guests from Curtin's Binar team, a showcase of Digital Artistry by Scott Bell, a demonstration of electromagnetic simulations by Daniel Ung, and a tour of the specialised test facility for observing directed energy effects on electronic devices and systems (thanks to Dr Budi Juswardi, Scott Haydon, and Aaron Silvestri), visitors were left suitably impressed by the diversity of the tangential and complementary engineering capabilities supporting radio astronomy.

WOMEN IN PHYSICS: FIRST-YEAR AFTERNOON TEA

To help build community for first year physics students, whilst highlighting the female role models within the field, this event aimed to create awareness of radio astronomy pathways and how CIRA will play a role in their undergraduate studies including astronomy courses and research projects.

Spearheaded by Dr Gemma Anderson, this event welcomed a small group of first year physics and engineering students to CIRA, where they heard from PhD students and staff who work in different roles at CIRA, including astronomy researchers, engineers, laboratory technicians and project managers.

Following a casual afternoon tea meet and greet, presenters showcased their work props such as 3D printed radio telescopes and MWA dipoles. Students were then treated to soldering demonstrations and discussions about the variety of different areas which feed into radio astronomy.

PIA WADJARRI VISIT AND INDIGENOUS ARTISTRY

In mid-September 2022, students from the Pia Wadjarri Remote Community School came on a week-long excursion to Perth. Facilitated by CSIRO's STEM Professionals in Schools program, they learned about geology, radio astronomy, space exploration, meteorites, planets, and supercomputers.

The students attended CIRA to learn more about the Murchison Widefield Array (MWA) telescope. The MWA is located at *Inyarrimanha Ilgari Bundara*, the CSIRO Murchison Radio-astronomy Observatory, on Yamatji Wajarri country – not far from the students' home at Pia.

The Pia students had recently visited the MWA, and we were delighted with the opportunity to link the spider-like antennas that they had seen at the site with CIRA in Perth.

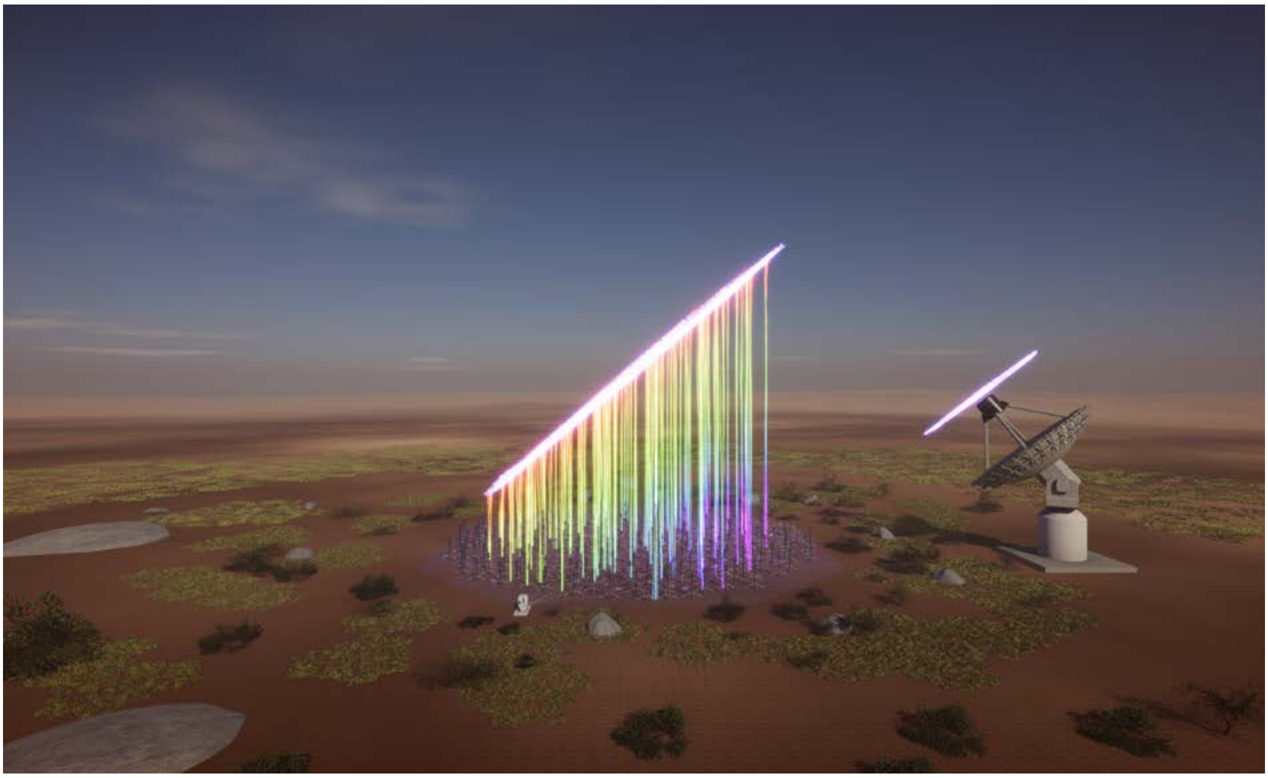
There is a long history of collaboration between CIRA and the Wajarri community in the field of Aboriginal artwork. To continue that connection, we facilitated an artwork activity with the students during their visit involving the decoration of an MWA antenna. This artwork now sits at the main entrance to CIRA, with the Wajarri name for the MWA telescope, Gurlgamarnu, meaning, "the ear that listens to the sky."

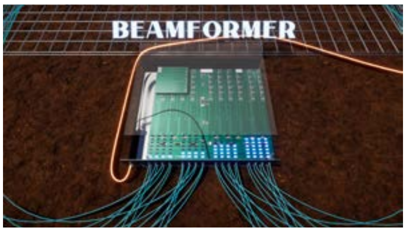
CURTIN CONNECTIONS

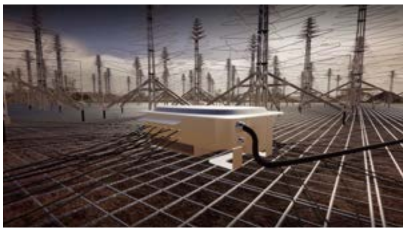
2022 saw us focusing on leveraging our connections across campus to support T&I activities. We toured the state-of-the-art Media Production Studio (including podcast facilities) at the Faculty of Humanities. (Incidentally, the booking system for the podcast facility is available to all Curtin staff and very user friendly!)

We linked in with Science and Engineering's Student Engagement team, and the Curtin STEM Outreach team to support us with our goal of increasing CIRA visibility and showcasing radio astronomy on campus. We also connected with the Curtin Careers team, who presented some of their services at Journal Club in November. A dedicated careers workshop to support CIRA students is being planned for 2023.

In the same vein, we wanted to connect CIRA with other areas of the University where natural synergies existed. Connections with Curtin's Space Science and Technology Centre (SSTC) grew through research and professional collaborations with the Desert Fireball Network and Binar projects. We also learned that researchers from Curtin's School of Earth and Planetary Sciences (EPS) undertake research projects on rocks from Wajarri country, home of the MWA telescope. Both CIRA and EPS are involved in STEM Outreach activities with the local Pia Wajarri community, and 2022 saw us come together to host the children from the Pia community at Curtin.







DIGITAL ARTISTRY

The Digital Artistry project continued to develop engaging and multi-use visualisations that bring aspects of radio astronomy to life in new ways. Scott Bell's career trajectory with us epitomises the non-traditional radio astronomy career paths that can be fostered under the T&I banner: commencing his journey with CIRA as a HIVE intern in 2021, Scott joined us as a casual CIRA employee in 2021 to produce a library of visualisations.

Scott has now transitioned from employment at ICRAR-Curtin to his own consultancy, Actualized Fantasy. We are supporting Scott to showcase his work to develop relationships with other university stakeholders, and can engage Scott to support discrete projects, so please continue to let us know if there are some concepts or projects that you're working on that could benefit from visualisation!

INDIGENOUS AUSTRALIAN ENGINEERING SCHOOL (IAES)

CIRA hosted a visit by the Indigenous Australian Engineering School (IAES) and staffed a stall at the IAES Careers night where they learned about the pathways into radio astronomy.

We facilitated an internship for IAES Alumni, Stevo Trott, who enjoyed working with the Pulsar group to categorise potential pulsars and learning some on-the-job tech skills in the labs with Ash Nambiar and Venus Chico.

HIGH SCHOOL VISITORS

In June, CIRA welcomed visitors from Fremantle Christian College and a work experience student from Great Southern Grammar. Our work experience student, Alec, learned about the fundamentals of receiving radio signals and built his very own Horn Antenna. The students heard from Mia Walker, who pitched an overview of the MWA and expertly navigated the room to provide audience-appropriate, technical explanations about correlators, and electronic steering delays, before Daniel Ung demonstrated the simulation of antennas' electromagnetic beam patterns.

TEA AND I

Aimed at raising internal CIRA awareness and engagement, "Tea & I" gave us a reason to hold morning teas to chat with interested staff and students.

Ideas "brewed" over Tea & I included the Women in Physics Afternoon Tea, student engagement, and other ideas for growing awareness of radio astronomy for students on campus.

Thanks to everyone who participated, shared their ideas and insights, and provided some guidance on our ideas. We really appreciate the engagement and look forward to drinking more tea with you all in 2023!

Emmaline at the AARP.

SPACE DOMAIN AWARENESS

Translating radio astronomy techniques and technologies to bring impact in the complex and multifaceted field of space domain awareness (SDA) is one of our biggest T&I programs.

Although funding for SDA activities is predominantly driven by the Defence sector, the data generated by an array modelled on radio astronomy technology has potential for broad application: from detecting and characterising resident space objects, to collision mitigation to protect assets in space; from assisting to support the policing of space regulation, to informing emergency management for space debris re-entry.

The Portable SDA project, led by Randall Wayth and funded by WA Defence Science Centre, progressed to completion this year. The team had a fantastic opportunity to get some practical, hands-on, fieldwork experience in deploying and testing the prototype.

Meanwhile, negotiations were underway with Nova Systems to deploy 16 tiles of locally designed and manufactured CRAB antennas at the Nova Systems Space Precinct in Peterborough, South Australia. The T&I team supported the negotiation of the contract with Nova, and work closely with Randall and Rob Howes to track the project activities. With an array of this size, we can better demonstrate a wider cross-section of SDA applications to potential commercial and government clients.

Teaching

JAMES MILLER-JONES
DAVID DAVIDSON

2022 marked a shift back to pre-pandemic teaching modes, with the full return of in-person classes and the re-institution of face-to-face assessments and exams. The beginning of the year was fraught with uncertainty, requiring contingency plans for many of our teaching activities. However, we were delighted to see how capably our teaching staff handled the situation, and reiterate our gratitude once again to all our staff and students who contribute to CIRA's teaching activities. It has not been an easy few years, and the frequent policy changes have increased workloads, but it has been impressive to see how hard the group has worked to ensure the continued delivery of a high-quality student experience throughout. Furthermore, some of the more positive innovations from the past few years have been retained, such as the facilitation of on-line participation where possible. Aspects of these innovations were documented by Dr Maria Kovaleva in her contributions to "Advancing Engineering Education Beyond COVID: A Guide for Educators", published by CRC Press in 2022.

Our staff continued to teach into multiple areas across the School in 2022, with CIRA staff engaged in 17 different undergraduate units, which combined had a total enrolment of almost 500 students. While most of our effort goes into the delivery of units in the Physics & Astronomy and Electrical Engineering (EE) disciplines, the past year saw CIRA staff deliver units within the Mathematics & Statistics discipline for the first time. It has been great to see CIRA engaging more broadly across the School, leveraging new opportunities, building new collaborations, and exposing new groups of talented students to the exciting work that we do. In this context, it is worth noting that some of the EE modules are also taught on two of Curtin's offshore campuses, with overall unit coordination done from Curtin.

Beyond our delivery of coursework units, our staff supervised multiple student projects over the course of the year, from summer projects through third-year and Honours projects in the Physics major, final-year Engineering projects, and Computing capstone projects. The potential impact of student projects was highlighted by the 2022 publication in the prestigious journal *Nature* of a new ultra-long period pulsating source that was discovered during Tyrone O'Doherty's Honours project in 2020. However, with CIRA having hosted 38 project students over the course of 2022, we recognise the significant effort that this represents, and thank all our staff who contribute to student supervision. In particular, we would like to express our gratitude to Dr Jess Broderick, who will be stepping back from his role as ICRAR summer student co-ordinator in 2023, after several years of service in this position.

The strength of our undergraduate teaching programs directly impact our HDR enrolments, with high-quality teaching both inspiring students to continue their engagement with CIRA, and giving them the fundamental knowledge to underpin their future research work. The strong and highly-competitive RTP cohorts of the past few years attest to the excellent work being done by our staff in the teaching space. Indeed, 2022 saw CIRA's student cohort exceed 30 for the first time, providing much of the Institute's research capacity, and ensuring that it remains a vibrant, exciting place to work.

Media & Awards

MYSTERIOUS OBJECT UNLIKE ANYTHING ASTRONOMERS HAVE SEEN BEFORE

Dr Natasha Hurley-Walker
Tyrone O'Doherty

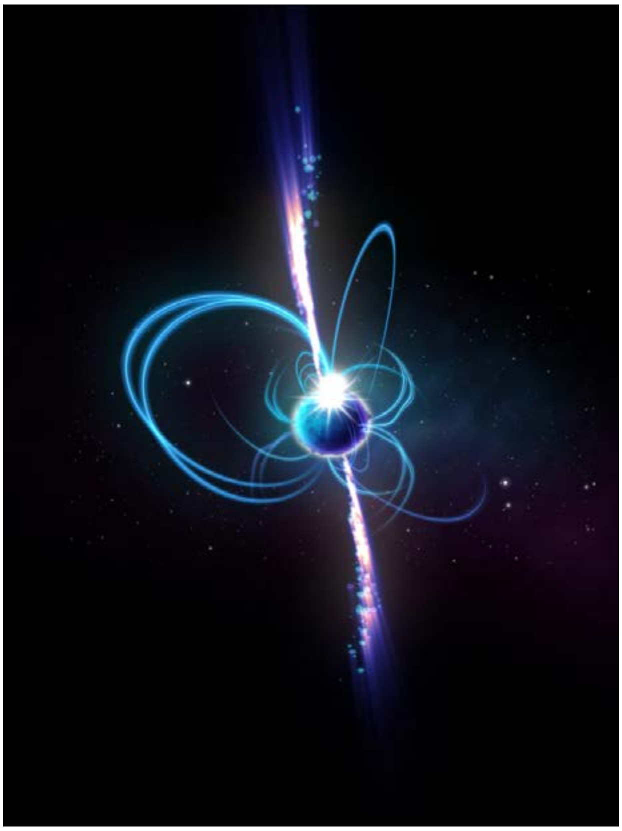
A team mapping radio waves in the Universe has discovered something unusual that releases a giant burst of energy three times an hour, and it's unlike anything astronomers have seen before.

The team who discovered it think it could be a neutron star or a white dwarf – collapsed cores of stars – with an ultra-powerful magnetic field.

Spinning around in space, the strange object sends out a beam of radiation that crosses our line of sight, and for a minute in every twenty, is one of the brightest radio sources in the sky.

The ICRAR press release led to more than 3,000 articles in 100+ countries and an estimated audience of 13M people. The supporting video assets created for this release almost half a million views in the space of two weeks. This was the biggest media release in ICRAR's history by a significant margin, and the best for a *Nature* paper release, with coverage from *Guardian Australia*, *IFL Science*, ABC News, *Guardian UK*, *VICE*, *NY Times*.

https://www.icrar.org/repeating-transient/



↗ An artist's impression of what the object might look like if it's a magnetar. Magnetars are incredibly magnetic neutron stars, some of which sometimes produce radio emission. Known magnetars rotate every few seconds, but theoretically, "ultra-long period magnetars" could rotate much more slowly. IMAGE: ICRAR

STAR TRACKS

Current and former CIRA staff and students, Professor Steven Tingay, Profesor Melanie Johnston-Hollitt Kat Ross, and Mia Walker appeared in 'Star Tracks' *The Hidden Universe – Discovering the Square Kilometre Array*, aired on Channel 7.

This documentary took a special look at scientific efforts to build one of the world's most powerful telescopes in the Western Australian outback, capable of peering into the far reaches of the cosmos.

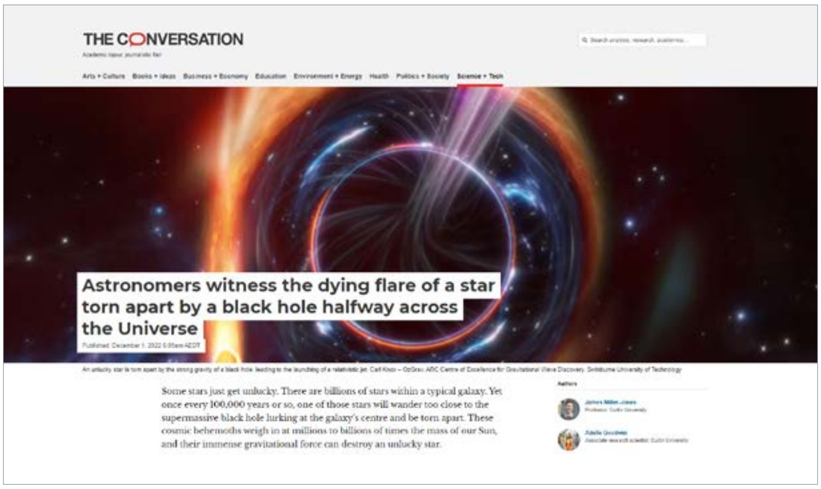
DR BEN McKINLEY

Media release on Dr McKinley's lead author *Nature Astronomy* paper, “Multi-scale feedback and feeding in the closest radio galaxy Centaurus A”. This publication contained the most comprehensive image of radio emission from the nearest actively feeding supermassive black hole to Earth, using the MWA radio telescope.

The emission is powered by a central black hole in the galaxy Centaurus A, about 12 million light years away.

↗ ‘Centaurus A’ cover of *Nature Astronomy*.
IMAGE: Ben McKinley

THE CONVERSATION

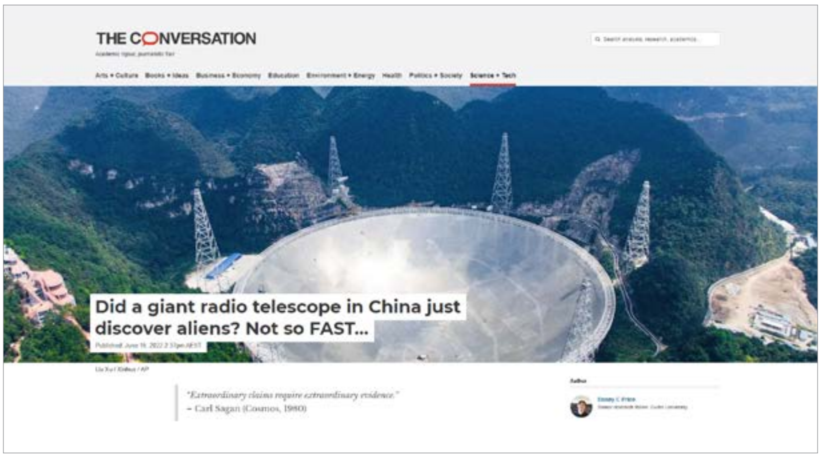


Astronomers witness the dying flare of a star torn apart by a black hole halfway across the Universe

An unlucky star is torn apart by the strong gravity of a black hole, leading to the launching of a relativistic jet. Carl Knox – OzGrav, ARC Centre of Excellence for Gravitational Wave Discovery, Swinburne University of Technology

Some stars just get unlucky. There are billions of stars within a typical galaxy. Yet once every 100,000 years or so, one of those stars will wander too close to the supermassive black hole lurking at the galaxy's centre and be torn apart. These cosmic behemoths weigh in at millions to billions of times the mass of our Sun, and their immense gravitational force can destroy an unlucky star.

James Miller Jones
Dr Adelle Goodwin
“Astronomers witness the dying flare of a star torn apart by a black hole halfway across the Universe”



Did a giant radio telescope in China just discover aliens? Not so FAST…

> *“Extraordinary claims require extraordinary evidence.”*
> – Carl Sagan (Cosmos, 1980)

Danny Price
“Did a giant radio telescope in China just discover aliens? Not so FAST…”

DR MARCIN GLOWACKI

Media release on “Astronomers detect giant space laser”. A powerful radio-wave laser, called a “megamaser”, has been observed by the MeerKAT telescope in South Africa. The record-breaking find is the most distant megamaser of its kind ever detected, at about five billion light years from Earth. The discovery was made by an international team of astronomers led by Dr Marcin Glowacki.

PREMIER'S SCIENCE AWARDS

CIRA researchers were award winners and finalists in three of the six categories in the 2022 Premier's Science Awards. These Awards recognise and celebrate the outstanding scientific research and engagement taking place in Western Australia.

↗ Kathryn Ross

Kathryn Ross

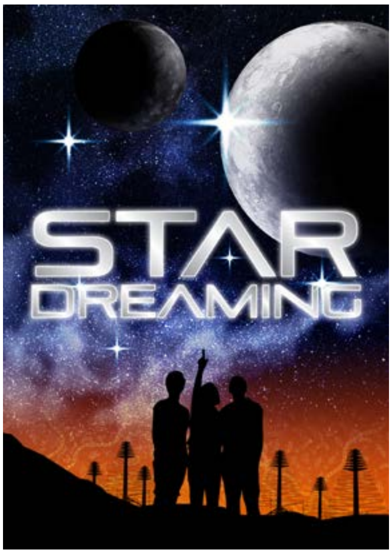
Joint Winner, Premier's Science Award for the ExxonMobil Student Scientist of the Year

Awarded to an outstanding postgraduate student who has demonstrated a commitment to science at an early stage and shows great promise in reaching the highest levels of excellence. Kathryn studies supermassive black holes in the centres of galaxies, focusing on baby black holes that are smaller than typical galaxies. Using telescopes around Australia, Kathryn discovered these black holes are not as young as previously thought, but frustrated teens being restricted by a surrounding cloud of gas. Kathryn is a science communicator promoting STEM to audiences nationally and internationally. Kathryn is also an activist leading a national campaign, IncludeHer, working to diversify the representation of scientists in schools.

Dr Natasha Hurley-Walker

Finalist, Mid Career Scientist of the Year

Dr Hurley-Walker's discoveries include the remains of stellar explosions, insights into the lives of supermassive black holes, and a new kind of repeating radio source unlike anything astronomers have seen before.



Star Dreaming

Finalist, Science Engagement Initiative of the Year

This award category recognises initiatives that have made an outstanding contribution to community awareness, interest and/or participation in science in Western Australia. *Star Dreaming* is a 180-degree immersive film experience that follows two children from Geraldton as they discover the Square Kilometre Array and the Yamaji culture of the Traditional Owners of the land on which it is built. The film explores science, art, technology and Indigenous culture side-by-side. Awarded the Best Astronomy Education award at the Dome Under Festival, its opening season at the WA Maritime Museum in Fremantle was experienced by thousands of people. Selected by international film festivals, it will be distributed internationally and will bring Western Australian science and culture to the world.

↗ Danny Price (3rd from right) wins a Young Tall Poppy Science Award at the 2022 WA Young Tall Poppy Science Awards.

WESTERN AUSTRALIAN YOUNG TALL POPPY SCIENCE AWARDS

As Australian Project Scientist for the Breakthrough Listen program, Dr Danny Price is leading the Search for Extraterrestrial Intelligence (SETI) in Australia. Dr Price specialises in building systems to sift through vast amounts of telescope data, to search for evidence of intelligent life beyond Earth.

WITWA – CONFERENCE & AWARDS

The WiTWA Awards celebrate the achievements of women and allies who are making an impact through technology.

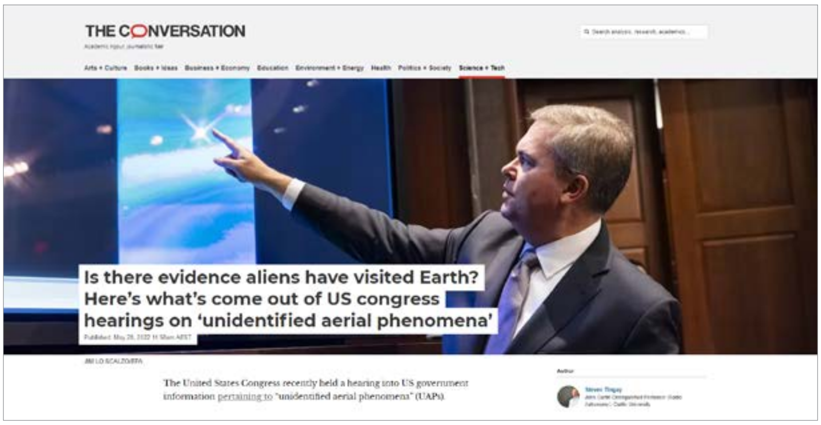
↗ Mia Walker with her Shining Star Award.

Mia Walker
Winner of the Shining Star Award in the category of Sales, Marketing and Business Support for her role in supporting project operations.

Dr Natasha Hurley-Walker
Winner of the Shining Star Award in the category of STEM Academia and Research.

Kathryn Ross
Congratulations also to Kathryn Ross, who presented the opening Keynote speech at the WiTWA Conference held the day prior to the awards. Kathryn presented a talk on Unconscious Bias and the history of #IncludeHer.

CURTIN RESEARCH AND ENGAGEMENT AWARDS CEREMONY



THE CONVERSATION

Arts + Culture · Books + Ideas · Business + Economy · Education · Environment + Energy · Health · Politics + Society · Science + Tech

Is there evidence aliens have visited Earth? Here's what's come out of US congress hearings on 'unidentified aerial phenomena'

The United States Congress recently held a hearing into US government information pertaining to "unidentified aerial phenomena" (UAPs).

John Curtin Distinguished Professor Steven Tingay
Highest readership of an article on *The Conversation* (>577k).

Dr Danny Price
STEM award

Dr Natasha Hurley-Walker
Most prolific media commentator in Faculty of Science and Engineering.

Dr Natasha Hurley-Walker
Tyrone O'Doherty
Dr Gemma Anderson
Most outstanding Curtin research news story: "Mysterious object unlike anything astronomers have seen before" (https://www.curtin.edu.au/news/media-release/mysterious-object-unlike-anything-astronomers-have-seen-before/)

Professor James Miller-Jones
Dr Arash Bahramian
For publications in Science.

FACULTY AWARDS FOR EXCELLENCE

Directed Energy Research Team:
Senior Lecturer Adrian Sutinjo
Dr Maria Kovaleva
Dr Budi Juswardy
Mr Daniel Ung
Mr Aaron Silvestre
Mr Scott Haydon
Research Team Award for Industry Engagement and Impact, in examining the effects of high power microwaves on electronics.

Professor James Miller-Jones
Researcher of the Year.

PROFESSOR JAMES MILLER-JONES

Appointed Chair of the Faculty of Science and Engineering Gender Equity and Diversity Committee.

PROFESSOR CATHRYN TROTT

Appointed Deputy Director of A3D Centre of Excellence.

2022 ASTRONOMICAL SOCIETY OF AUSTRALIA (ASA) AWARDS

The following staff and students were recognised in the 2022 Astronomical Society of Australia (ASA) awards.

Dr Adelle Goodwin
ASA Charlene Heisler Prize for the most outstanding PhD thesis in astronomy or a closely related field, accepted by an Australian university. Adelle predicted an outburst from neutron star SAX J1808.4–3658, enabling five groups of researchers and seven telescopes to examine the onset of such an event in detail for the first time.

Dr Natasha Hurley-Walker
ASA Anne Green Prize for a significant advance or accomplishment in astronomy by a mid-career scientist: work and leadership in producing an all-sky radio catalogue using the GLEAM survey.

Callan Wood
1st prize Best Student Talk.

Kathryn Ross
3rd prize Best Student Talk.

SUPERSTARS OF STEM

Dr Adelle Goodwin
Dr Goodwin was named as one of Science and Technology Australia's 60 new Superstars of STEM, for aiming to increase the public visibility of women and non-binary people as role models in STEM fields, Dr Goodwin's research focuses on how stars are destroyed by supermassive black holes, helping us to better understand the universe.

DR MARIA KOVALEVA

Awarded a Fulbright Future Scholarship.

MWAX TEAM

Finalist in Engineers Australia Awards, in Project category.

JOINT KJM PRIZE WINNERS

Jishnu Thekkeppattu
Torrance Hodgson
The Ken and Julie Michael Prizes recognise the outstanding achievements of our graduate students at both ICRAR nodes.

The 2022 award recipients include Torrance Hodgson and Jishnu Thekkeppattu.

WA AUSTRALIAN INSTITUTE OF PHYSICS

Callan Wood
Best talk at WA Australian Institute of Physics student conference.

↗ Dr Hurley-Walker pictured in the winning t-shirt.

NATIONAL SCIENCE WEEK SCIENCE SHIRT COMPETITION

Dr Natasha Hurley-Walker
'Galactic Blooms' by Dr Natasha Hurley-Walker and Becski Design, exploring the parallels between astrophysics and the native flowers of Western Australia.

CALLAN WOOD

Curtin University award for the best Honours student in Physics and Astronomy, and also the best Honours student in the Bachelor of Science degree in 2021.

CONGRATULATIONS TO THE GRADUATING PHD STUDENTS OF 2022

Alexander Williamson
James Buchan
Steve Prabu
Dilpreet Kaur
Hongquan Su
Torrance Hodgson
Jishnu Thekkeppattu
Rene Baelmans
Stefan Duchesne

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Staff & Student Directory

Staff and students are pictured alphabetically by first name.

Aaron Silvestri
Research Assistant

Dr Adela Kawka
Senior Research Fellow

Dr Adelle Goodwin
Associate Lecturer

Dr Adrian Sutinjo
Senior Lecturer

Aishwarya Selvaraj
PhD Candidate

Alessandro Paduano
PhD Candidate

Dr Alexander Williamson
PhD Candidate

Alison Smith
Project Officer

Dr Amir Forouzan
Research Associate

Andrew McPhail
Technical Operations
Coordinator

Dr Andrew Williams
Instrument Engineer, M&C

Angelica Waszewski
PhD Candidate

Dr Anshu Gupta
ASTRO3D Fellow

Aoife Stapleton
Project Lead

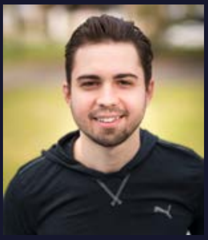
Dr Apurba Bera
Associate Lecturer

Dr Arash Bahramian
Research Fellow

Ashwathi Nambiar
Technician

Bach Nguyen
PhD Candidate

Dr Ben McKinley
Research Fellow



Benjamin Quici
PhD Candidate

Dr Bradley Meyers
Research Associate

Brandon Venville
PhD Candidate

Brendan Hennessey
PhD Candidate

Brian Crosse
Project Lead

Dr Budi Juswardy
Research Engineer

Callan Wood
PhD Candidate

Cary Wintle
Maintenance Crew Lead

Prof Cathryn Trott
Professor

Chamila Thrum
Administrative Officer

Dr Chris Jordan
Research Fellow

Dr Christene Lynch
Research Fellow

Dr Chuneeta Nunhokee
Research Associate

Dr Clancy James
Senior Research Fellow

Clinton Ward
Senior Technical Officer

Danica Scott
PhD Candidate

Dr Daniel Price
Senior Research Fellow

Daniel Ung
Support Engineer, Aperture Array

Dave Emrich
Instrument Engineer, Site Ops

Prof David Davidson
Director of Engineering

David Kenney
Project Engineer

David Minchin
Senior Technical Officer

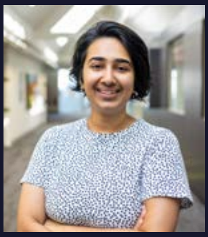
Dev Null
Developer

Dr Dilpreet Kaur
PhD Candidate

Emmaline Yearsley
Manager – Translation and Impact

Ferry Lanter
PhD Candidate

Garvit Grover
PhD Candidate



Gayatri Aniruddha
PhD Candidate

Dr Gemma Anderson
Senior Research Fellow

Gregory Sleap
Software Team Lead

Harrison Barlow
ASVO Web Developer

Himanshu Tiwari
PhD Candidate

Dr Hongquan Su

Ian Kemp
PhD Candidate

Dr Ian Morrison
Research Fellow

Dr Jack Line
Research Associate

Jaiden Cook
PhD Candidate

Jake Jones
Senior Technical Officer

Dr James Buchan
PhD Candidate

Prof James Miller-Jones
Director of Science

Dr Jess Broderick
Senior Research Fellow

Dr Jishnu Nambissan Thekkeppattu
Research Fellow

Joe Grundy
PhD Candidate

Dr John Morgan
Research Fellow

Jun Tian
PhD Candidate

Kariuki Chege
PhD Candidate

Kathryn Ross
PhD Candidate

Luke Verduyn
Technical Specialist

Luke Williams
Developer

Dr Marcin Glowacki
Research Associate

Dr Marcin Sokolowski
Research Fellow

Dr Maria Kovaleva
Lecturer

Mawson Sammons
PhD Candidate

Mia Walker
Project Officer

Mihaela Safta
Program Manager

Mike Kriele
PhD Candidate

Nahal Rasti
MWA Database Intern

Dr Natasha Hurley-Walker
Senior Research Fellow

Nicholas Swainston
PhD Candidate

Dr Nichole Barry
Research Fellow

Dr Nick Seymour
Senior Lecturer

Dr Nipanjana Patra
Research Fellow

Phillip Giersch
Technical Officer

Dr Rajan Chhetri
Research Associate

Dr Ramesh Bhat Senior
Research Fellow

Ranauq Bhushan
Project Manager

A Prof Randall Wayth
Associate Professor

Ravi Jaiswar
PhD Candidate

Dr Rene Baelemans
Research Associate

Robert Howes
Engineering Project Manager

Dr Samuel McSweeney
Associate Lecturer

Scott Bell
Digital Artist

Scott Haydon
Research Assistant

Sean Paterson
PhD Candidate

Shih Ching Fu
PhD Candidate

Silvia Mantovanini
PhD Candidate

Dr Stefan Duchesne
PhD Candidate

Dr Steve Prabu
Associate Lecturer

Prof Steven Tingay
Executive Director

Susmita Sett
PhD Candidate

Teresa Slaven-Blair
Outreach Support Officer

Dr Tim Galvin
Associate Lecturer

Tina Salisbury
Business Manager

Tom Booler
Director of Operations

Dr Torrance Hodgson
PhD Candidate

Tyrone O'Doherty
PhD Candidate

Ulrike Hautmann
Program Manager

Venus Chico
Technician

Wayne Arcus
PhD Candidate

CONTACT

Curtin Institute of Radio Astronomy
Curtin University
Building 610, Technology Park
1 Turner Avenue, Bentley, WA 6102

GPO Box U1987, Perth WA 6845

Tel: +61 9266 9899
Email: cira.admin@curtin.edu.au

astronomy.curtin.edu.au

Aurora Australis, Herron WA.
IMAGE: Susmita Sett. Taken on 27 February 2023.

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