CIRA

CURTIN INSTITUTE OF RADIO ASTRONOMY

2017 ANNUAL REPORT

Curtin University

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This annual report covers the calendar year 2017

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Images of the front and back highlight CIRA activities in 2017

Front cover, counter clockwise from the top right: the Murchison Widefield Array (MWA) at the Murchison Radio-astronomy Observatory (MRO, credit: Curtin University). Radio, optical, and X-ray image of the galaxy cluster Abell 85 (MWA data shown in magenta, credit: Stefan Duchesne et al. 2018). MRO site crew in front of Low-Frequency Aperture Array (LFAA) antennas (credit: Curtin University). AstroFest at Curtin University (credit: ICRAR). An MWA tile at the MRO (credit: Curtin University). PhD student Bradley Meyers at an outreach event (credit ICRAR).

Back cover, counter clockwise from the top right: an MWA image of the galaxy cluster Fornax A (credit: Ben McKinley and the MWA collaboration). Prof Peter Hall with King Willem Alexander and Queen Maxima during Their Majesties visit from the Netherlands to Curtin University (credit: Curtin University). A radio colour view of the sky above an MWA tile (credit: radio image by Natasha Hurley-Walker and the GLEAM TEAM, MWA tile and landscape by Dr John Goldsmith/Celestial Visions). Site crew working at the MRO (credit: Curtin University).

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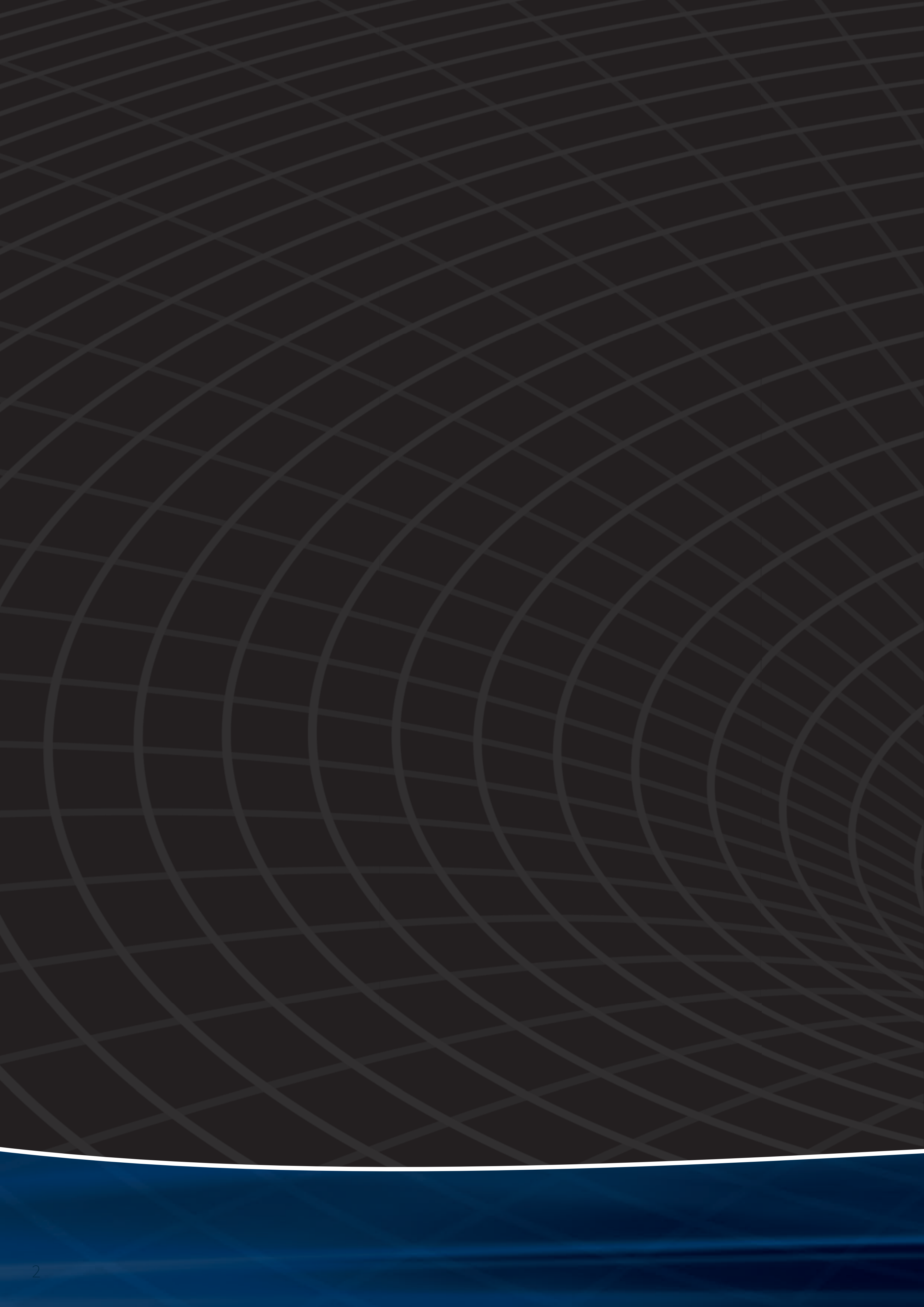


CIRA

Governance

Institutes at Curtin University conventionally have Boards to advise the University and Directors on policy and directions. CIRA and its programs are very closely aligned with the recently formed International Centre for Radio Astronomy Research (ICRAR), an equal Joint Venture between Curtin University and The University of Western Australia. ICRAR has a fully-constituted Board, including representation from Curtin University. CIRA's Co-Directors are also Directors of ICRAR. To minimise duplication in reporting, CIRA's programs are formally monitored and assessed via the ICRAR Executive and Board.

Curtin University

EXECUTIVE SUMMARY

Steven Tingay

Director's Report

The last twelve months have seen probably the most significant changes at CIRA since it was established more than a decade ago. Prof Carole Jackson left CIRA in April to take up the position of General Director at ASTRON in the Netherlands, prompting my early return from secondment in Italy (it is great to be back at Curtin University!) Further, Prof Peter Hall, founding CIRA co-Director with me, retired in 2017. Assoc Prof James Miller-Jones and Mr Tom Booler stepped up as Acting Directors until I returned to CIRA later in 2017. Upon my return to CIRA, I decided to depart from the co-Director model and restructured CIRA with an Executive Director (me), and Directors of Science (Assoc Prof James Miller-Jones promoted into the position), Engineering (with Prof David Davidson arriving from South Africa in 2018, to replace Prof Peter Hall), and Operations (with Mr Tom Booler promoted into the position). The new structure is working very well. At the same time, Curtin University restructured its Faculty and School system. While all these changes have required care and patience to bed down properly, the changes have left CIRA in an even stronger position. Previously, CIRA was split across two Schools. Now, all CIRA staff and students are contained within a single School, dramatically increasing the efficiency of administration and exposing CIRA staff to a wider range of undergraduate teaching opportunities.

Further, the University has released a new research strategy, with which CIRA is very closely aligned, based on our significant efforts toward fundamental research, as well as demand-driven research which involves industry partnerships and the translation of radio astronomy knowledge and techniques into a range of industry and commercial applications. This demand-driven focus has unlocked new revenue streams, in addition to the usual success through the Australian Research Council. Over the last decade, CIRA has built a formidable cohort of internationally recognised staff and has a strong reputation for successfully delivering big projects, such as the recently expanded Murchison Widefield Array (MWA). We have also welcomed a new Director of the MWA to CIRA, Prof Melanie Johnston-Hollitt, who moved from New Zealand and will start in 2018.

Underpinning our growth and activity over the last decade has been the ICRAR Joint Venture partnership with The University of Western Australia and the Western Australian Government. It is extremely pleasing to note that the WA Government will continue to support ICRAR over another five year period, 2019 - 2024, with renewed and enhanced co-investment from Curtin University and The University of Western Australia. Alongside other funded collaborations such as the ARC Centre of Excellence for Astrophysics in 3D, ICRAR will ensure that Western Australian radio astronomy is well supported in the next critical five year period, as the SKA commences its construction phase. The process to establish the SKA as an international treaty organisation has gathered momentum over the last twelve months, and by 2024 we expect the first data to flow from the SKA.

The next year will be one of planning for the ICRAR extension, continuing to strongly support the final stages of the SKA design effort, and continuing to reap the scientific harvest from the MWA. Other big opportunities are looming at the same time. The Commonwealth Government has announced the establishment of a national space agency, which is highly relevant to the skill set at CIRA. The Pawsey Supercomputing Centre will embark on a $70M upgrade, providing new processing power for the MWA and other facilities. And CIRA's ties with radio astronomy in China are growing and strengthening on the back of decades of engagement between researchers. Looking ahead to the SKA, international partnerships such as this will be critical to fully exploiting the vast capability of next generation radio telescopes.

There is a huge volume of exciting work to do and CIRA has the support and skills to take on these challenges. The first decade of CIRA has been an amazing success. The next decade looks even more exciting.

James Miller-Jones

Director's Report

2017 saw significant and unforeseen changes to the leadership structure of CIRA, as our Science and Operations Director, Prof Carole Jackson, departed to take on the role of Director General of ASTRON in the Netherlands. Despite these changes, I am pleased to report that the high scientific productivity of the Institute continued unperturbed. It is a testament to the culture established by my predecessors in this role, Prof Jackson and Prof Steven Tingay, that the major transitions of the past year were navigated so smoothly, with minimal disruption to the delivery of our scientific outputs, commitments or obligations. Nonetheless, we were extremely pleased to welcome back Prof Tingay as the new Executive Director of CIRA in the middle of the year. His return provided invaluable high-level strategic direction as we negotiated a raft of University-wide reviews and commenced the planning process for the next five years of CIRA's activities, within the overarching framework of the International Centre for Radio Astronomy Research (ICRAR).

The most high-profile of CIRA's scientific activities over the past year was our part in the global effort (involving around 15% of the global astronomical community) to follow up the discovery by the LIGO and Virgo detectors of the first binary neutron star merger event, GW170817. Seventeen CIRA staff and students contributed to these efforts as part of the Murchison Widefield Array, Australian Square Kilometre Array Pathfinder, or Desert Fireball Network teams, highlighting both the impact and collaborative nature of the work being done at CIRA.

Another notable highlight was the detection of the first Fast Radio Burst by the Commensal Real-time ASKAP Fast Transients Survey (CRAFT). This marked the culmination of many years of effort, which has been led from CIRA since the project's inception in 2010, and which is set to deliver a plethora of exciting new results over the coming years.

It has been especially pleasing to see CIRA's research being recognized externally over the past year, with success in the highly-competitive ARC funding space, as well as a number of prestigious awards, both local and national. Of particular note was the continuing recognition for the GLEAM survey, which was the product of a sustained team effort over several years, with leadership and significant contributions coming from many CIRA staff.

SKA has of course remained at the forefront of our activities, with our scientific staff contributing to the project through representation on major national and international committees, SKA Visiting Fellowships, and input to major initiatives such as the cost control project. Particularly noteworthy was the highly successful "Realising SKA Low" conference hosted in Perth in March, which brought together over 100 science and engineering experts from around the world to drive forward the progress of SKA-Low.

With a new organizational structure in place, and strengthened by several new arrivals, CIRA is well positioned to build on our success over the coming year, with the launch of the ASTRO-3D ARC Centre of Excellence set to further enhance our capabilities.

Finally, my report would not be complete without thanking the entire CIRA team for their professionalism over the transition period. I am indebted to the senior staff for their support and their strong team ethos. I am especially grateful to Tina Salisbury for helping me to understand CIRA's operations; and to Tom Booler, in whose dependable and highly capable company I have enjoyed sharing the many challenges of the past year.

ENGINEERING & OPERATIONS

Tom Booler

Director's Report

2017 was a year of change. CIRA's Foundation Engineering Director, Professor Peter Hall, took extended leave from early in the year before officially retiring, Professor Emeritus, in August; and Science Director, Professor Carole Jackson, departed in April to assume the role of Scientific and General Director at the Netherlands Institute for Radio Astronomy, ASTRON. The departures of the co-Directors coincided with important milestones in a number of CIRA's key programs, and the commencement of a number of significant Faculty and University level reviews with ramifications for the institute.

I am happy (and relieved!) to report that in spite of the rate and scope of change that characterized 2017, CIRA had another excellent year. The articles that follow showcase some of the highlights of the year, which span the Engineering and Science programs.

On the engineering front, the research program again produced quality publications with high utility to CIRA's instrumentation programs and the field in general. This program is also to the fore following the completion in 2017 of the SKA demonstration and test system AAVS1. The successful deployment and commissioning of AAVS1 at the Murchison Radio-astronomy Observatory (MRO), coordinated and led by the CIRA Engineering Operations Team, enabled the CIRA led verification program to commence in earnest.

The Murchison Widefield Array (MWA) continued to provide the local context for many of CIRA's engineering activities in 2017. A highlight of the MWA program in 2017 was the completion of the second and final stage of the Phase II expansion program -- the deployment of 56 new long baseline tiles. 2017 saw both of the new, MWA Phase II, configurations exercised operationally for the first time.

In 2017 CIRA again owes much of its success to engagement and collaboration. Local and international industry partners; international-SKA consortia partners; MWA-partners, including the CSIRO; regional communities; projects sponsors and funding agencies; and our ICRAR-JV partners all make important contributions to the success of CIRA. 2017 saw our industry partners GCo Electrical and Balance Utility Solutions continue to make impactful contributions to SKA preconstruction activities; at the same time as we forged new relationships with partners including Defence, technology companies, community groups, and government agencies.

CIRA's performance in meeting the challenges of 2017 is testament to the success of the former Directors—including foundation Science Director Professor Steven Tingay—in building a confident, competent and high-performing institute.

On a personal note: the daunting task of stepping into Professor Hall's shoes as caretaker of the Engineering program pending the arrival of his successor, Professor David Davidson, was made immeasurably easier by the support I received from the CIRA Team. I owe special thanks to Randall Wayth and Adrian Sutinjo for accepting and helping the engineering group to overcome my technical limitations; to Tina Salisbury for helping me to orient and navigate the wider University landscape; and the Operations Team for getting on with business in my absence. I would also like to acknowledge James Miller-Jones, who assumed the mantle of Science Director throughout 2017 and shared my 'Acting' journey. James' substantive appointment to the role from 2018 reflects the aplomb with which he handled the role.

Diversity, Inclusion & Equity

The CIRA Development Committee

Gemma Anderson

> *"At CIRA we value the participation of each member of the institute and want all staff, students, and visitors to have an enjoyable and productive experience during their time here. As part of the Curtin community, we support the Curtin values of Integrity, Respect, Courage, Excellence, and Impact. CIRA encourages an equitable, diverse, tolerant, and friendly work environment for all staff and students, regardless of personal circumstances, including age, disability, role, gender, sexual orientation, ability, political opinion, cultural and religious backgrounds, and family situation."*
>
> *CIRA statement of values drafted by DevCom*

As the 2017 chair of the CIRA Development Committee (internally known as DevCom), it is my honour to report on our recent endeavours toward encouraging and supporting diversity, inclusion, and equity in our workplace. DevCom receives incredible local support from the CIRA executive team (including a budget to carry out initiatives), which has led to fruitful collaborations throughout CIRA. The DevCom chair regularly meets with CIRA Executive Director Prof Steven Tingay, a process that helps guide our efforts and encourages ready mechanisms for DevCom to feed our initiatives throughout the institute. In 2017, we teamed up with Curtin University representatives (Prof Linley Lord, Ms Pip Rundle and Dr Shamim Samani) of the Science in Australia Gender Equity (SAGE) Pilot, which is an Australia-wide initiative to improve gender equity in science, technology, engineering, and mathematics (STEM).

2017 was an exciting year for DevCom that built upon progress from the 2016 committee. Through an application submitted by the 2016 DevCom to the Inclusion, Diversity, and Equity in Astronomy chapter of the Astronomical Society of Australia, CIRA maintained its Pleiades Bronze level status. Due to the hard work of the 2016 DevCom, with assistance from Mr Jon Tickner, Prof Carole Jackson, and Ms Tina Salisbury, the 2017 committee was able to announce new parenting facilities at CIRA, which included installing a baby changing table in a newly labelled gender neutral restroom, and upgrading a room in CIRA to make it useful for breast-feeding mothers. CIRA is the first institute on campus to organise their own parenting facilities.

At the end of 2016, DevCom ran a climate survey to assess the equity and diversity environment at CIRA. We surveyed well in these spaces, and the 2017 Devcom used the survey results to inform strategies for future initiatives. In 2017, DevCom ran several activities to attract more female students and staff to CIRA, to educate on unconscious bias, and to encourage cultural inclusiveness.

In an effort to look for opportunities to encourage more young women to pursue an undergraduate degree in physics and astronomy, in February 2017 we invited the ICRAR Outreach team to present a seminar on opportunities for members of CIRA to connect with the

DevCom-organised cultural lunch held at CIRA in July 2017. Image Credit: Gemma Anderson

Morning tea celebrating the Chinese Lantern Festival led by CIRA PhD students Xiang Zhang, Mengyao Xue, Qingzeng Yan, Hongquan Su (from right to left). Image Credit: Gemma Anderson

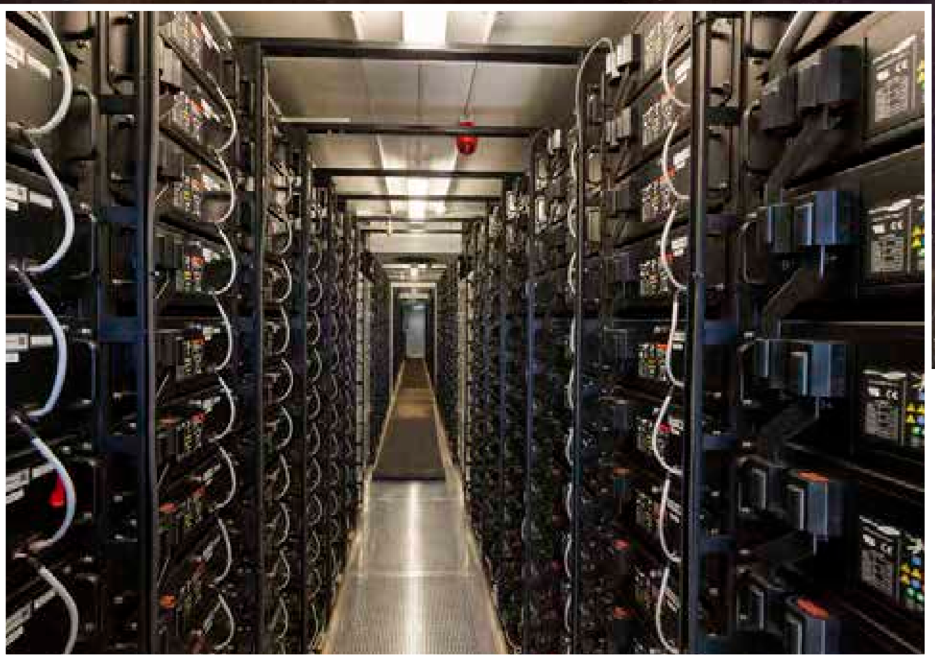
general public. DevCom also worked closely with Prof Steven Tingay and A/Prof James Miller-Jones to come up with suggestions for improving CIRA's diversity with future hires. This resulted in recommendations relating to future ICRAR job adverts, interviews, and selection, and it has already been trialled on a position. As part of that initiative, DevCom produced hiring "cheat-sheets" that list excerpts from Curtin policies on recruitment and diversity for CIRA line managers who are hiring, and for people who are acting on selection panels. Several other activities, seminars, and discussions on unconscious bias, work-life balance, and gender equity, led by the ICRAR Visiting Women's Fellow Dr Francesca Primas from the European Southern Observatory, were also organised by DevCom in the second half of 2017.

The 2017 DevCom team also ran several events to encourage cultural inclusiveness at CIRA. In February, DevCom supported a Chinese Lantern Festival morning tea led by Chinese PhD students Mengyao Xue, Xiang Zhang, Hongquan Su, and Qingzeng Yan. In July we held a Cultural Lunch, where members of CIRA brought food that represents their cultural background. The aim of this event was to encourage cultural inclusion and celebrate CIRA's cultural diversity. This event was a hit for staff and students, and it stimulated many conversations surrounding staff and student's cultures. DevCom intends to run this activity annually.

2017 has been an excellent staging point for initiatives and diversity training that will continue in 2018, particularly as we move towards our upcoming application for the Pleiades Silver Level award. We are excited to be leading efforts that support Curtin University and CIRA's commitment to diversity, inclusion, and equity.

The 2017 CIRA development committee consisted of Gemma Anderson (Chair), Rich Plotkin (Deputy Chair), Guillaume Drouart (Secretary), Rajan Chhetri, Paul Hancock, Ronniy Joseph (student rep), Franz Kirsten, Greg Sleap, Ryan Urquhart (student rep), Mia Walker, Sarah White, and Mengyao Xue (student rep).

HIGHLIGHTS



SCIENCE

Images credit: ICRAR

The unexplained phenomenon of fast radio bursts

Jean-Pierre Macquart

Part of the ASKAP array undertaking the CRAFT fly's-eye survey. CRAFT detected 20 new FRBs during this survey, and the range of burst brightnesses and dispersion measures has enabled us to answer important questions regarding their origin. Image credit: Robert Hollow (CASS).

Variously attributed to everything from neutron stars collapsing into black holes, to the outbursts of highly magnetised stars, and even to aliens accelerating interstellar spacecraft, the bright millisecond flashes of energy known as Fast Radio Bursts rank as the most conspicuous of unexplained astrophysical phenomena known today. Yet FRBs are so famously elusive that, since their discovery by Duncan Lorimer and colleagues with the Parkes radio telescope in 2007, only twenty-five more examples were found in the decade that followed. Although several thousand FRBs are inferred to occur across the sky each day, the relatively narrow field of view of most conventional radio telescopes has meant that even the most successful of FRB detection machines has only averaged an FRB discovery every six months. The small sample of known events and generally poor characterisation of their basic properties -- such as their position on the sky, distance, and even their true brightness -- has thwarted attempts to uncover their identity.

CRAFT: the early years

The study of transient events such as Fast Radio Bursts has been a prominent component of CIRA's research activity since its inception. An early collaboration with NASA's Jet Propulsion Laboratory led to the transformation of the Very Long Baseline Array (VLBA) into a fully-commensal all time FRB detection machine, and to the development of hardware capable of searching for transient events on the next generation of radio telescopes. At CIRA, an interdisciplinary team of engineers and scientists tackled the formidable challenges of sifting such short duration events out of the vast amounts of data needed to find an FRB on next-generation telescopes, particularly the Australian SKA Pathfinder, ASKAP.

From the outset it was realised that the phased-array feed technology on ASKAP, giving each of its 36 antennas a 30 square degree field of view, would revolutionise FRB searches. Based at the radio-quiet Murchison Radio Observatory, a fully-operational ASKAP would easily surpass the detection rates of existing telescopes by an order of magnitude. A team at CIRA and JPL recognised the opportunity and led the technical and scientific development for ASKAP under the banner of the Commensal Real-time ASKAP Fast Transients (CRAFT) survey.

Overseen by Prof Peter Hall and notably assisted by Dr Nathan Clarke and Tim Colegate, the CRAFT team developed a system architecture capable of accessing a wide field of view on the sky yet sensitive enough to detect FRBs at a high rate with ASKAP. Through the efforts of Nathan Clarke and Larry D'Addario (JPL), this led to both the implementation of an interface capable of handling high time resolution data processing on ASKAP, and to the development of FPGA-based hardware capable of identifying FRBs in real-time. Meanwhile, Dr Jean-Pierre Macquart set about investigating the basic properties of FRBs and the most effective means to prosecute surveys for them. For instance, how could one augment the detection rate by changing the configuration of a radio array, by having the dishes all point in different directions, in a "fly's-eye" mode? Dr Randall Wayth and Prof Steven Tingay and a team at JPL used the VLBA as a test-bed for the development of software and algorithms to better weed out genuine astrophysical events from the clutter of Earth-based radio interference.

"So, what do you plan to do with the CRAFT mode we've built into ASKAP?"

In 2016 a chance conversation at Marsfield in Sydney re-invigorated the CRAFT collaboration: informed by the early technical development by Clarke and D'Addario, ASKAP engineers had implemented a high-time resolution system in ASKAP that enabled access to millisecond total power measurements of the radio sky across the entire ASKAP field of view. Software development to support this system began in earnest.

And so it was that ASKAP detected its first FRB on 7th January 2017, after just 3.5 days of observing on a small test array that utilised only a fifth of ASKAP's full potential. This marked the start of an auspicious year for the CRAFT project. The team used a small 4 to 8 antenna engineering test array on ASKAP to survey the sky in a "fly's-eye" mode, in which each antenna looks at a different patch of sky. This approach maximises field of view at the cost of sensitivity.

CRAFT detected 20 new FRBs as a result of this shallow wide-field survey, nearly doubling in a single year the number of FRBs that had been detected by all the world's other telescopes in the previous ten.

The survey was able to address several key unanswered questions about FRBs. CRAFT was able to provide the first reliable measurements of a number of key properties of these enigmatic bursts, yielding a sample that was amenable to thorough statistical analysis. The phased array feeds on ASKAP enabled us to directly determine the fluence and spectrum of each burst, a key shortcoming of the previous Parkes detections.

The survey measured the statistics of the very bright end of the FRB distribution and thus has been able to establish that the population is located at cosmological distances.

Almost as formidable as the CRAFT results themselves is the team at CIRA who have played a large role in their generation. Jean-Pierre Macquart has teamed up with Curtin Adjunct Professor Ron Ekers to investigate the statistical properties and the origin of FRBs, while adding to the interpretation of CRAFT FRB properties. Ryan Shannon (now moved to Swinburne) is a vital player in the mechanics of the CRAFT observing and FRB detection, as well as the interpretation of their properties. The team was augmented by the arrival of Dr. Clancy James in mid-2017 to work on CRAFT, and he has since applied his skills to benchmarking the survey sensitivity, and to numerous statistical problems involved in the interpretation of the results.

The co-location of both CRAFT and MWA key operational personnel has made it possible to institute a mode that allows the MWA to shadow the locations of ASKAP antennas, thus enabling searches for low-frequency emission coincident with the detection of CRAFT FRBs. This project has been driven heavily by Drs Ramesh Bhat and Marcin Sokolowski, who have co-observed a number of FRBs with the MWA.

The project has been successful in attracting external funding through the award of an Australian Research Council Discovery Project grant to Drs Macquart, Shannon and Bannister (CSIRO) in late 2017. The group anticipates the arrival of a new postdoctoral fellow funded by this position later in 2018.

As of the beginning of 2018, the group has further expanded with the addition of PhD candidate Seema Morab and five talented Curtin 3rd year students, who are undertaking projects on topics ranging from follow up observations with the 110m Green Bank Telescope, to understanding the properties of the matter through which FRB radiation propagates. At the same time, the software engineering efforts of PhD candidate Wayne Arcus have been preparing CRAFT for its next leap forward — the arcsecond localisation of FRBs.

A glimpse of the high-resolution future

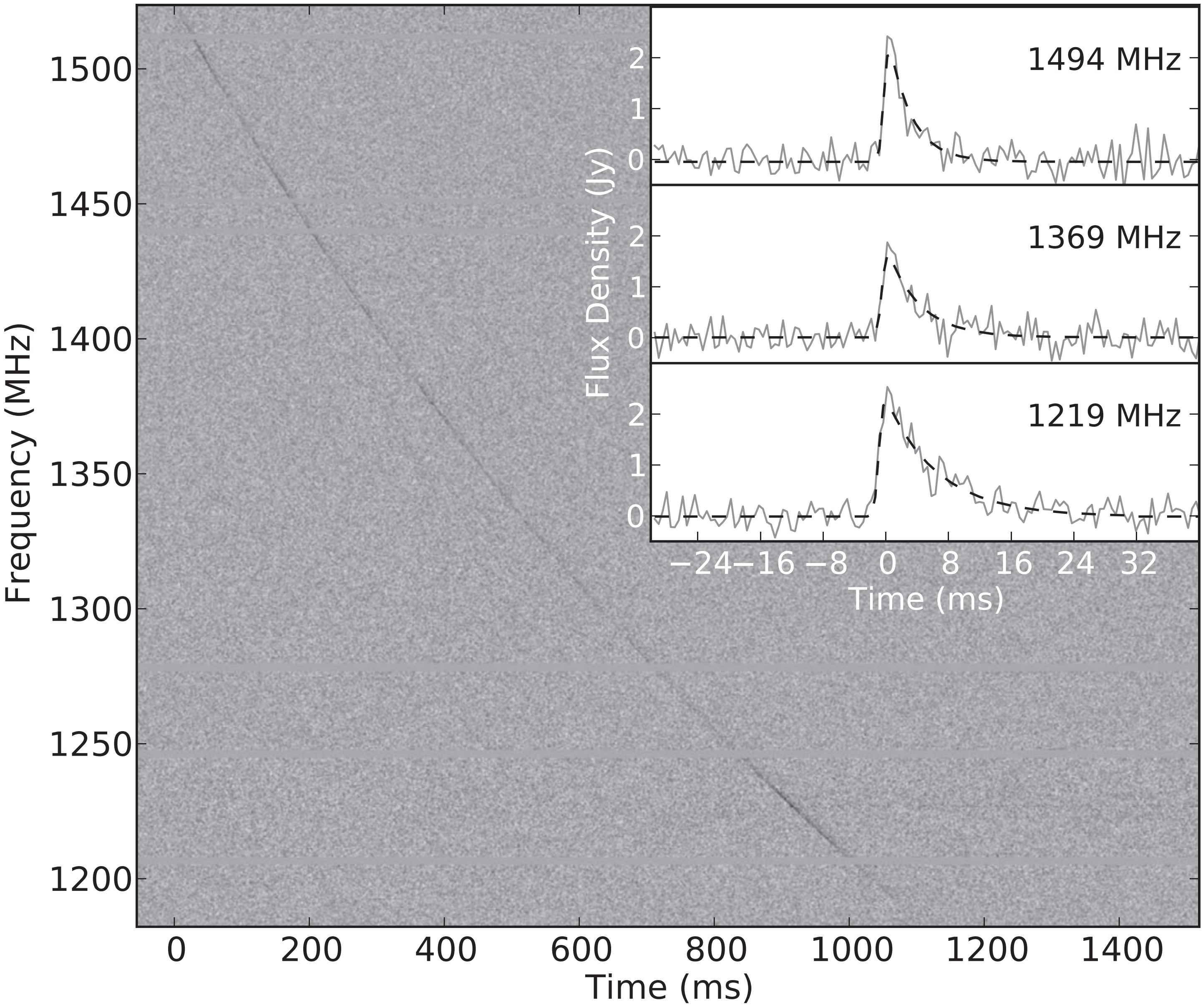
The next big leap in FRB research is to measure their exact distances directly. This requires being able to identify which galaxy any given FRB has emanated from. This has hitherto been impossible for all but one object (the single FRB that is observed to show repeat bursts, which may well be an entirely different type of object compared to the remaining one-off events that have been detected). This is because instruments such as Parkes and the fly's-eye mode of ASKAP only determine the direction of an FRB to within about 100 square arcminutes, about a factor of 36,000 too large to unambiguously attribute an event to any given galaxy.

By May 2018 CRAFT will begin collecting interferometric data for every single FRB that it detects. In concert with an optical follow up programme on several 8-m class optical telescopes, especially the European Southern Observatory's Very Large Telescopes, we will obtain spectroscopic redshifts for all our FRBs and thus determine their exact distances.

This information is important for two reasons. Firstly, it will give us a clue what causes the enigmatically bright emission from FRBs in the first place. There are currently more theories for FRBs than there are known bursts, and hard observational constraints on their properties are desperately needed to understand exactly what an FRB actually is.

The second reason is that it will enable us to weigh the Universe. This is because the pulse arrival time of every single FRB is retarded by an amount that is directly proportional to the amount of ordinary matter (not dark matter) through which the signal has propagated on its way to Earth. This effect is frequency dependent. So if you measure the signal arrival time across a range of frequencies you have an instant measure of the number of atomic nuclei and electrons between you and the burst. Once you know the burst distance, you have the density of the matter in the Universe.

But this is just the starting point. All our discoveries so far have been made with a fraction of ASKAP's full potential; as more antennas are added to the array our detection rate stands to increase by a factor of five. There have been many suggestions how to use FRBs as precision probes of the Universe in which we live, from probing feedback processes that restrict galaxy growth, to even measuring the nature of dark energy. Large numbers of FRBs from a well-controlled survey are required to undertake these ambitious projects. The CRAFT team stands poised to deliver.



An example of a Fast Radio Burst, as reported by Thornton et al. in 2013. The arrival time of this 8 millisecond duration pulse from FRB11020 changes with frequency: the quadratic sweep in the time-frequency domain is characteristic of having propagated through a large column of ionized material. The column of material is known as the dispersion measure (DM). In the present case, the DM is so large (i.e. the sweep is so shallow) that the burst must have propagated through ~40 times more ionized material than is contributed by our Galaxy, implying a distance so great that the burst likely occurred several billion years ago.

Peering into the lair of a mysterious cosmic radio burster

Charlotte Sobey

A flash from the Fast Radio Burst source FRB 121102, originating from deep in extragalactic space, is observed at the 305-metre Arecibo telescope in Puerto Rico. This burst is highly polarised, and the extremely magnetised plasma between the source and us causes its light to become twisted. The result appeared on the cover of the 11 January 2018 edition of Nature (Michilli et al. 2018, Nature, 553, 182).
Image credits: Image design: Danielle Futselaar - Photo usage: Brian P. Irwin / Dennis van de Water / Shutterstock.com

Observations from two of the world's largest radio telescopes have enabled us to unveil the astonishingly extreme and unusual environment of a mysterious source of repeating 'fast radio bursts', or 'FRBs'. The source is embedded in a hot, dense environment with an exceptionally strong magnetic field. Compelling explanations are that it is either situated in the neighbourhood of a massive black hole or embedded within a nebula of unprecedented power.

FRBs are swift, sudden radio flashes discovered just over a decade ago. So far, most of the FRBs detected have been single, millisecond, flash in the pan events, even after hundreds of hours of follow-up observations. FRB 121102 is the exception because it is the only source that keeps repeating. This FRB factory provided us with an exclusive chance to carefully monitor and scrutinise the signals.

FRB 121102 sends its bursts towards us from an area of massive star formation and death within its host dwarf galaxy over three billion light years away. At this distance, an immense amount of energy must power each burst -- if one went off on the other side of our Galaxy, it would disrupt radios on Earth.

Since its discovery, FRB 121102 has been monitored using several radio telescopes, including the Arecibo Observatory in Puerto Rico and the Green Bank Telescope, USA. Microsecond structures within the bursts require specialist observing modes to capture them, resulting in a vast data volume – the equivalent of 18,000 DVDs per hour. Although none of the bursts look alike (they vary in brightness, shape and structure) the shortest time span of the signals is about 30 microseconds. This means that the size of the region creating the FRBs must be tiny by astrophysical standards – less than just 10 kilometres across.

In work published in the journal Nature (Michilli et al. 2018, Nature, 553, 182), we found that the signals from FRB 121102 are about 100 per cent polarized, by detecting the bursts at the highest radio frequencies to date. The Sun's light is unpolarised – it emits electromagnetic waves that vibrate in all directions perpendicular to their direction of travel. In contrast, the light from FRB 121102 vibrates in only one direction.

Using the behavior of FRB 121102's polarised light, we discovered that the mysterious object creating the bursts is embedded in an exceptionally magnetised and dense plasma (ionised gas) environment. As polarised electromagentic waves travel through a plasma with a magnetic field, the vibration angle of the wave becomes 'twisted' – the stronger the magnetic field, the greater the twisting. Detecting the bursts at higher radio frequencies than ever before also enabled us to measure the tremendous amount of twisting imparted by the extreme environment -- among the largest ever measured in a radio source and 500-times that for other FRBs. We estimate that the magnetic field strength near FRB 121102 is a few milliGauss -- about a thousand times greater than the magnetic field strength in the Solar System's neighbourhood within the Milky Way.

We expect that the source of FRB 121102 is located within the extremely magnetised environment because the monitoring observations reveal that the amount of twisting varies by a large amount (about ten per cent) over the timescale of a few months. Another surprising finding is that the twisting imparted on the FRBs is very clean; there appears to be little interference on the signal throughout its three-billion-light-year journey to us.

FRB 121102's extremely magnetised environment could mean that it is in close proximity to a massive black hole, or cocooned in a nebula of unprecedented power. Radio waves from the region close to the massive black hole in the centre of our Galaxy also show a large amount of twisting. As such, the object may be in a similar environment within its host galaxy. Another hypothesis is that the source is embedded in a powerful nebula that would have to be a million times more energetic than the Crab nebula (a bright supernova remnant a few thousand light years from Earth that can be seen with binoculars). Monitoring the repeating FRB over the next year will provide more information that can help us distinguish between these possible scenarios.

The repeating FRB 121102 has also shed some light on the mysterious physical object creating the immensely powerful signals. Currently, fewer FRBs have been discovered than there are theories about their possible progenitors. The emission mechanism for FRB 121102 cannot involve a cataclysmic event, destroying the object in the process, because the bursts repeat. A pulsar (neutron star) origin is one leading theory because the signals we receive are somewhat similar – short, polarised bursts generated in an area a few kilometres in size. However, unlike pulsars, no periodicity has been found in FRB 121102. The signal would also have to be about a million times brighter than the brightest pulsars in our Galaxy or amplified through a cosmic 'magnifying lens' by dense plasma. However, FRB 121102 is also quite atypical and may belong to a unique class compared to the other FRBs, analogous to the different types of gamma-ray bursts released from supernovae or merging binary neutron stars.

Although FRBs are not rare – flashing somewhere in the sky roughly every 10 seconds – technologies are still being developed to observe larger patches of the sky so that we can discover many more. International collaborations are continuing the great FRB hunt using large radio telescopes, particularly in Australia, including CSIRO's Parkes radio telescope, the recently upgraded Molonglo Observatory Synthesis Telescope, and the recently constructed Australian Square Kilometre Array Pathfinder (see the previous article). The current push is towards discovering more FRBs in real time so that they can be studied as a population and each localised to their own host galaxy. In the future, the Square Kilometre Array will be able to detect and localise many more FRBs so that we can unravel more mysteries about their nature and origin.

A flash from the Fast Radio Burst source FRB 121102 travelling towards the 100-metre Green Bank telescope, in the USA. The burst shows a complicated structure, with multiple peaks, which may be created during the burst's emission or imparted during its three-billion-light-year journey to us.
credits: Image design: Danielle Futselaar - Photo usage: Shutterstock.com

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RADIO ASTRONOMY

A search for extraterrestrial intelligence (SETI) with the MWA

Chenoa Tremblay and Steven Tingay

In November 2017, Chenoa Tremblay was awarded the Ken and Julie Michael ICRAR Prize for the most outstanding piece of research in the field of radioastronomy science, engineering, or data intensive astronomy.

Over the centuries we have developed a keen interest in understanding if we are alone in the Universe. In the early 1800s our first attempt to communicate with beings not of Earth involved creating mathematical symbols in the Siberian forest. This was with the hope of communicating to people living on the moon that intelligent beings were on Earth. In the early 1900s, William Pickering suggested communicating with people on Mars via Morse code using the sun and giant mirrors.

Although these ideas seem naive to us now, they initiated a fundamental curiosity that keeps us searching for extraterrestrial intelligence (ETI) today. We have now come to realise that other beings are unlikely to be close enough to see signals on the Earth directly. Instead, our best chance of communication is through light waves, since light travels faster than any spaceship we can build.

By using the Murchison Widefield Array (MWA) we are looking for incoming radio waves that could be associated with ETI in the forms of electrical communication, or more indirectly by searching for molecules that are associated with life forms here on Earth. The MWA detects light at the same wavelengths as digital television and commercial radio. Given that we regularly detect this type of light within our houses, cars, and mobile phones, it is reasonable to expect that we could also detect such signals from space if a civilization has technology similar to our own

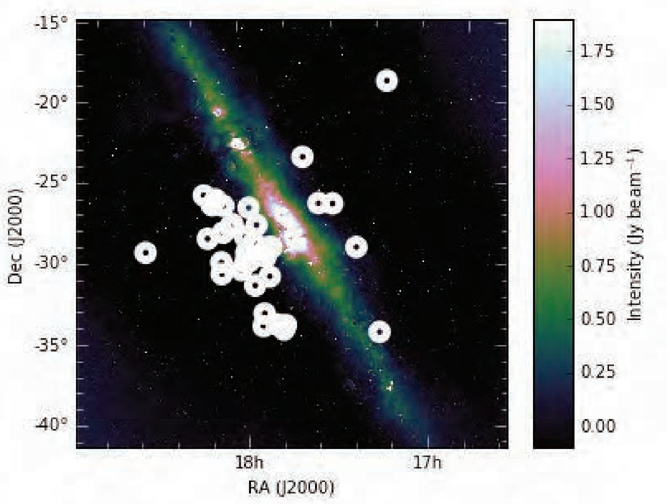
The MWA offers a very distinct advantage over other ETI searches by offering a wide field-of-view. When the MWA looks up at the sky it sees an area that would take approximately 2000 moons to fill, giving us the opportunity to look at tens of thousand of stars and planets at once. We can either search blindly in all directions to look for signals, or we can target areas of the sky that are known to contain planets outside of our solar system, i.e., exoplanets.

In work done by Tremblay et. al. (2017), we developed a process to calibrate and image the sky to look for emitted light that can only be detected with sensitivity to small changes in wavelength. By using this process, we surveyed a region towards the Galactic Centre and the Orion molecular cloud, to look for signals associated with molecules and potential electronic communication.

In the work published by Tingay et al. (2016) for the Galactic Centre and Tingay et al. (in press) for the Orion molecular cloud, we targeted regions of known exoplanets (http://exoplanet.eu/catalog/) to look for signals that may be associated with sharp electronic signaling. Although we did not detect any signals significantly above the noise, we were able to set limits on searches for the future.

In the work published by Tremblay et al. (2017) for the Galactic Centre and Tremblay et al. (ApJ submitted) for the Orion Nebula, we searched for signals associate with molecules. By looking for gas-phase molecules, we can hope to detect life that may not have developed the intelligence to send their own signals. Both surveys yielded detections of nitric oxide in evolved stars, a molecule that is critical in the early evolutionary development of humans, and important for the biomechanical development of infants. We also detected molecular oxygen (O2) and deuterated formic acid (a simple organic acid), both of which are required for the formation of amines. Amines are important chemicals in the brain function of humans. Although these are not direct detections of life, their detection would demonstrate that life is possible with the molecules we find in stars and gas clouds throughout our Galaxy.

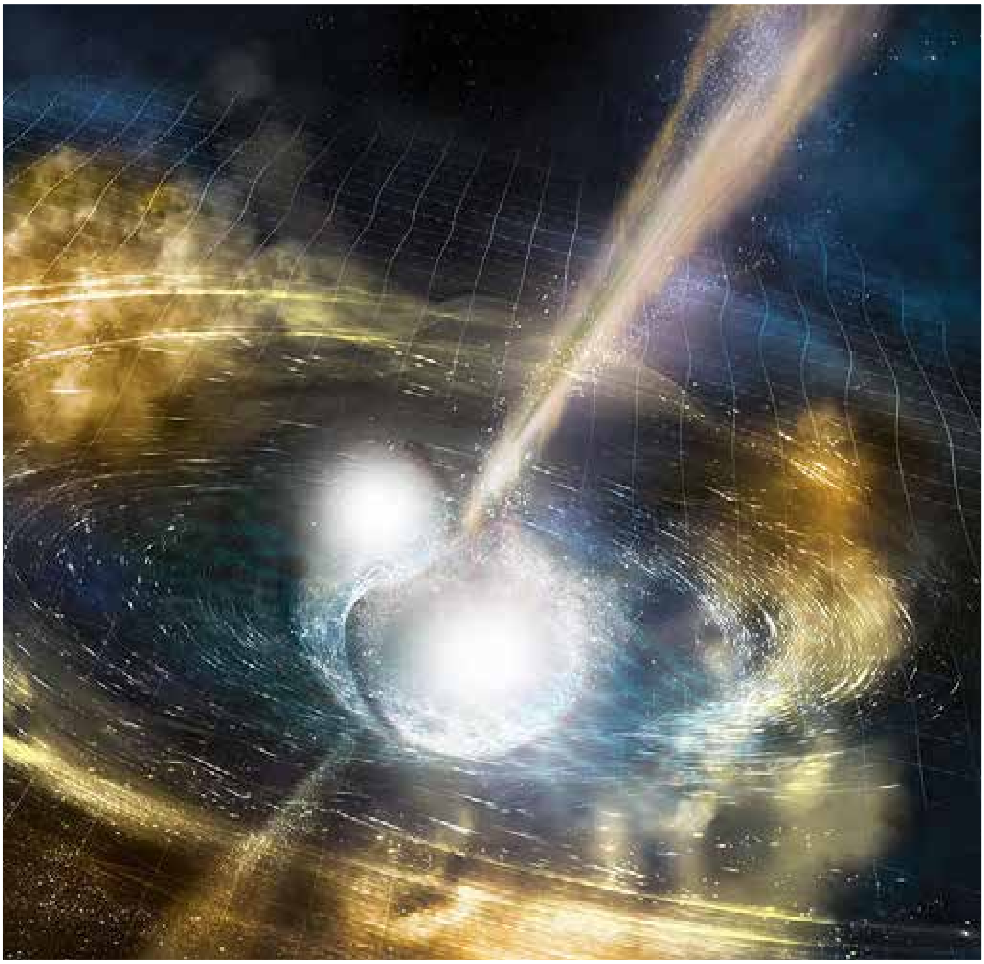
By using the MWA we join the SETI community of telescopes to look for light from electronic communication of due to molecular reactions. Since we do not know when, how, or where an ETI signal may come from, the MWA's large field-of-view is an asset allowing us to simultaneously cover large patches of sky. With the new data analysis pipeline developed by Tremblay et al. (2017) these types of searches are now possible. However, through collaboration with Breakthrough Listen (https://breakthroughinitiatives.org/), the telescope and data processing will be further optimised for the search of electronic signals from intelligent civilizations in the future.



The Galactic Centre field searched for moledcules and SETI. The circles represent areas of known exoplanets. The molecular surveys were blind searches covering the full field-of-view while the SETI search targeted regions with knownexoplanets.

Chasing radiation from gravitational wave events with the Murchison Widefield Array and the Desert Fireball Network

Marcin Sokolowski, Randall Wayth,
Paul Hancock, Brian Crosse,
Luke Horsley, Andrew Williams



An artist impression of two merging neutron stars, the type of system responsible for the gravitational wave event and gamma-ray burst discovered on 17 August 2017. These types of events are likely the dominant production sites of many types of heavy elements in the Universe. Image Credit: NSF/LIGO/Sonoma State University/A. Simonnet

The first ever direct detection of gravitational waves was made on 14th September 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO). That event was caused by coalescence of two black holes in a binary system (with masses around 30 and 35 times the mass of the Sun). Only two years later the Nobel Prize in physics went to R. Weiss, K. Thorne and B. Barish for "for decisive contributions to the LIGO detector and the observation of gravitational waves". The era of gravitational wave astronomy started merely two years ago, and every year it brings new fascinating results, which help us to understand the physical processes causing these extraordinary events.

Last year, on 17 August 2017, another breakthrough gravitational wave event GW170817 was observed. For the first time in history, a counterpart to the gravitational wave event was also observed across the entire electromagnetic spectrum , from low radio frequencies up to gamma-rays. The event was caused by a merger of two neutron stars, which are very dense objects nearly 150% more massive than our Sun packed into the size of a small city (a few kilometres). During the few seconds of the gravitational wave event, enormous energy was released, which in gamma rays alone reached approximately 1040 Watts (the same as the Sun releases in about a million years). The discovery and subsequent multi-messenger observations were given a Breakthrough of the Year award by the journal Science.

Neutron star (merger events have long been theorised to cause short Gamma-Ray Bursts (flashes of intense gamma-ray emission), and GW170817 provided strong evidence to support this prediction. Besides the gravitational wave detection by the LIGO detectors, the event was also independently detected by the Fermi and INTEGRAL satellites with gamma-ray detectors on-board. Subsequently, multiple gamma-ray, X-ray, ultraviolet, optical, infrared and radio instruments (robotic and manually operated) performed broadband follow up of the event, providing flux measurements or upper limits. Neutrino telescopes also observed the position of the event, but they did not detect any candidates consistent with the source.

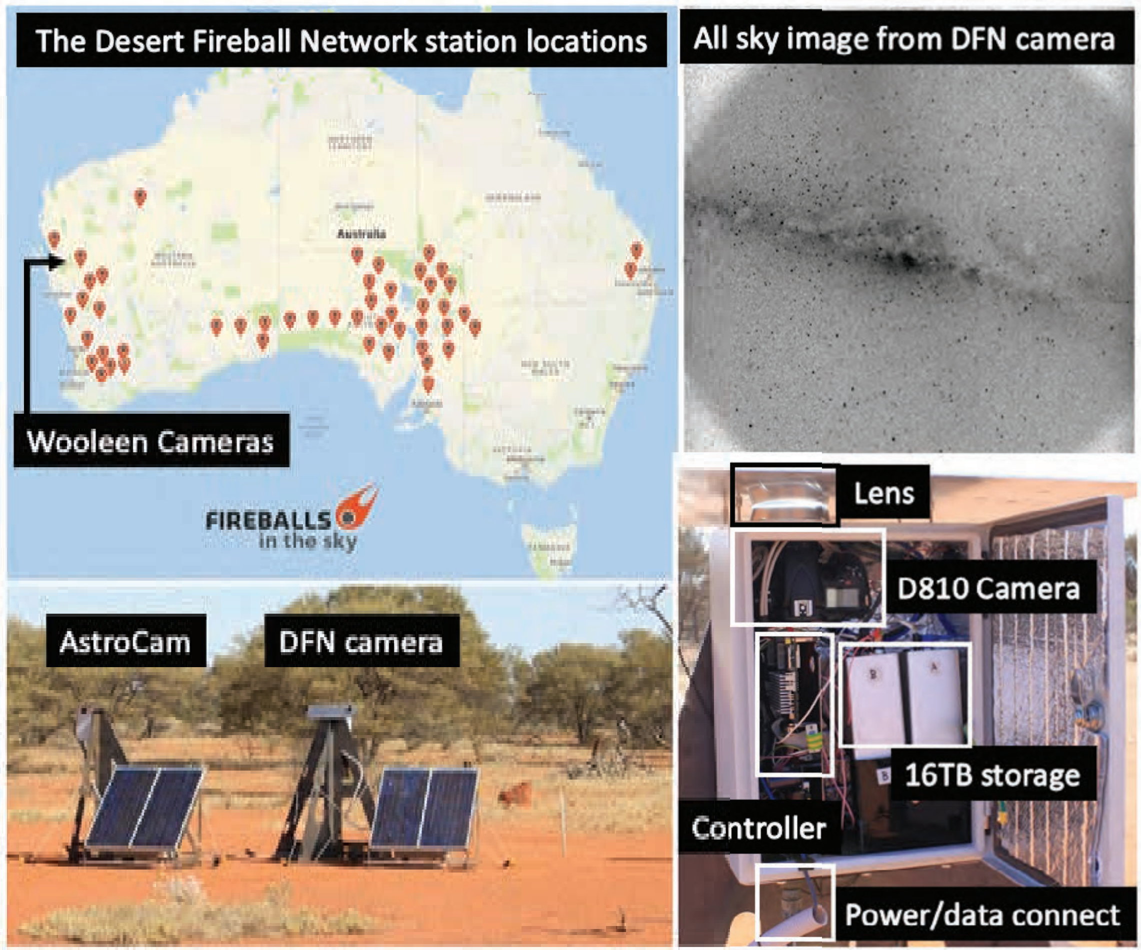
Analysis of the above multiwavelength data provided final confirmation, after 60 years of speculation, that the merging of two neutron stars provides the main production of heavy elements in the Universe (like gold), via the rapid neutron-capture process. The astronomical instruments operated by Curtin University, namely Murchison Widefield Array (MWA) and Desert Fireball Network (DFN), provided significant input into the extensive multiwavelength and multi-instrument international campaign. The DFN network of cameras, continuously monitoring the night sky above Australia observed the position of the GW170817 before, during, and after the event. The DFN was the only optical telescope worldwide observing the position during the event (see the next article).

The MWA started to observe the position of GW170817 about one day after the gamma-ray burst and provided the earliest and the most sensitive low radio-frequency (185 MHz) upper limit. Although the telescope was in the middle of reconfiguration, thanks to a quick reaction and immediate site-trip of the MWA Operations Team from CIRA (Brian Crosse and Luke Horsley), it was possible to improve telescope's sensitivity for the follow-up observations. Initially, the MWA performed 1.5 hour observations of the location every day, but over time the observations became less frequent. Nevertheless, the GW170817 position is still being monitored and observations are collected at least once a month, as there are theoretical predictions for a possible low frequency afterglow about one year after the event.

The direct discovery of gravitational waves by LIGO and Virgo detectors of the event GW170817, which was the first GW event to be observed in electromagnetic spectrum, will lead to many significant breakthroughs in astrophysics in the years to come. Both Curtin instruments, the MWA and DFN, significantly contributed to an extensive multiwavelength international observing campaign of GW170817, and they are very well setup to continue producing high impact science on gravitational wave counterparts in the future.

Desert cameras were the first on target for the binary neutron star merger GW170817

Paul Hancock, Jaime de Gois, Steven Tingay, Tom Booler



The Desert Fireball Network consists of 50 stations around Australia. The Wooleen station has a regular DFN camera with a full sky field of view, and the AstroCam with a narrow field of view and increased sensitivity. A single station is built from a Nikon D810 camera, with a Fish-eye or rectinlinear lens, an ob-board computer controller, attached storage, and is powered by a solar backed battery.

In September 2015, a team of CIRA astronomers and DFN geophysicists installed two cameras in the remote Western Australia desert. The goal: detect fireballs, meteors, and rare optical transients. Since installation, these cameras have detected thousands of meteors, including many fireballs (very bright meteors). On August 17th, 2017 these desert cameras were the first responders to the event of the century – a merger of two neutron stars, some 130 million light years distant.

The Desert Fireball Network (DFN) has installed 50 cameras around Australia with the aim of detecting bright meteors as they fall to Earth. The brightest meteors are known as fireballs, and are capable of surviving the trip through the atmosphere. The DFN cameras are designed to detect these meteors, locate the fallen metorites, and identify their pre-collision orbit. In September 2015 CIRA astronomers Prof Steven Tingay and Dr Paul Hancock joined forces with Mr Hadrien Devillepoix and Dr Martin Cupak from the DFN, to build and install two new cameras at Wooleen station. One of the cameras was a DFN camera designed to search for meteors, whilst the second (AstroCam) was designed for astronomy use. Being only 200km from the Murchison Widefield Array (MWA) means that the two Wooleen station cameras are able to provide overlapping optical views of the sky that the MWA observes. The cameras are fully automated and capture the entire night sky every night at a cadence of just 13 seconds.

Through 2015 to late 2017 the two cameras at Wooleen station were used to detect metoers and fireballs as part of a project to find radio emission from fireballs. This project detected many hundreds of meteors with the optical cameras but no detection of any radio emission.

In 2017 a project was begun by CIRA undergraduate student Mr Jaime de Gois to provide a calibration solution for the AstroCam images, so that the resulting images could be used for science purposes. In particular, the image should be able to provide the widest continuous coverage of the night sky. With such a data set in hand it would then be possible to conduct a survey for very bright and very rare transients. On August 17th of 2017 one such event occurred within the field of view of the DFN camera – the detection of a gravitational wave event corresponding to the merger of two neutron stars. The host galaxy for this event was later identified as NGC4993, which at the time of the merger was only 30 degrees above the western horizon as viewed from the MWA and Wooleen station. At such a low elevation the AstroCam was not able to observe the event, however the all sky view of the DFN camera was.

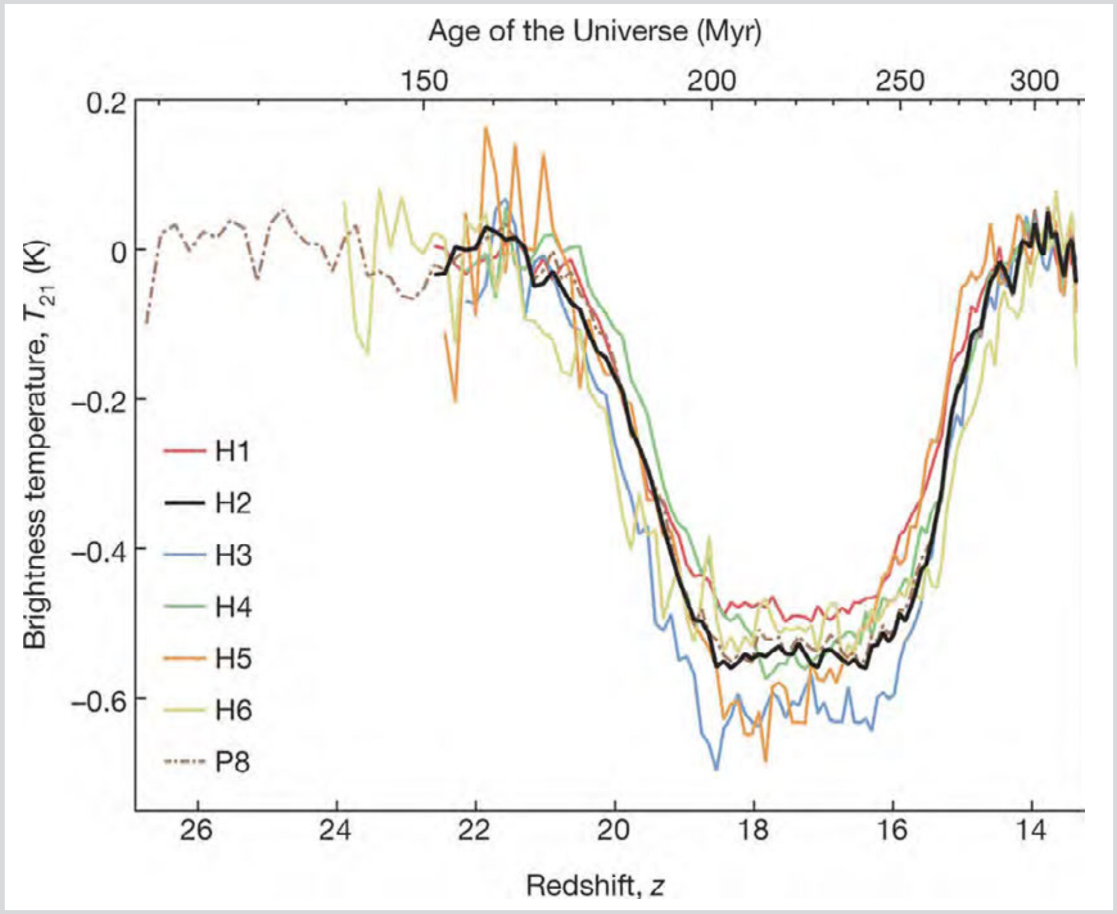
An expedition was mounted to travel to Wooleen station and retrieve the hard disks containing the images from the night of the gravitational wave event. Dr Paul Hancock and Mr Tom Booler flew to Geraldton, drove to Wooleen to change hard drives in the blazing sun, and then returned to Perth in an epic road trip. The data were calibrated using a process based on the work of Mr Jaime de Gois, and the final images were inspected by eye to search for a transient at the location of the host galaxy NGC4993. No transient was detected brighter than 6th magnitude. Despite the lack of a detection this road trip and data processing provide a number of important points. Firstly, the Wooleen cameras' geographical location, all sky view, and high cadence makes them ideal for providing information about rare transients. Indeed the Wooleen cameras provided the first optical observations of GW170817, and were "on source" many hours before the event. Secondly, the calibration project demonstrated that the Wooleen cameras can provide data with a precision and accuracy required to make useful scientific contributions.

At the end of 2017, CIRA is now in a position to develop a new capability -- an all sky optical monitor that can cover the field of view of the MWA, in the search for rare optical transients. Continued work on the calibration project will result in a more robust and automated process that could one day be installed directly on the camera control computers, so that instead of sleeping through the mid-day heat, these computers could process the previous night's worth of data. Future work also includes a project to process the extensive archive of the DFN in search for non-fireball transients, and to provide the most complete high cadence record of the Australia night sky above 8th magnitude.

A DFN view of the galaxy NGC4993 in which the binary neutron star merger GW170817 occurred. Objects visible to the naked eye are annotated in green. No early afterglow brighter than 6th magnitude was detected.

Modelling extended source structure for Epoch of Reionisation science

Cathryn Trott, Randall Wayth



First detection of hydrogen in the Cosmic Dawn, pre-dating the Epoch of Reionisation, and providing some clues to the physics of the early Universe. (Credit: Bowman et al. 2018, Nature)

The Epoch of Reionisation (EoR) presents one of the remaining unexplored periods in the history of the Universe. Occurring in the first billion years after the Big Bang, this era witnesses the transformation of the Universe from a dark and electrically-neutral background, to a sparse, illuminated, ionized expanse of the galaxies and stars we observe today. The astrophysics underlying this transformation include the birth and death of the first stars and black holes, and provide an insight into the location and density of galaxies in the early Universe. It therefore provides key information about the type and distribution of the first stars, how and where they formed and how rapidly they evolved, and what they looked like in their death.

We can detect and explore this key period using the neutral hydrogen between galaxies to trace the growth of structure and the physical conditions in the gas. Neutral hydrogen atoms each have one proton bound to one electron. The presence of the electron changes the conditions in the hydrogen nucleus, absorbing and emitting light at a known, resonant frequency. Tracing this emission and absorption allows to see where the gas is still neutral, how hot it is, and when it disappears. All of these factors allow us to 'see' the earliest stars and black holes, and how they transformed this gas. This radiation, when emitted more than 12 billion years ago, has been redshifted by cosmological expansion to low radio frequencies, detectable with arrays such as the Murchison Widefield Array (MWA) and the future Square Kilometre Array (SKA). We are pursuing this weak signal with the MWA.

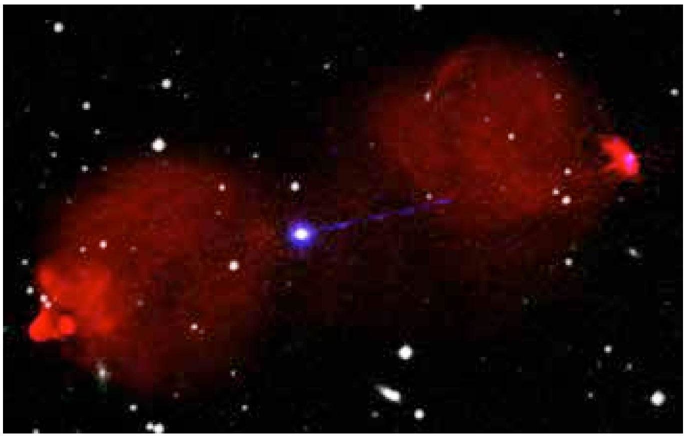
There are many impediments for finding and characterising this signal. Firstly, it is extremely weak compared with the rest of the radio sky, requiring many hours of deep observation to detect. Secondly, these astrophysical "foregrounds" have a signature that mimics that from the EoR, requiring very careful calibration of our instrument and careful subtraction of these signals, to obtain the clean data required. As part of both of these processes, we require a detailed and precise understanding of the radio sky. Without this, we cannot hope to explore this early Universe signal. Many radio galaxies in the sky appear as points of light in our data, making them relatively easy to characterise and remove. However, many radio galaxies are large and close to us, and look more like normal optical galaxies with complicated spatial and spectral structure. These can present large problems for us, because they have signals on the same size scales as the early Universe signal. To remove these, we need very detailed models for them, which requires a good telescope to obtain.

A radio interferometer is a special telescope that uses information collected from an array of distinct antennas to represent the sky signal. The location and spacing of these antennas on the ground describes the angular scales on the sky to which the telescope is sensitive. Sky signal on angular scales that are not measured cannot be recovered from the telescope data, and therefore the layout of the telescope is crucial for determining the information that can be derived about an astrophysical source. No radio interferometer yields perfect information, with all having well-sampled and unsampled angular scales.

For the SKA, as the best, most complete southern hemisphere radio telescope of the future, the SKA itself will provide the sky model for these extended sources. This is because the SKA array layout is superior to all current and previous interferometers for EoR science. However, the information is still imperfect, because even the SKA does not obtain complete information, and therefore our models for these extended sources necessarily contain missing information. In this work, we studied the impact of residual signal from the unmodelled components of these extended sources, and we determined whether EoR science could be performed with a set of different telescope models for the low-frequency component of the SKA.

We were able to show that, for the precision EoR exploration proposed for the SKA, a minimum array density and size was required. Without this information, the extended source models would be incomplete and the residual signal could contaminate our efforts to explore the early Universe. This is particularly true for the Cosmic Dawn signals, the first two hundred million years when the first stars and galaxies are formed and begin to change the Universe. The spatial evolution of the Universe in the Cosmic Dawn is one of the primary science drivers for SKA.

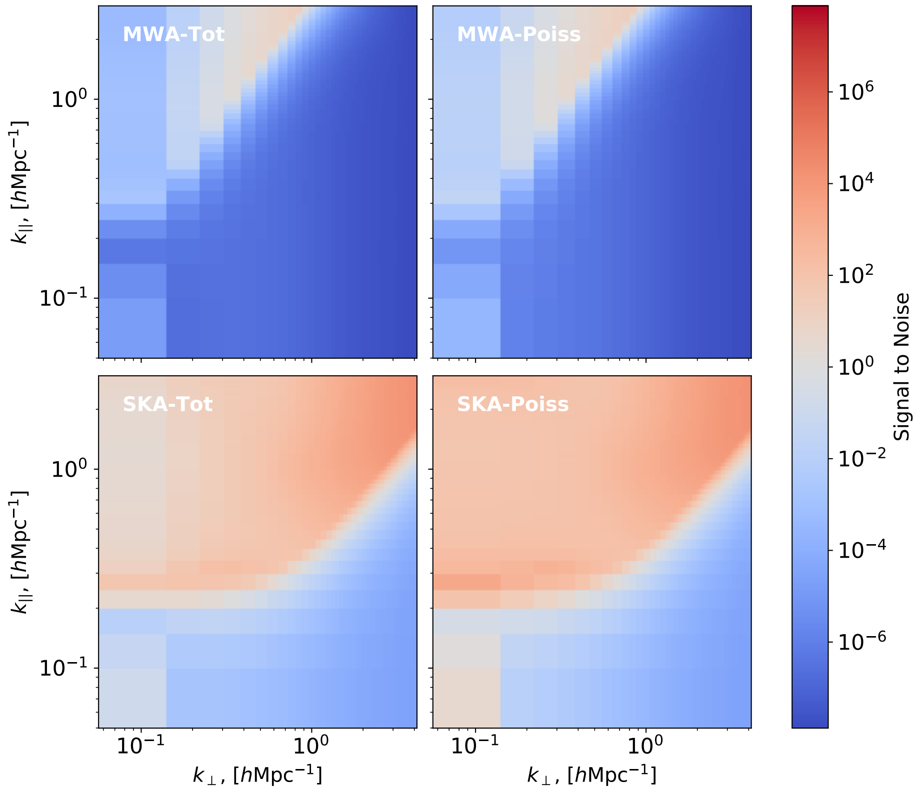
This analysis is useful for designing the SKA, and how we approach the EoR experiment to best exploit the information we can obtain about the sky.



Multi-wavelength image of Pictor A, a major extended source in the southern hemisphere, which has signal on many spatial scales. (Credit: Wilson et al. 2011, Chandra, ATCA)

An improved statistical point source foreground model for the Epoch of Reionisation

Steven Murray



The signal - to - noise of 2D power - spectra corresponding to the fiducial parameters from Fig. 1. Each panel is a different combination of telescope and assumed foreground model. The SKA clearly gives a much higher signal-to-noise. The structure of the clustered sources arises as the diminishing signal-to-noise on the left-hand edge of the left panels.

The Epoch of Reionisation (EoR) is one of the last unexplored eras of cosmic history -- the transition from the "dark ages" before galaxies existed, to the modern era of rich galaxy populations. The most promising method of observing the EoR is to measure the radio-frequency emission of neutral hydrogen (HI), which is abundant in the early universe, but reionised as galaxies form and heat it.

This emission is both extremely weak and distant, requiring massively powerful and carefully calibrated radio telescopes for detection. Additionally, the EoR hides behind a gamut of obscuring "foregrounds." The atmosphere, our Galaxy, and every other galaxy in the Universe drown out the signal by a factor of over 1000, rendering it incredibly difficult to ascertain whether any measured signal is truly from the EoR itself. Thus a major theme of the EoR hunt involves developing sophisticated statistical methods to differentiate the signal from these foregrounds, enabling clean extraction.

A key insight which has been extensively used is that because the foregrounds are a random combination of many sources of emission, their brightness as a function of frequency is expected to be very smooth. Conversely, the EoR signal itself is expected to be bumpy in frequency, owing to the patchiness of the physical processes from which it derives. This difference can be exploited in Fourier space, where the foregrounds are confined to large scales, opening up a "window" on small scales through which the signal might be detected.

This is more difficult than it might seem at first glance. One must be able to predict with confidence the level of foreground "noise" at any scale, and also its correlation with other scales, to be able to accurately remove it and yield a reliable estimate of the signal. Previous work on these foreground models have been useful, but rather simplistic -- due to the necessary mathematical complexity, they have been restricted to consider a spread of cosmological galaxies which is essentially uniform (though random) across the sky. It is not a priori clear that this is a valid simplification to make; indeed, the very cosmological perturbations that gave rise to the signal we expect are those that produced the distribution of galaxies that now obscure it. Could the spatial structure of these sources provide an extra complication that requires analysis?

In a paper published in the Astrophysical Journal in July 2017, we set out to extend the mathematical formalism which specifies the foreground contamination within realistic observations. We developed several extensions, but the most important was to describe the impact of the extra-galactic foregrounds when they are spatially clustered according to the background cosmology.

We highlighted a couple of novel results. Firstly, including spatial clustering adds a single extra term to the previous calculations, which tends to boost the predicted noise on large on-sky scales. The magnitude of this effect can be anywhere from insignificant to overwhelming, depending on the precise layout of the galaxies and their brightness distribution. In general, populations with a higher relative abundance of faint sources tend to exacerbate the relative effect of the clustering, which suggests that taking this into account may be crucial for future instruments such as the Square Kilometre Array.

Most notably, we found that for certain choices of the foreground parameters -- which are quite uncertain due to a scarcity of low-frequency observations -- a failure to account for the spatial clustering as derived in this work would lead to a false detection. That is, due to the mismatch between expected and actual noise, certain measurements would appear to be detections of the EoR signal when in fact they were attributable to un-suppressed foregrounds.

The caveat to this work is that it compares the bias involved in analyses in which the contamination of our own Galaxy are neglected. In further work prepared for the Proceedings of the International Astronomical Union Symposium 333, we consider a hypothetical analysis which included removal of the Galactic foregrounds, plus the extragalactic sources that we have already described. It turns out the Galactic component shadows the structure of the extra-galactic sources to a large degree, and that current methods to deal with the Galaxy will likely deal with the greater portion of the extant cosmological sources as a mere side-effect. This has the potential to greatly reduce the necessity of performing the more intensive calculations of our extended framework, which is a positive result for the field.

As the precise distribution of the foreground sources becomes more clear as deeper observations at low frequencies are performed, the actual extent of these effects will be constrained, and our formalism will provide the necessary means to account for it.

A census of radio pulsars with the Murchison Widefield Array

Mengyao Xue, Ramesh Bhat, Steven Tremblay, Charlotte Sobey

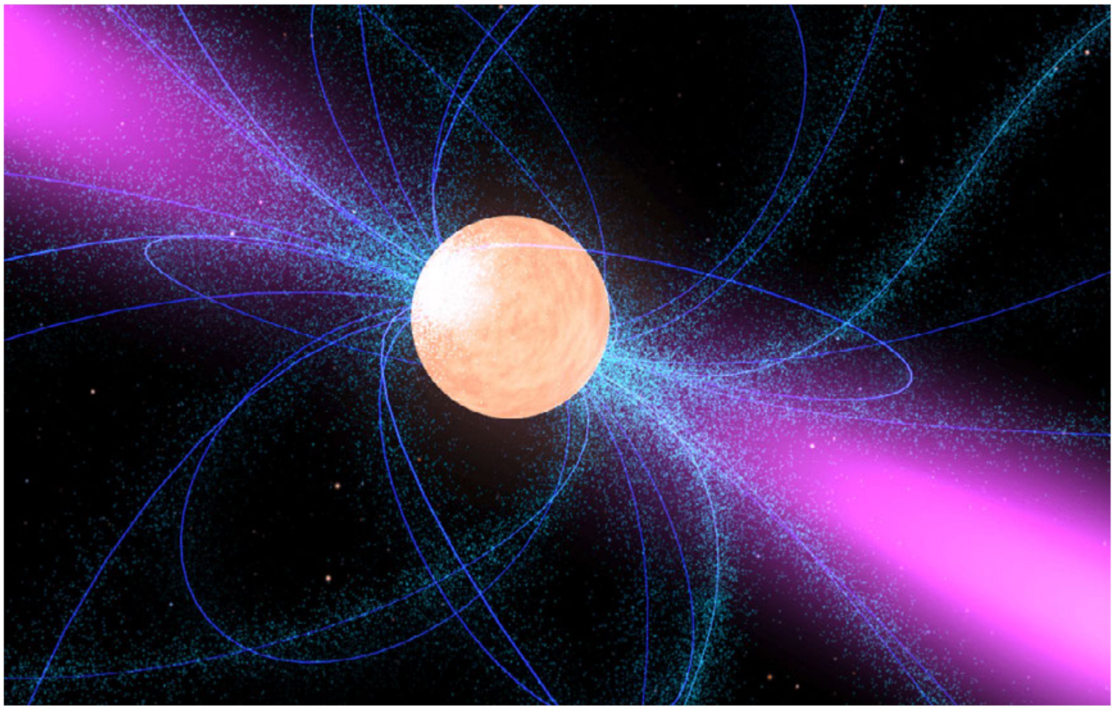


Image Credit: NASA

2017 was a memorable year for pulsar astronomy. It was the 50th anniversary of the discovery of pulsars by Dame Jocelyn Bell Burnell, who gave the opening address to an International Astronomical Union symposium focussed on "The next 50 years of pulsar astrophysics" at Jodrell Bank Observatory, UK, in September. Closer to home, we successfully detected over 50 pulsars using the Murchison Widefield Array (MWA).

Pulsars are small, rapidly-rotating, highly-magnetised stars, consisting of nuclear matter from the dense core of a massive progenitor after it has gone supernova. Thought of as 'cosmic lighthouses', pulsars create beams of radio waves as they rotate, and when these beams point towards Earth we can detect them as pulses. Pulsars provide a wealth of information about neutron star and plasma physics, and the clock-like stability of their lighthouse beams can be used to test general relativity, and to probe the structure and magnetic field of our Galaxy.

Pulsars were originally discovered at a very low radio frequency (81.5 MHz). Subsequent low-frequency observations played an important role in early years of pulsar research. However, much of observational pulsar astronomy has since moved to higher frequencies (above 300 MHz) to alleviate the propagation effects caused by the interstellar medium (ISM) and to reduce interference from the diffuse radio continuum emission from our Galaxy. With the advent of new generation radio telescopes and affordable computing technologies, low-frequency radio astronomy is witnessing a major renaissance, bringing renewed interest in pulsar research at low frequencies. All this will also serve as an important preparatory step toward building the Square Kilometre Array (SKA).

The MWA is now equipped with pulsar capability; it is also the precursor telescope to the low-frequency component of the SKA (SKA-Low), which will be built in Australia. The most distinguishing feature of the MWA is its very large field of view (~450 deg2 at a frequency of 185 MHz), which allows us to detect multiple pulsars during each observation. As a pilot to our eventual goal of conducting a full pulsar census in the southern sky, last year we carried out an initial census using the MWA, at a frequency of 185 MHz.

To capture each pulsar's unique pulse profile (like a 'fingerprint'), we observed them at high-time and high-frequency resolution using the MWA's 'Voltage Capture System' (VCS). We processed 46 individual observing sessions, amounting to 37 hours, taken during the first two years of MWA-VCS operations (2014-2016). These observations covered roughly 17,000 deg2 of the sky -- which corresponds to 55% of the visible sky from the MWA. To efficiently process the data from each observation, we developed a new processing pipeline, the Wide-field Pulsar Pipeline, which automatically attempts to detect all known pulsars positioned within the MWA's tile beam.

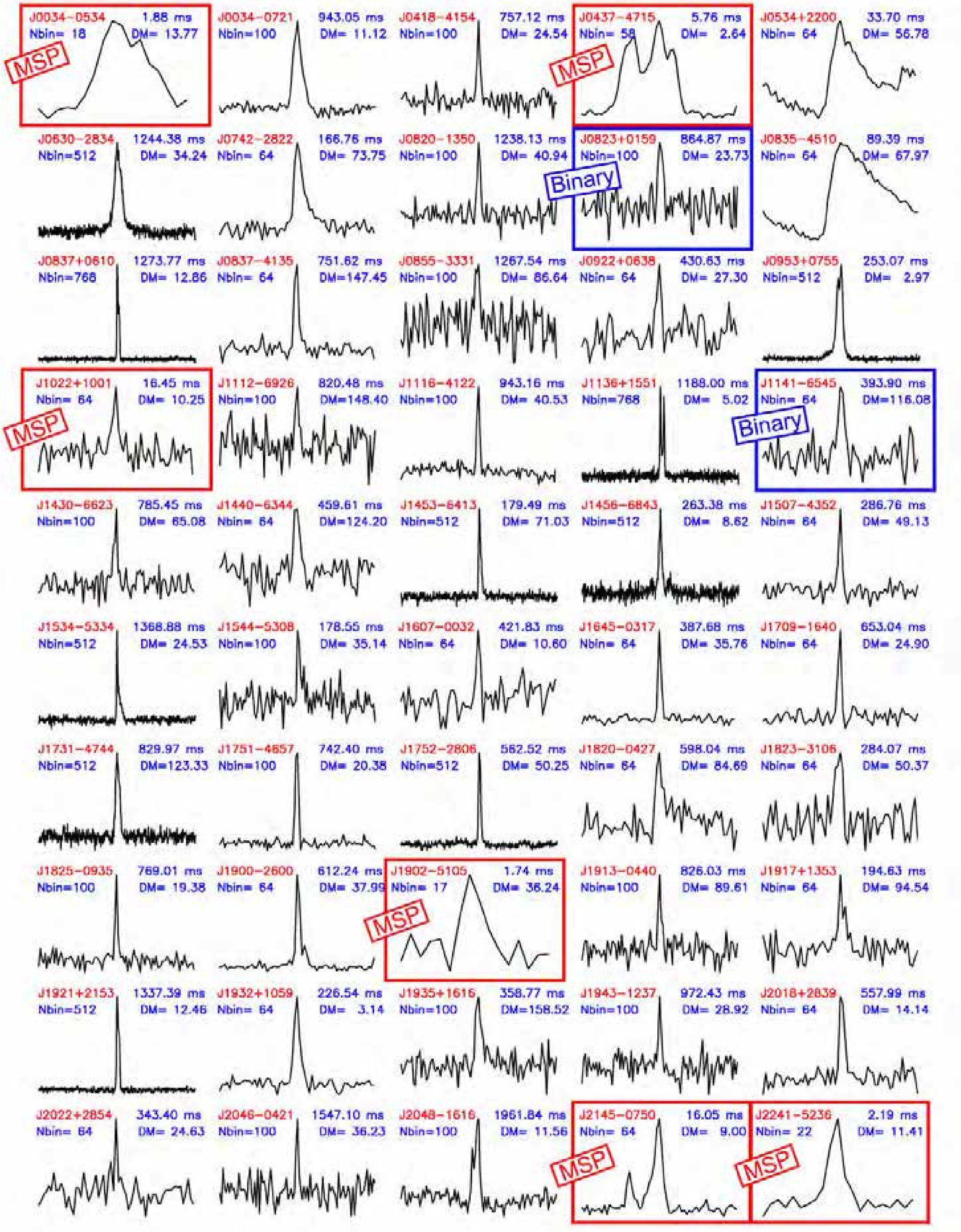
Our analysis led to the detection of over 50 pulsars, including six millisecond pulsars (MSPs). We investigated theoretical pulsar emission models by combining our data with those previously published and studying the pulsars' pulse profile evolution across a broad frequency range. For nine southern pulsars (south of -28 degrees in declination), we obtained the lowest frequency detections, extending the frequency range available for those by a factor of up to seven.

We also detected two pulsars in binary systems that have longer rotational periods than MSPs. These are: J1141-6545, a relatively young pulsar in an eccentric 4.74-hour orbit, and a powerful laboratory for testing the theories of gravity; and J0823+0159, a recycled pulsar in a wide-orbit (1232-day period) binary system, with a relatively low-mass companion. These detections vividly demonstrate the MWA's ability to detect a diverse range of pulsars.

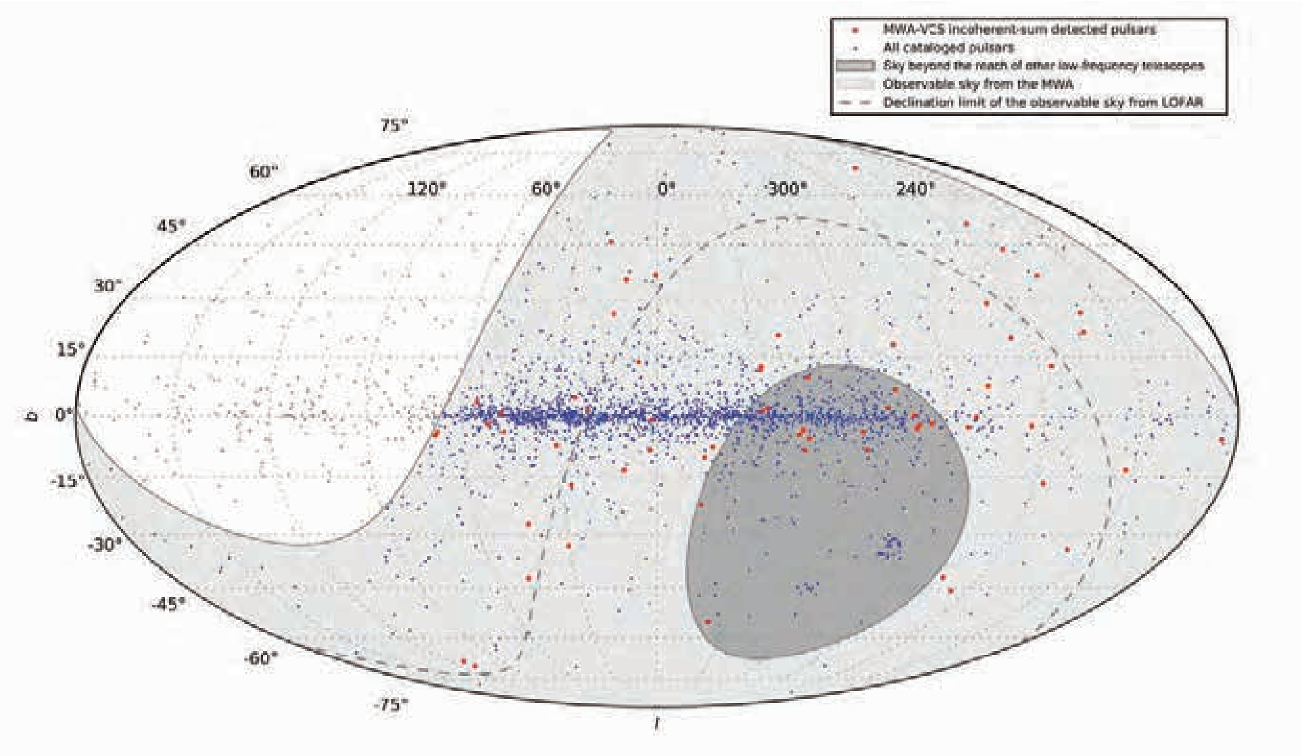
This initial pulsar census is just 'the tip of the iceberg' as our analysis utilised only a few to 10 per cent of the full sensitivity achievable using the MWA. The coherent addition of signals from 128 tiles can potentially yield 10 times improvement in sensitivity. This capability is now being routinely used for pulsar science, and it is very promising for detecting hundreds of pulsars using the MWA.

Using the knowledge gained from this MWA pulsar census together with related simulation studies we performed, we forecast that Phase 1 of SKA-Low will potentially detect around 9400 pulsars – i.e. more than three times increase in the currently known pulsar population. This result is also consistent with other recent predictions, e.g. SKA science case "A Cosmic Census of Radio Pulsars with the SKA" in "Advancing Astrophysics with the Square Kilometre Array." In the coming years, we will exploit the unique advantages of the MWA to embark on an in-depth study: a full-sky pulsar census in high time resolution and full polarimetry. Besides numerous useful insights into pulsar emission physics and ISM properties, this will also serve as an important reference for pulsar science with SKA-Low.

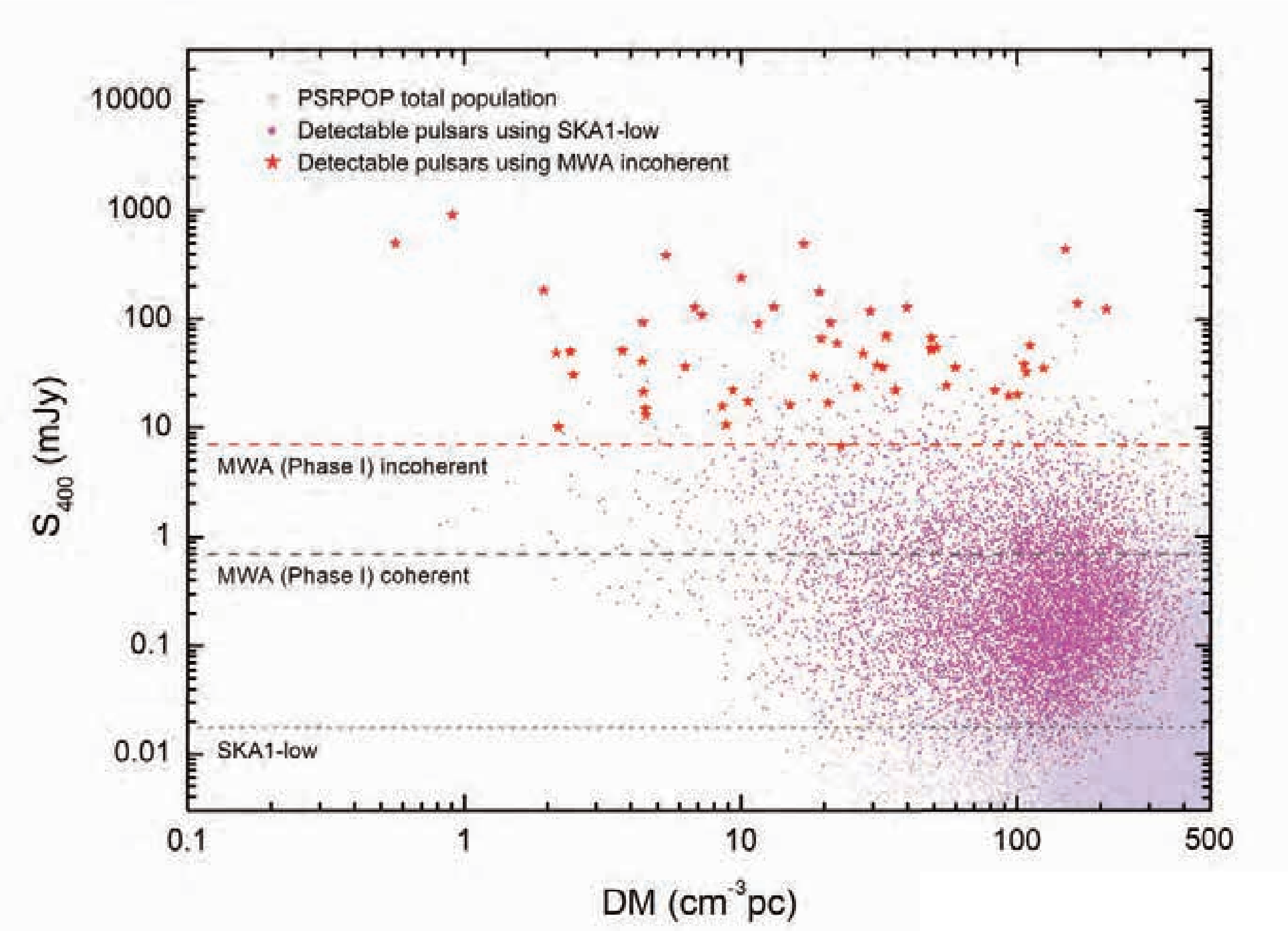
Reference: Xue M., Bhat N., Tremblay S., et al., 2017, PASA, 34, e070



Gallery of pulse profiles for 50 pulsars detected in the MWA pulsar census at 185 MHz. The millisecond pulsars (MSPs) and pulsars in binary systems are highlighted.



The distribution of pulsars detected in the MWA pulsar census at 185 MHz (red dots) and all of the known pulsars (blue dots). The range of observable sky (light grey) and exclusive low-frequency sky (dark grey) for the MWA is also shown.



An example simulated pulsar population (grey dots) and predicted pulsar detections using the same MWA setup that we used for the pulsar census (red stars) and the expected performance of SKA1-Low (magenta dots). The expected sensitivity limits of the MWA and SKA1-Low are also shown (dashed lines). The x and y axes are flux density at 400 MHz and dispersion measure.

Giant radio pulse emission from pulsars at megahertz to gigahertz frequencies

Bradley Meyers, Steven Tremblay,
Ramesh Bhat, Ryan Shannon

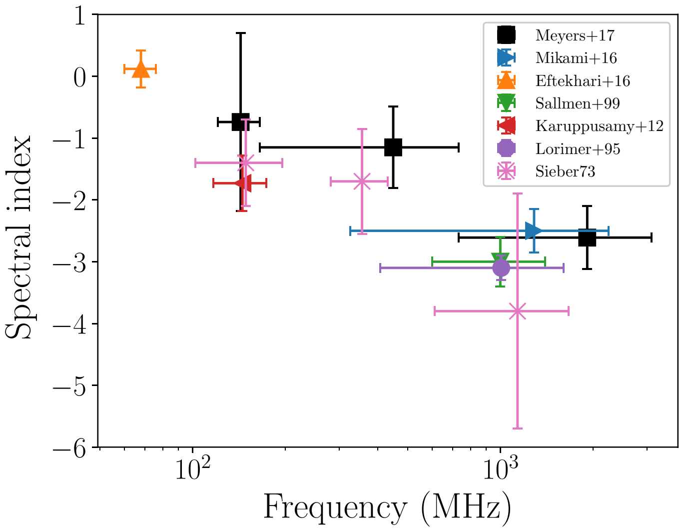
The Crab nebula as a composite of radio (VLA), infrared (Spitzer), optical (Hubble) and X-ray (XMM Newton and Chandra) data. The Crab pulsar (PSR J0534+2200) resides in the centre of this nebula and emits extremely bright and very short duration "giant pulses". Image Credit: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires), 2017.

Pulsars emit beams of radiation along their magnetic axes, which we observe as a series of periodic bursts (or pulses) each time a beam sweeps through our line-of-sight. The young and energetic pulsar that resides in the Crab Nebula (PSR J0534+2200) has been of special interest to both observers and theorists alike due to a curious emission characteristic. This pulsar spins at a rate of approximately 30 times per second and is located at a distance of 6000 light-years from Earth. Unlike the vast majority of known pulsars, it was discovered through its emission of "giant radio pulses" — extremely bright, very short-duration bursts, with energetics many orders of magnitude higher than those of the regular pulses. The physical mechanisms that give rise to the emission of such giant pulses, and numerous other pulsar radio emission phenomena, remain unknown. Giant pulses thus provide excellent opportunities to explore how pulsars emit in the first place, and to probe the microphysics occurring within the relativistic plasmas surrounding the neutron star.

In general, the strength of a pulsar's emission (i.e. brightness or flux density) rapidly declines with increasing frequency. This behaviour can be characterised in terms of its spectrum, which describes how much energy is produced as a function of frequency. For regular pulsar emission, this generally follows a power-law, and in some cases can exhibit either a break or turnover at frequencies below 300 MHz. Similar characterisation for giant pulses has been inherently difficult because of their sporadic nature, and the complexity stemming from the fact that emission observed at one frequency does not necessarily imply that the same type of emission will be seen at another.

To attack this problem, we leveraged the wide frequency coverage that is now achievable via simultaneous use of the Murchison Widefield Array (MWA) and the CSIRO Parkes radio telescope. We performed such a study on the Crab pulsar, sampling frequencies from 100 MHz (MWA) to 4 GHz (Parkes). We detected hundreds of giant pulses in our observations, and we cross matched each of them between five well-separated frequency bands across the 100 MHz to 4 GHz range spanned by our data. The number of detected giant pulses ranged from around 6000 (at 732 MHz) to nearly 100 at lower frequencies (120.96 MHz). The frequency-dependent detection rate is likely due to differences in sensitivities and from propagation effects of the interstellar medium (particularly in the MWA range) for different frequency bands. Our observations revealed seven giant pulses coincident at all five frequencies of our observations. From this we were able to examine how the properties of an individual instance of giant pulse emission behaves as a function of frequency. In addition, we also computed spectral index distributions for all giant pulses matched between adjacent pairs of frequency bands to examine how the average spectral index is changing.
Our analysis showed at frequencies above 300 MHz the flux density (or energy) of giant pulses scales steeply with frequency. However, at lower frequencies, the spectral index flattens. An important implication of this is that giant pulses are not as bright as expected at low radio frequencies. Had this not been the case, we would have detected ~1000 times as many giant pulses than we did in the MWA frequency bands.

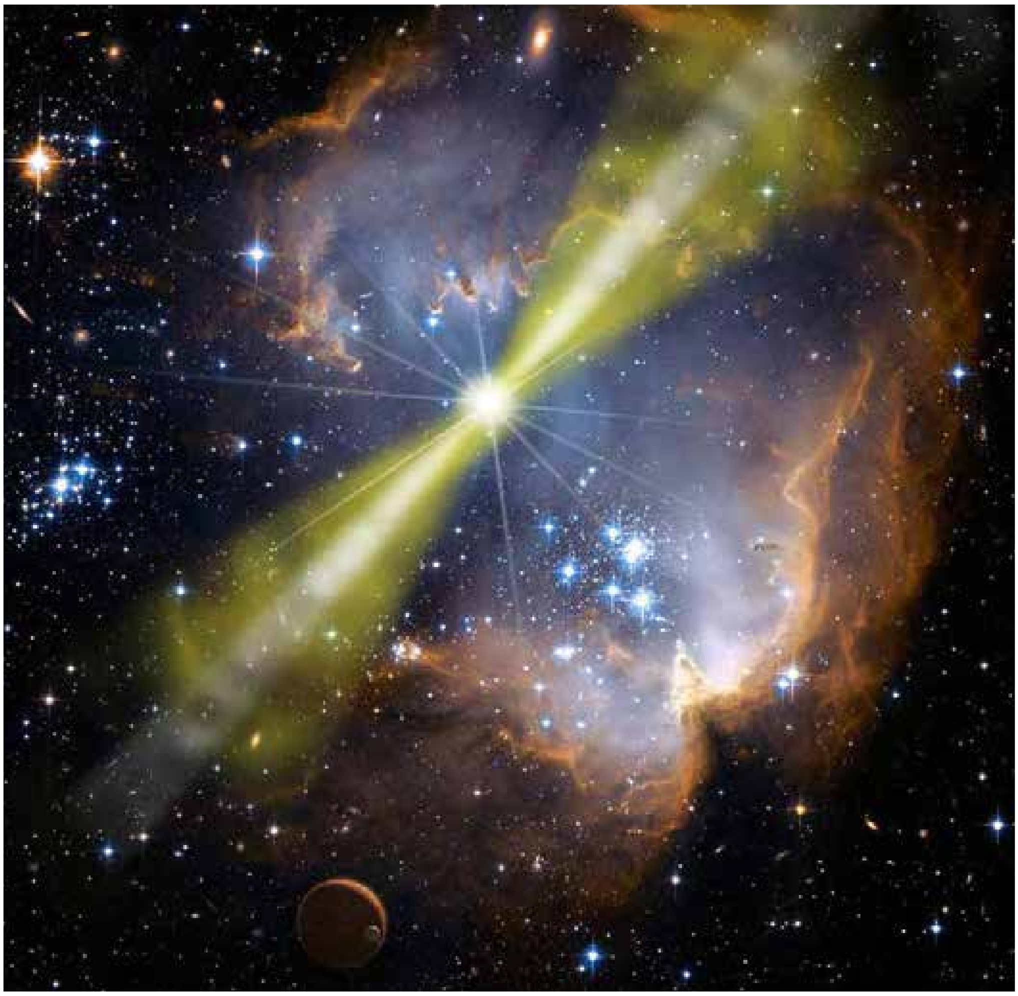
This result opens up several interesting questions. For example: Is this behaviour typical of only the giant pulses from the Crab, or is such a property also seen for other giant-pulse emitting pulsars? Further, what does it mean for the physical processes producing giant pulse emission vis-a-vis pulsar radio emission in general? It makes quite a compelling case for undertaking similar studies of other giant-pulse emitters, and if it holds, may also have implications for the detectability of pulsars in external galaxies (via giant pulses). In order to gain further insights into many of these questions, we intend to undertake a global observing campaign of the Crab pulsar in the coming year, where we will engage a large number of telescopes for a dense sampling across a very large frequency range.



Spectral indices vs. frequency, highlighting the flattening spectrum of Crab giant pulses at low frequencies. The horizontal bars represent the frequency range over which the spectral index was calculated. The vertical bars represent the error in the measurements or the quoted spectral index distribution widths.

Catching the early-time radio emission from gamma-ray bursts using a robotic telescope

Gemma Anderson



An artists illustration of a gamma-ray burst, one of the most energetic events in the Universe that could represent the explosion of a very massive star. Image credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

The Universe is an extremely dynamic place, where explosions or outbursts from weird stars or black holes are constantly occurring. However, few explosions are as powerful as gamma-ray bursts (GRB), which are produced by the collapse of a massive star known as a supernova that leaves behind a black hole. These events are so powerful that the bright gamma-ray emission they emit can be observed from across the Universe. GRBs are detected by dedicated telescopes (satellites) in space, such as the Neil Gehrels Swift Observatory, which are capable of localising these explosions to within a fraction of a degree, in turn providing accurate positions for multiwavelength follow-up observations by ground-based telescopes.

The very first detection of the radio afterglow from a GRB was in 1997 and the following 20 years of discovery have revolutionised our understanding of these energetic events. The detections of such radio afterglows provide an important piece to the GRB puzzle, as the study of their radio radiation allows astronomers to directly probe the amount of energy released, the strength of their associated magnetic fields, and the characteristics of the environment they explode into. However, only about 30% of GRBs have been detected at radio wavelengths. This low detection rate may be due to the rarity of radio telescopes, which means that GRBs may not be observed until several days following their discovery, at which point the radio emission may have faded below detectability, if the event was even observed at all.

In order to improve the GRB radio afterglow detection rate, it is necessary to observe many more events as quickly as possible following their discovery. In order to do this we implemented a robotised observing system on a radio telescope based in the United Kingdom called the Arcminute Microkelvin Imager (AMI). On receiving the position of a new GRB from Swift, this observing system allows AMI to automatically repoint its dishes and begin observing the explosion within minutes of discovery. Such observations allow us to probe the rapidly varying radio afterglow of a GRB before it disappears forever.

Using the AMI robotised system, we triggered rapid follow-up observations of 132 GRBs discovered by Swift. On receiving the alert from this satellite, AMI could be on target within two minutes, automatically scheduling later start times if the source was still below the horizon. Further AMI observations were then manually scheduled for several days following the initial GRB detection.

Through this program, AMI has obtained some of the earliest radio detections of GRBs. Due to its robotised system, AMI observed 39 GRBs within 1 hour of their discovery, providing some of the most stringent early-time upper-limits on their radio brightness. In total, AMI detected the radio afterglows of at least 12 GRBs. Of these 12 GRBs, the radio afterglows of 6 GRBs had not been previously detected by other radio telescopes. The rapid follow-up and survey strategy of the AMI program allowed us to increase the rate of observed radio afterglows from GRBs by 50% within an 18-month period. These results demonstrate the importance of having robotised radio telescopes capable of automatically observing cosmic explosions in order to detect any associated short-lived radio radiation before it fades away forever. Due to the success of this experiment with AMI, robotised observing systems have recently been installed on Australian radio telescopes, including the Murchison Widefield Array (MWA) and the Australia Telescope Compact Array (ATCA). It is envisaged that such experiments will directly test observing strategies for the Square Kilometre Array (SKA).

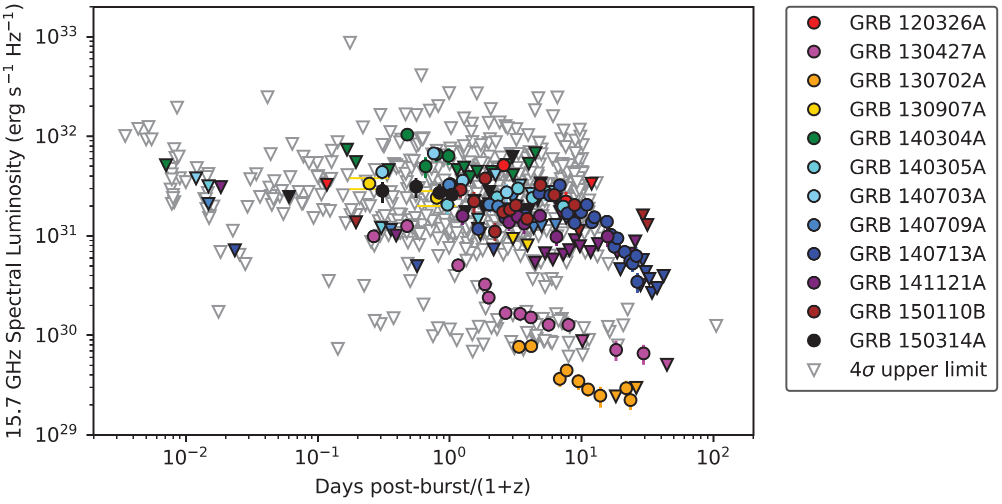
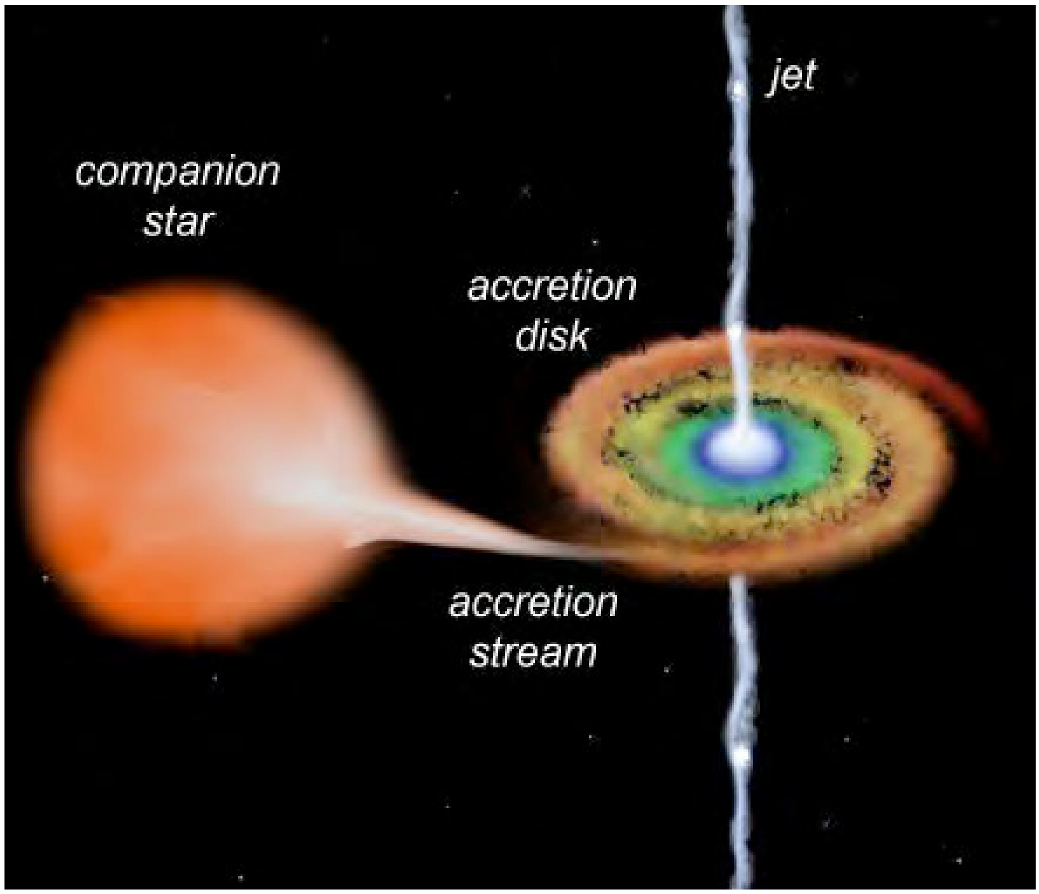


Figure showing the radio luminosity of gamma-ray bursts detected by the Arcminute Microkelvin Imager starting hours after the gamma-ray explosion was discovered. Prompt radio emission was detected for 12 gamma-ray bursts, and upper limits (gray open triangles) for another ~100 systems. Such rapid radio response was possible because of the robotised nature of the Arcminute Microkelvin Imager, and similar strategies are now in place for Austrlian facilities including the Murchison Widefield Array and the Australia Telescope Compact Array.

Jets from accreting neutron stars

Vlad Tudor

For this work, Vlad Tudor was awarded the 2017 O'Connor HDR Publication Prize (2017), which is awarded to a Higher Degree Research student enrolled in the Department of Physics, Astronomy and Medical Radiation Sciences, who published an outstanding paper in 2017 in a high quality, peer reviewed journal for which the recipient was the principal contributor to the research.



An artist's impression of an X-ray binary, where a neutron star or black hole accretes material from an orbiting star. The infalling material emits large amounts of X-ray radiation. Some systems also launch relativistic jets that emit strong amounts of radio waves. This work compares the radiation emitted by infalling vs. outflowing material for the most complete sample yet of neutron star and black hole X-ray binaries. Image Credit: NASA/Chandra/M.Weis

When massive stars end their lives through supernova explosions, they leave behind compact remnants, either neutron stars or black holes. Neutron stars are the densest objects (containing ordinary matter) in the Universe, usually containing 1.5 times more mass than our Sun crammed into a space about the size of small city (one teaspoon of a neutron star would weigh 10 million tons!) Black holes are completely collapsed by their own gravity, containing at least 3-5 times more mass than our Sun crammed into a single infinitesimal point. Both types of systems allow us to test physics under extreme gravity.

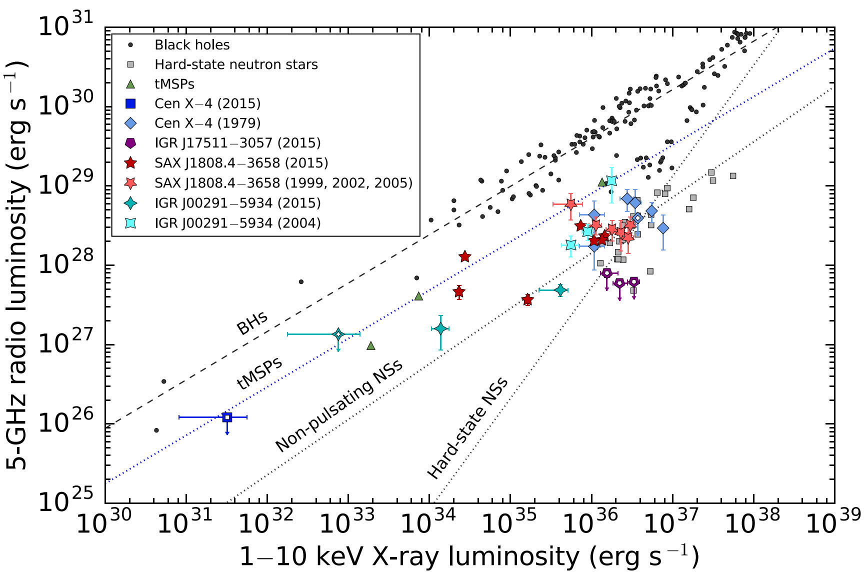
If a black hole or neutron star is orbited by an ordinary star, then the compact object can pull off the outer layers of the orbiting star, if the size of the orbit is small enough. As material falls toward the compact object, it will heat up to high energies and emit intense amounts of X-ray radiation. We therefore refer to these types of accreting objects as “X-ray binaries.” Often, not all of the material falling toward the compact object hits the surface of the neutron star (or flows through the black hole event horizon). Instead, some amount of material is channelled into collimated jets of material that get shot away from the black at nearly the speed of light. These jets shine brightly at radio frequencies. Thus, by observing X-ray binaries with different telescopes across the electromagnetic spectrum, we are able to gain a complete picture of how material flows toward the compact object (probed by X-ray telescopes) and how material is shot away from the compact object (probed by radio telescopes).

How these jets get launched is still an outstanding problem. One way to gain insight is through comparing the jets launched by different types of accreting objects. Key differences between neutron stars and black holes are that black holes lack a hard surface, and black holes are more massive. These differences can manifest themselves into different radiative signatures. Obtaining requisite observations to compare neutron star vs black hole X-ray binaries is challenging though, because it requires coordinating radio and X-ray telescopes to simultaneously observe the same object, which can place a burden on already scarce resources. Such coordination has been achieved for a sizeable number of black hole X-ray binaries, but coverage of neutron star X-ray binaries is lagging behind.

In 2017, we published a paper that simultaneously observed four different neutron star X-ray binaries. We used data largely from the Karl G. Jansky Very Large Array in the radio, and the Neil Gehrels Swift Observatory in the X-ray. Comparing their joint radio and X-ray observations to other neutron star X-ray binaries and black holes, we find that neutron star jets tend to always be less powerful in the radio waveband than black holes (at a fixed X-ray luminosity). At the time, this work represented the most complete analysis combining both neutron star and black holes in a single study.

Several black hole X-ray binaries display predictable patterns between variations in their radio and X-ray emission. However, for our neutron star X-ray binary with the best data coverage, we found significant radio flaring activity, with non-trivial radio/X-ray correlations (if any). We also modelled whether the presence of a strong magnetic field in some neutron stars (which is related to the neutron star surface, i.e., a phenomenon not relevant for black holes) could explain periods of enhanced radio emission. We found that model to be inconsistent with the data, suggesting that other properties of neutron stars vs. black holes are responsible for their differences in relative radio to X-ray emission.

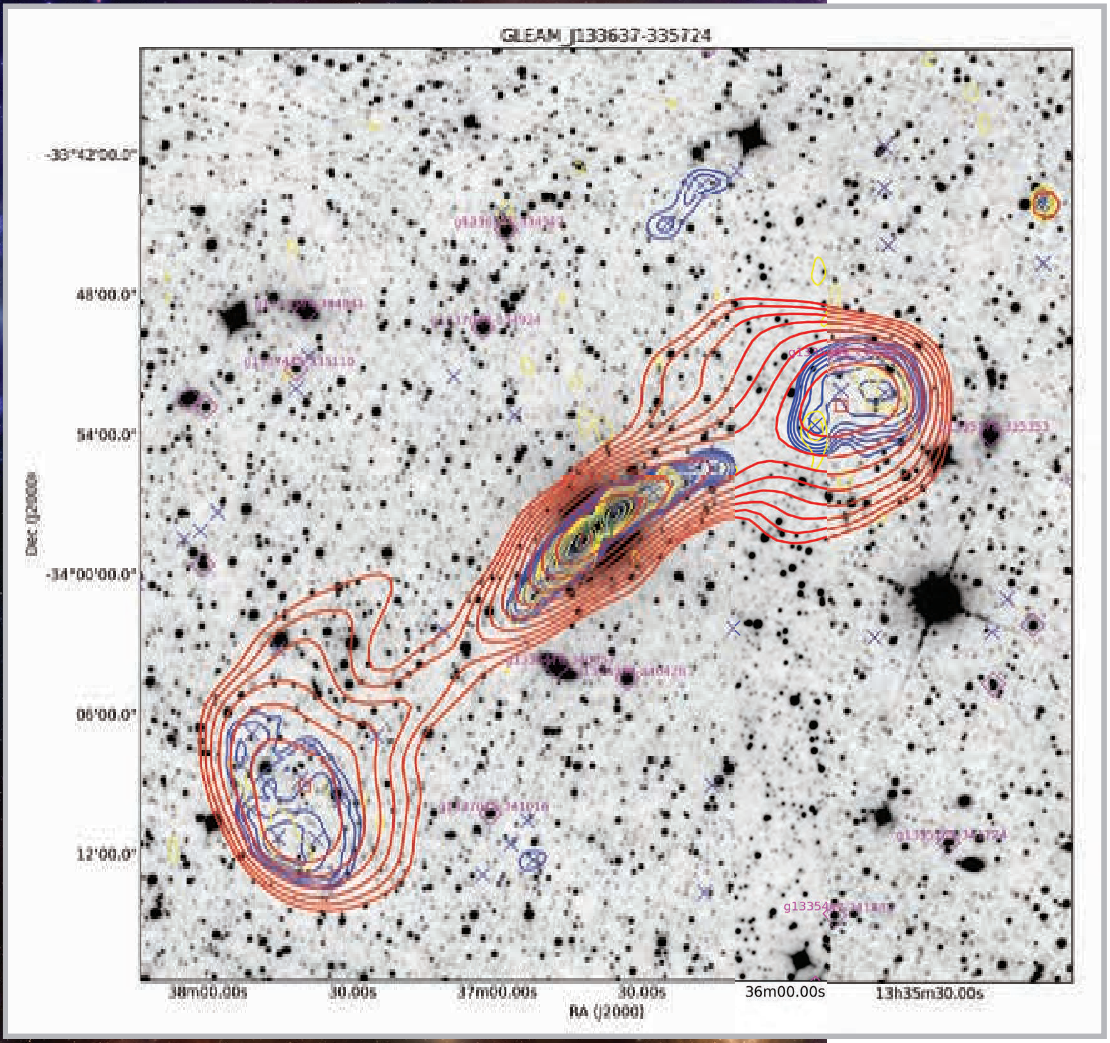
Ultimately, continuation of this work will allow us to pinpoint the fundamental parameters that allow compact objects to launch jets, and to understand if we can use the relative amounts of radio to X-ray emission as a diagnostic tool to classify the type of accreting compact object in X-ray binaries.



Comparison or radio luminosities (from jets) vs. X-ray luminosities (from the infalling material) for neutron and black hole X-ray binaries. The colour symbols represent systems studied in detail in this work, and the diagonal lines roughly delineate where we find black holes (BHs) and subclasses of neutron stars. We generally find that neutron stars have less powerful radio jets than black holes, and neutron stars also display a larger dispersion in their radio to X-ray luminosity ratios.

The most powerful radio sources in the southern hemisphere

Sarah White



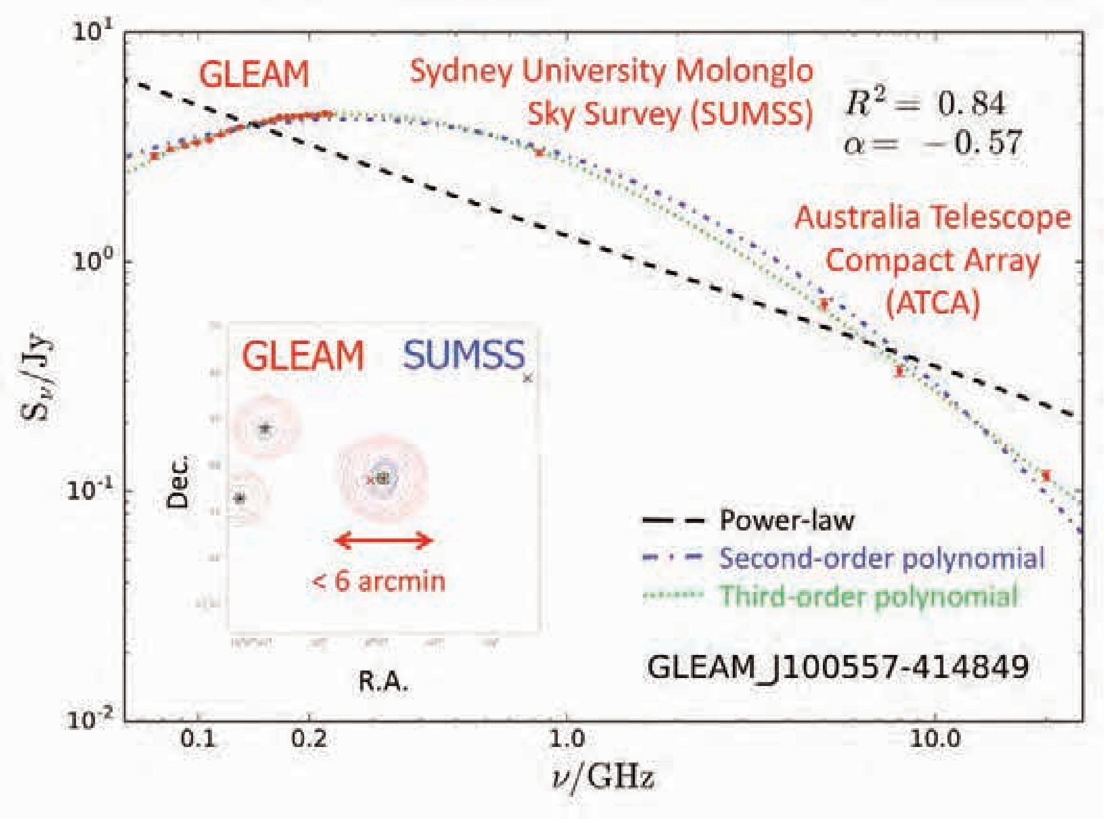
An overlay image of the active galaxy, IC 4296, with the black/grey dots representing the mid-infrared emission from distant galaxies and nearby stars. Radio-brightness contours based on Very Large Array data (blue) and Giant Metrewave Radio Telescope data (yellow) reveal the inner jets and outer lobes, but only the MWA data (red) is sensitive to the extended, diffuse emission (White et al. in prep.). When we measure the apparent size, and take into account the distance to this radio source, we find that its physical size is 600 kpc (i.e. 20 times the size of the Milky Way).

A supermassive black-hole is believed to reside at the centre of every galaxy, and some of these launch incredibly powerful jets that influence how the galaxy evolves. However, we still don't understand whether such behaviour is an intrinsic property of these active galaxies, or if it is strongly influenced by the environment. As a result, these objects are at the heart of a key "nature versus nurture" debate in galaxy-evolution research.

To investigate, we need a larger sample of powerful, active galaxies than is currently used for such studies. This is so that we can test whether a particular property depends upon the galaxy's surroundings. We also want to be sure that we have a complete, representative sample that isn't biased towards active galaxies with jets pointing approximately towards us. (When this is the case, relativistic effects lead to the observed brightness of the jet's radio emission being given an extra 'boost'. This then needs to be corrected for, if we wish to determine the 'true' power of the active galaxy.) For this reason, it is best to select powerful, active galaxies at low radio-frequencies, where the radio emission is dominated by extended 'lobes' that accompany the jets. (This lobe emission is not affected by 'boosting', and so the brightest active-galaxies at low frequencies have a random orientation with respect to our line of sight.)

This is where the Murchison Widefield Array (MWA) comes in. It has been used to observe the entire southern sky at low frequencies, from 72 MHz to 231 MHz. The resulting GaLactic and Extragalactic All-sky MWA (GLEAM) catalogue contains over 300,000 detections, but we focus on those that are associated with about 1,800 of the brightest radio-sources in the survey. Being brighter than 4 Janskys at 151 MHz, we refer to this collection of objects as the 'GLEAM 4-Jy Sample', the vast majority of which are active galaxies. This is over ten times as many active galaxies as those belonging to the well-known '3CRR' (revised Third Cambridge Catalogue of Radio Sources) sample in the northern hemisphere, which was also selected at low frequencies.

The first step is to visually inspect each source, one by one, in order to record the morphology of the object – does it look compact in shape, or are there two jets/lobes present? For this we exploit other radio surveys over the southern hemisphere that have better spatial resolution than the MWA. If the object is very extended in shape, then it may have multiple detections in GLEAM that need to be collected together. Doing this classification manually allows us to establish a reliable base for testing against the results of automated procedures, since we will need to develop the latter in order to deal with the huge number of galaxies detected with the Square Kilometre Array (SKA).



An example of a broadband radio spectrum, which shows how the radio brightness of a particular source in the GLEAM 4-Jy Sample varies with frequency. Previously it has been assumed that radio emission follows a 'power-law' description, but by combining measurements taken over a wide range in frequencies, we demonstrate that spectral curvature needs to be taken into account (White et al. in prep.).

Another important part of our visual inspection is to identify the galaxy that is emitting the radio emission. This is done by overlaying the radio-brightness contours from different surveys onto mid-infrared images. The mid-infrared emission is due to hot dust associated with the galaxy, which (for our sample) is heated by the thermal energy released as material falls onto the supermassive black hole at the centre. Since the mid-infrared data provides more-accurate positions than the current radio data, this makes it much easier to identify sources from the GLEAM 4-Jy Sample in datasets at other wavelengths. Doing so is crucial for galaxy-evolution studies because emission from different parts of the electromagnetic spectrum provides information about different physical processes. As a result, we can investigate, for example, whether the presence of radio jets leads to star formation in the host galaxy being enhanced or suppressed.

Data at optical wavelengths is especially important because we use this information to calculate the distance of a radio source, based on how much its optical emission-lines appear to have been ‘shifted’. This quantity is referred to as the ‘redshift’ of the object. The 6-degree-Field Galaxy Survey is an optical survey over the entire southern hemisphere, but its limited sensitivity means that it provides redshifts for only ~100 sources in our sample. Therefore, we eagerly await observations from the Taipan Galaxy Survey team, who will take optical observations of the entire GLEAM 4-Jy Sample using the UK Schmidt Telescope. If we find that some radio sources are still too distant (and therefore too faint) to be detected, we will need to use a more-sensitive optical telescope (with a larger area for collecting photons).

Finally, a great strength of the GLEAM catalogue is that it provides measurements at 20 radio frequencies. This allows us to more-accurately study the radio spectrum (i.e. how the radio brightness of a source varies with frequency), and so distinguish between different processes taking place. For the GLEAM 4-Jy Sample we have supplemented these measurements with those at frequencies as high as 20 GHz, obtained using the Australia Telescope Compact Array. We find that some sources have a spectrum that curves downwards at low frequencies, which suggests that radio photons are being absorbed by neutral gas surrounding the active galaxy. In other cases, the radio spectrum curves upwards at high frequencies, which may be due to material falling onto the black hole during well-separated periods in time. Both of these scenarios are interesting because they tell us about how much gas is present -- a crucial factor for determining how the galaxy evolves -- and the timescale over which jets switch ‘on’ and ‘off’.

CIRA

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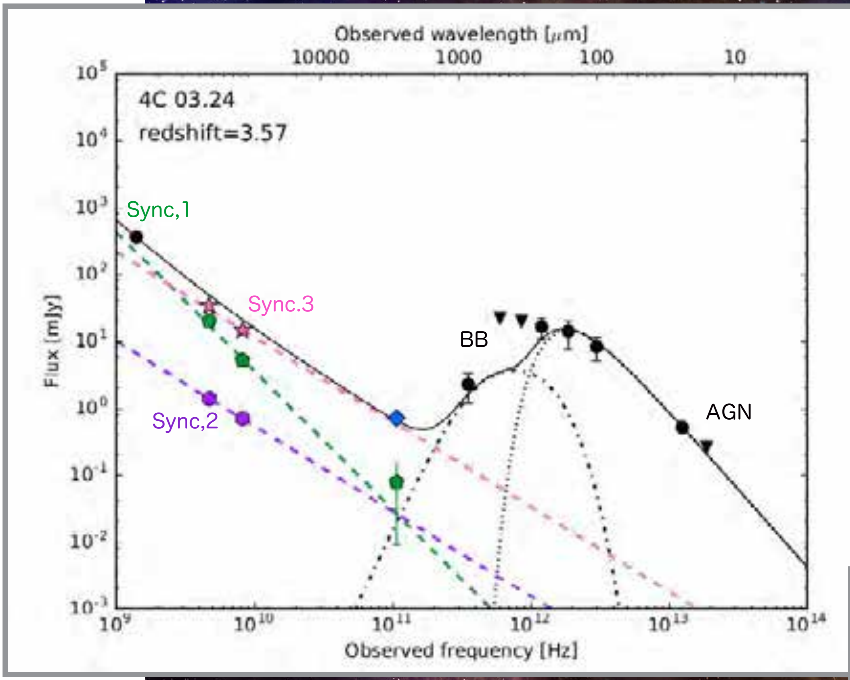
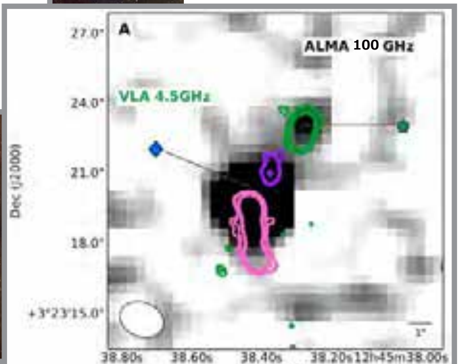
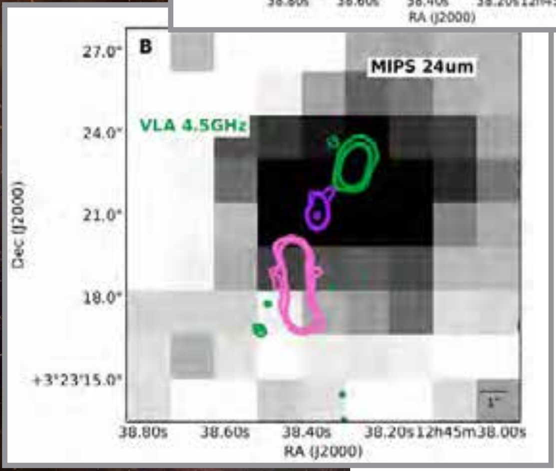
RADIO ASTRONOMY

Supermassive black hole feedback caught in action in powerful radio galaxies

Guillaume Drouart, Theresa Falkendal, Nick Seymour







Spectral energy distribution and corresponding images for a galaxy observed when the Universe was under two billions years old. The colours in the spectral energy distribution correspond to emission arising from the areas noted by similarly coloured contours in the images. The black points in the spectral energy distribution represent total emission from all components (which were previously unresolved in older observations before our study).

Every large galaxy harbours a supermassive black hole at its centre, with the most massive black holes living in the most massive galaxies. When matter accretes onto a supermassive black hole, gravitational energy from the infalling material is liberated into light, which causes the supermassive black hole to 'shine' as an active galactic nucleus (AGN).

The AGN contains several different components, including an accretion disk of infalling material, high-energy populations of electrons residing very close to the black hole, and large-scale tori of dust that are heated by the inner regions of the AGN. Sometimes large-scale jets are also produced that carry away particles at relativistic speeds to very large distances from the black hole. Each component radiates energy with a specific signature across the electromagnetic spectrum. Incredibly, the total amount of energy released by the AGN can exceed the total gravitational energy binding the stars of the host galaxy, such that it is possible that AGN can affect the evolution of the galaxies in which they live.

Of great interest are the most massive galaxies in the local Universe. Crucial questions include: how do the most massive galaxies form and evolve? What roles does the supermassive black hole play in their evolution? We aim to answer these questions not by observing local massive galaxies directly, but rather by looking at distant galaxies that represent their progenitors at an epoch when the Universe was about six times younger. Some fraction of the galaxy's gas and dust will be used to form new stars, while a different amount of gas and dust will be funneled toward the centre to fuel black hole activity. The energy released by the AGN can then 'feedback' with the host galaxy, thereby influencing how the rest of the galaxy forms new stars.

Distant powerful radio galaxies have been identified as the progenitors of the local massive galaxies of interest. By focusing on AGN with a particular orientation in the plane of the sky, we can simultaneously study both the supermassive black hole and the host galaxy: the dusty torus acts like a natural coronagraph, blocking a significant amount of ultraviolet/optical radiation from the innermost part of the AGN.

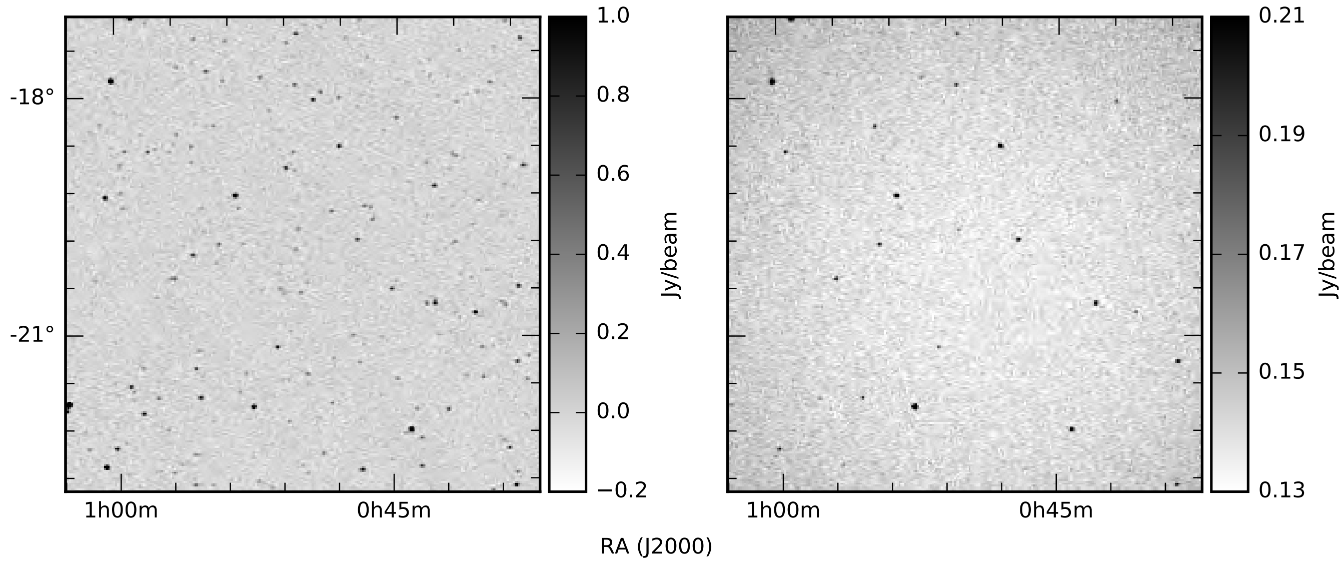
In the past decades, several teams of astronomers have collected data from ground-based and space-based facilities to better understand black hole feedback. However, limited spatial resolution in the sub-millimetre waveband was a big limitation for estimating the relative contributions from different components. The advent of the new Atacama Large Millimeter/submillimeter Array (ALMA) telescope allows to reach an unprecedented amount of detail in understanding the relative contributions from the AGN and from stars. Recently, our team combined previous data from the radio through infrared wavebands (using ground- and space-based telescopes) with new high-resolution ALMA observations in order to build a complete picture of the spectral energy distribution of the brightest radio sources in the Universe.

The drastic increase of spatial resolution from ALMA allows us to examine powerful AGN and their host galaxies in finer detail than ever before. However, with that finer resolution comes new challenges in fitting the broadband light emission. To overcome these challenges, our team developed a new fitting procedure using a Bayesian framework along with a recent MCMC algorithm (named Mr-Moose) to handle the complexity of having a large variety of data resolution and sensitivity across a large wavelength range. Thanks to this code, we were able to disentangle the contribution from the torus, from the stars, and from the supermassive black hole jets.

Our study led to some unexpected results. First, for a significant fraction of sources, most of the newly formed stars are not in the host galaxy but rather in a neighboring galaxy. This indicates that the average star formation rate in these distant radio galaxies is lower than their non-active counterparts. The direct implication is that efficient mechanisms (in the form of feedback) redistribute the energy from the AGN to the surrounding gas. Interestingly, a similar quenching effect (suppressing the formation of new stars) is necessary in cosmological simulations to reproduce observations of our Universe at large scales. While hints of this type of feedback has been observed in recent years, this is the first time that it appears with such clarity on a specific sample of galaxies. Second, synchrotron emission that originates from accelerated electrons in jets is at a much higher level than expected. This particular feature is puzzling as the sources from this sample were selected because we did not think that they would possess this feature. Some interpretations include more recent accretion activity onto the black hole or possibly a denser environment. This particular point will be under investigation in future papers, and it could provide valuable information on the evolution timescale of the accretion discs in these AGN.

Interplanetary scintillation with the Murchison Widefield Array: how to make a 400 km wide telescope

Rajan Chhetri, John Morgan,
J-P Macquart, Ron Ekers



The image on the left shows all objects detectable with the MWA at 162 MHz while the image on the right, produced using our technique, shows only objects that are smaller than 1 arcsecond. Our technique makes identifying compact objects very efficient (published in: Chhetri et al. 2018).

At low radio frequencies (a few hundred megahertz), the Universe is dominated by objects that can span up to millions of light years across. Known as 'radio galaxies', these very extended objects are produced by supermassive black holes (SMBHs) at the centres of galaxies. These SMBHs occupy volumes that are millions of times smaller than the radio galaxies themselves. Understanding the relationship between these very small central regions (known as active galactic nuclei) and their extended radio galaxies will help us to understand the important question of how these powerful objects evolve.

Surveys covering large areas of the sky such as the GLEAM survey, made with the Murchison Widefield Array (MWA), have given us an excellent understanding of the large scale properties of radio galaxies at low radio frequencies. However, at these low frequencies, there are no large surveys that have probed the compact structures in radio galaxies. To do so would require telescopes with a high angular resolution capability (better than 1 arcsecond, 1/3600th of a degree). Currently, achieving high angular resolution is done using a technique known as Very Long Baseline Interferometry (VLBI), where telescopes thousands of kilometres apart are combined to act as a single telescope. However, these telescopes can only observe a handful of objects at a time. Therefore, to examine a large number of objects (e.g., over 300,000 have been detected within the GLEAM survey) for compact components would require a vastly more efficient technique. This has resulted in a gap in knowledge between the large and small scales of radio galaxies. This gap will only be compounded as the very sensitive next generation radio telescopes, the Square Kilometre Array (SKA), will still be limited by angular resolution capabilities at low frequencies. We need a solution that very efficiently identifies large numbers of compact sources very rapidly from large parts of the sky.

At CIRA we have developed an effective solution to this challenge. Our technique is based on a well studied phenomenon at radio wavelengths, where objects that appear smaller than a critical angle in the sky scintillate, similar to the way in which stars "twinkle" in the night sky. This scintillation is the result of intensity variations that arise when waves from these distant objects pass through the solar wind. Only objects smaller than 1 arcsecond show this interplanetary scintillation (IPS). To reach this angular resolution capability with the MWA would require it to be expanded to over 400 km in width.

The MWA can image a large area of the sky at a rapid cadence of 0.5 seconds. This provides the capability to simultaneously observe fluctuations in intensity for large numbers of objects. To make this step even more efficient, we take measurements of the fluctuations and image them using a special imaging step. Only those objects that show IPS are present in the resulting image, making the identification process simple and extremely fast. In our recent papers, we identified approximately 300 sources that show IPS from over 2500 sources in the field using a 5 minute observation with the MWA.

The excellent frequency coverage of the GLEAM survey allows us to study the trends in spectra that provide important information we can use to classify different types of objects. The central cores of radio galaxies emit approximately equal energy across wide frequency bands (flat-spectrum sources), while the hot spots (places where the matter transported outwards from the SMBH by jets meets the intergalactic medium) show progressively less energy with the rise in frequency (steep-spectrum). An important class of objects are those that show a peak in their spectra. These peaked spectrum sources have been understood to be in the early stages of the evolutionary sequence of radio galaxies, with sizes in the range below a few tens of thousands of light years. This linear size means that they are compact to IPS scales, hence they scintillate strongly.

Our study has shown that the low radio frequency compact source population is dominated by these peaked spectrum sources. When these peaked sources evolve in linear sizes their peaks are expected to move to lower frequencies. When the peak moves below the observed frequencies, their spectra become inseparable from those of the extended lobes. Interestingly, this shifting of the peak also happens when the object is at extremely large distances (high redshifts). By using angular size information gained from IPS we can clearly separate compact objects from the extended lobes, and we can efficiently identify objects that may be at high redshifts and/or at a different evolutionary stage. Objects at very high redshifts are signposts that can be used to understand the environment in the early Universe, as well as to provide information about how galaxies have evolved across cosmic time. Thus, they are considered very important findings. The compact objects that we identify also play an important practical role -- that of calibrators for current and future low frequency telescopes.

The above are only select results obtained from two five-minute observations with the MWA. We have only barely scratched the surface of potential scientific discoveries, and we are currently processing data to cover a large part of the sky. Our objective is to obtain information complementary to current and future large surveys to study the demographics and evolution of radio galaxies with large statistics. Our further aim is to advance this new technique, developed at CIRA, to be implemented with future large telescopes like the SKA.

An improved low-frequency view of the Galactic Centre

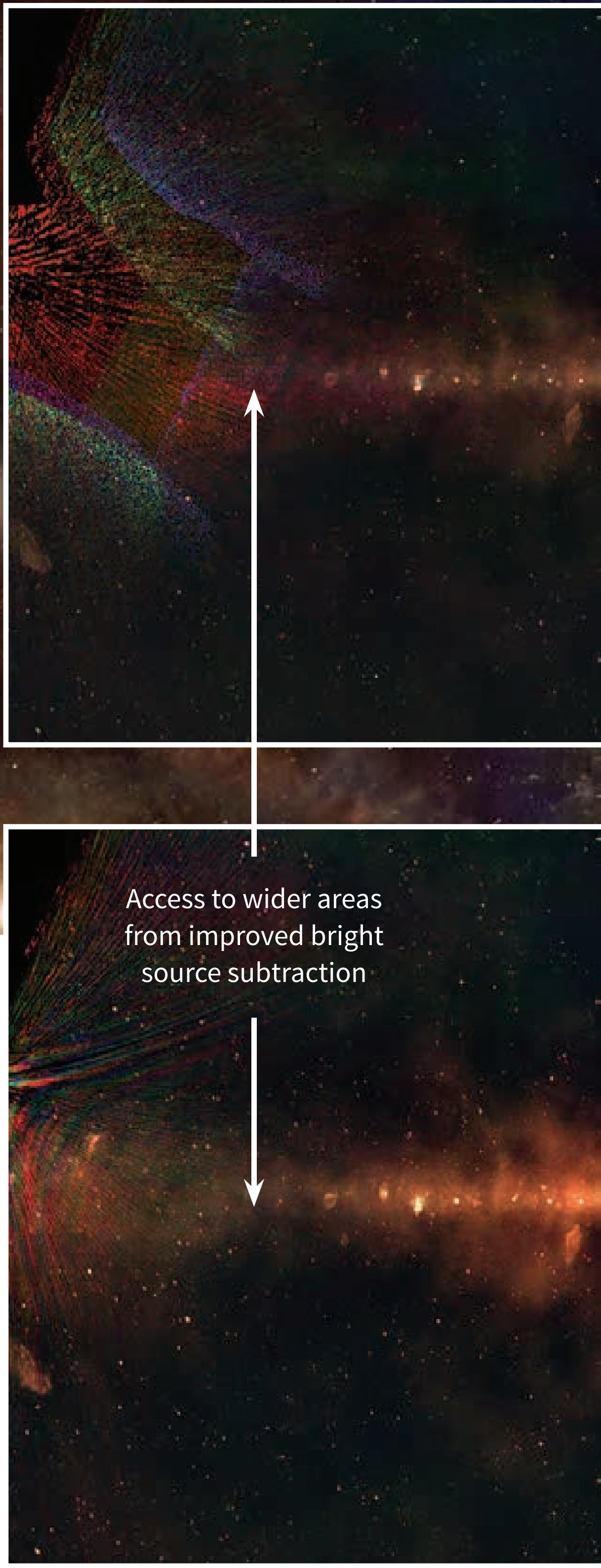
Natasha Hurley-Walker

2017

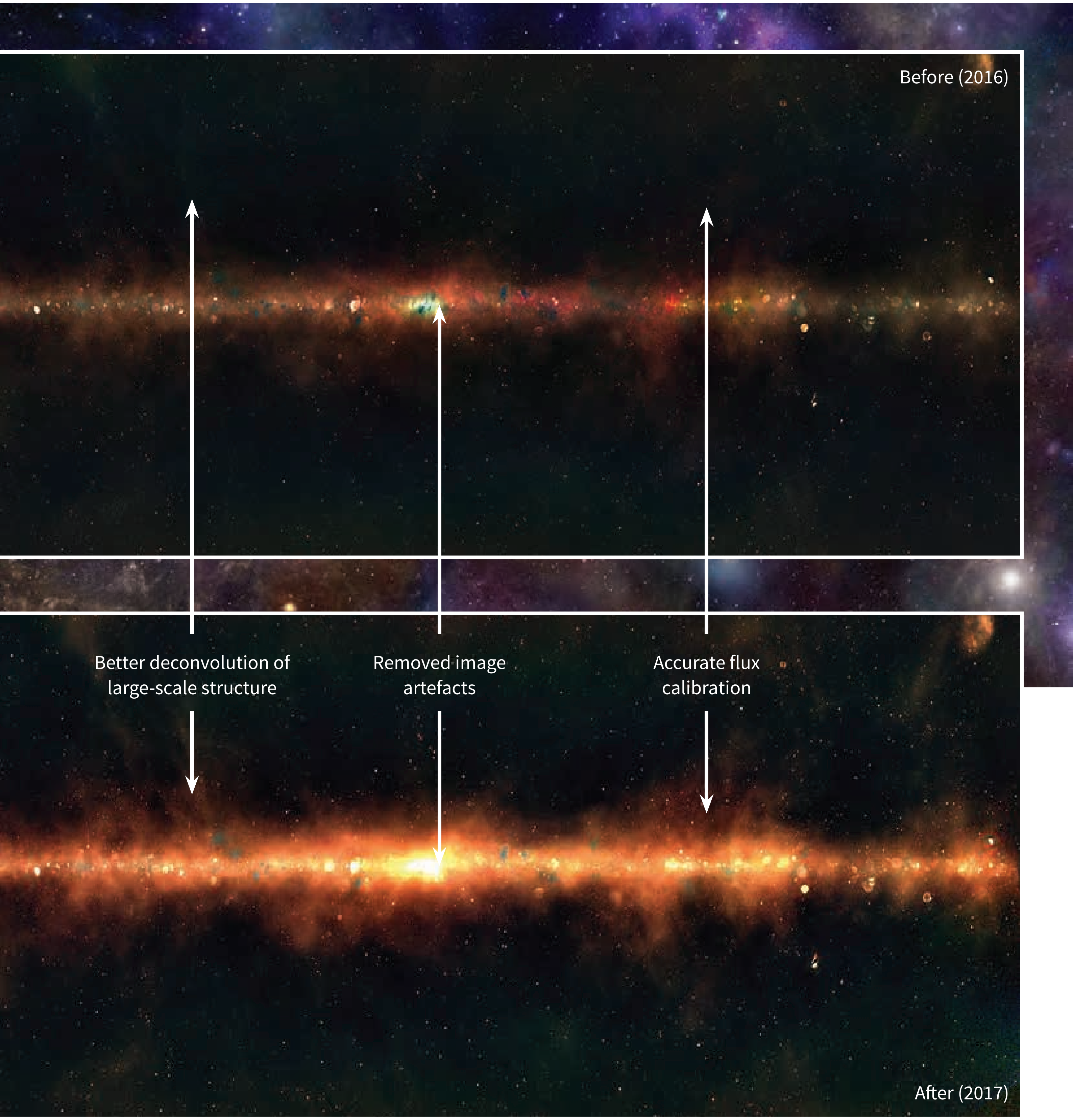
Western Australian
Young Tall Poppy
Scientist of the Year

Dr Natasha Hurley-Walker

In 2017, Dr Natasha Hurley-Walker was awarded the WA Young Tall Poppies Scientist of the Year Award. Additionally, the GLEAM team won the 2017 Curtin Research Impact and Engagement Award, showing the high impact of this work across the field, and the efforts the team had made to engage the public and inspire them with their research.



Access to wider areas from improved bright source subtraction

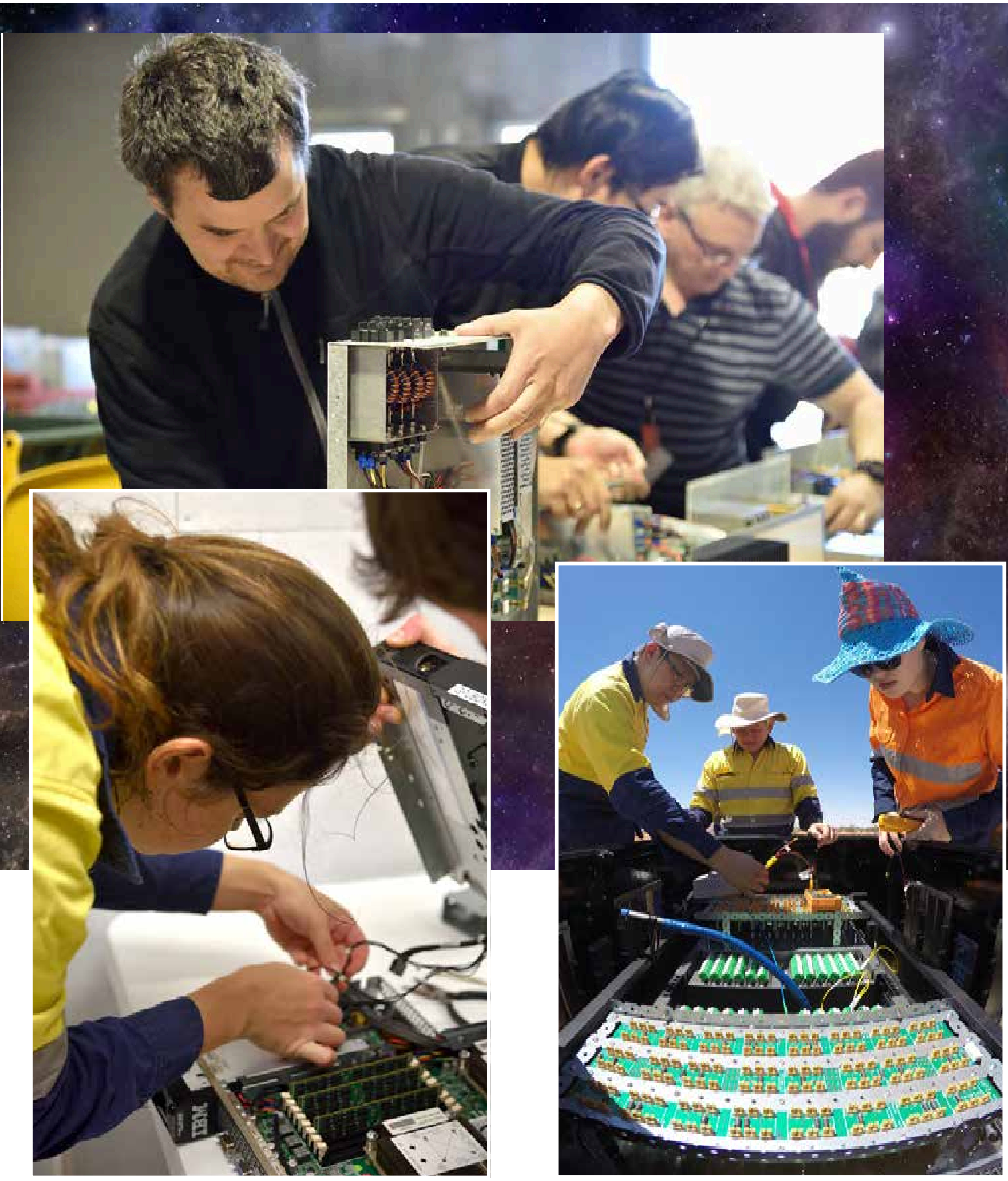


In 2017, the Galaxy supercomputer at the Pawsey Centre was used to reprocess the GaLactic and Extragalactic All-sky MWA (GLEAM) survey toward the Galactic Centre. The region before (above) and after (below) reprocessing is shown here, with improvements indicated by arrows. The increase in fidelity and accuracy is enabling better studies of cosmic ray tomography, and the detection of over 20 new supernova remnants, with publication expected in 2018.

HIGHLIGHTS

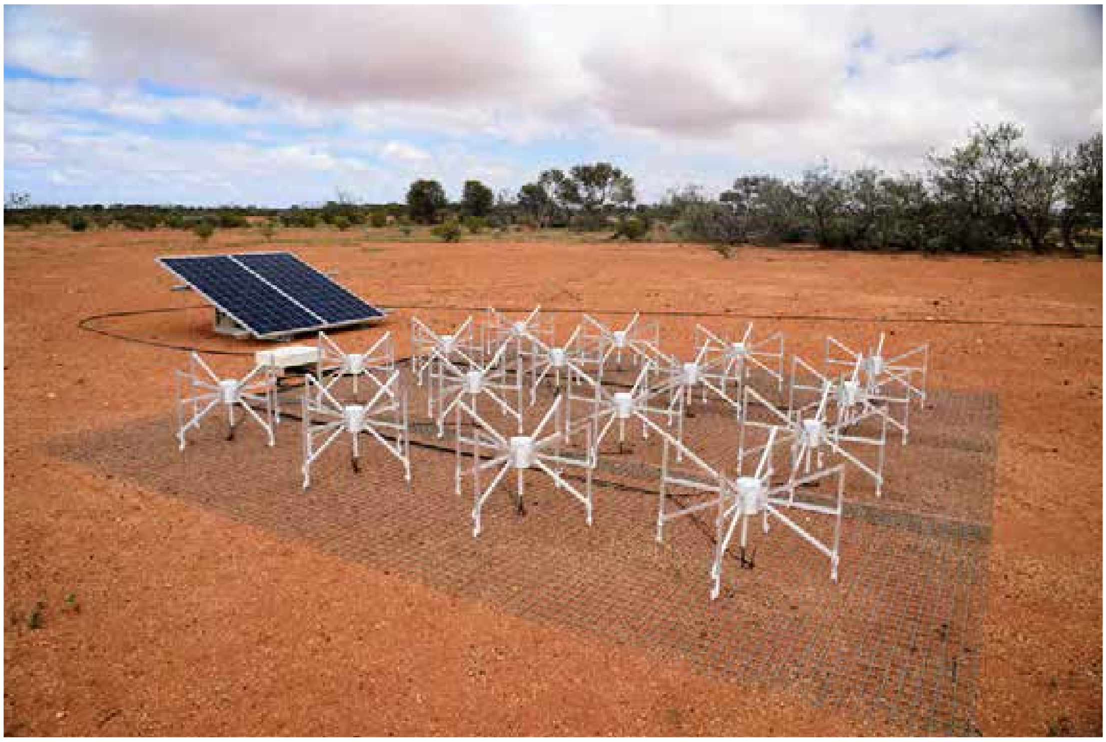
Image Credits: Curtin University

ENGINEERING & OPERATIONS



MWA ‘Phase II’ upgrade completion

Randall Wayth



A complete long baseline tile, September 2017. Image Credit: Kim Steele, Curtin University

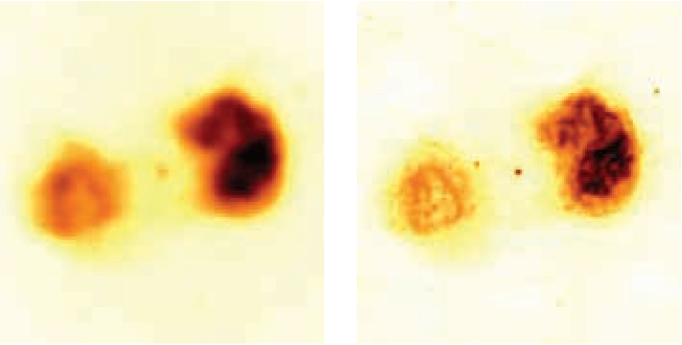
During the two years of 2016 and 2017, the Murchison Widefield Array (MWA) underwent its first major upgrade since telescope operations began in 2013. The process to upgrade the array began in 2015, with a successful ARC LIEF grant led by Prof Steven Tingay. The grant, combined with matching contributions from MWA partners in Australia and around the world, raised the capital required for the development, infrastructure works, and equipment for the upgrade.

The upgrade, generally referred to as "Phase II", was motivated by the desire to increase the scientific capability of the MWA in several of its key science areas. This includes Epoch of Reionisation (EoR) science, and several key science areas that are enabled by the imaging capabilities of the telescope. For the EoR science case, the upgrade delivers almost an order of magnitude improved sensitivity for the EoR power spectrum experiment compared to the originally deployed array. For image-based science, the resolution and image fidelity of the telescope were improved by a factor of two. The combined improvements to image-based science for MWA will also lead to an order of magnitude improvement in the sensitivity of deep MWA images.

Over the period of the upgrade, 128 new antenna "tiles" were deployed on the MWA site. A tile is the colloquial name given to a 4x4 dipole antenna array together with the electronics used to beam-form and steer these antennas. The first set of new antennas was deployed in mid-2016 and comprised two sets of 36 tiles, each arranged in a regular hexagonal configuration approximately 100 metres wide. The new hex arrays are primarily to support the EoR key science program. The remaining 56 new tiles, designated "long baseline" tiles due to their large distance from the MWA central core, were deployed in 2017. The long baseline tiles doubled the diameter of the MWA, but their distance from the existing MWA infrastructure required significant development work for the power and signal transport systems. This work is described in subsequent articles.

The MWA was reconfigured into its extended configuration in mid-2017 to commission the new long baseline tiles. No major issues were encountered and the array moved into operations in October 2017. The successful commissioning of the new hex configuration tiles in 2016 and the long baseline tiles in 2017 marked the successful completion of the MWA Phase II upgrade.

The Phase II upgrade of the MWA is just the first large step in a series of planned or proposed improvements to the telescope. The major focus for Phase II was deployment of new antenna tiles and adding associated infrastructure to support reconfiguration of the array. The existing digital receivers and digital correlator were not changed in the upgrade but are the focus of current and future work. Ongoing projects to further enhance the MWA include: development of new digital receiver hardware, based on commercially available equipment; a completely new correlator based on a codebase shared with the Swinburne-led UTMOST project; a new archive and data storage system that removes some of the bottlenecks of the existing system; and retro-fitting existing MWA tiles with RF-over-fibre technology to improve the bandpass characteristics of those tiles.



Side by side comparison images showing the old vs new resolution of the MWA. The images are of the giant radio galaxy Fornax A, in false colour. The angular size of the images is approximately 1 degree, or two full moons side by side. The radio images were made at 185 MHz and correspond to less than 10 minutes of data with the new expanded MWA. Credit - Dr Ben McKinley (Curtin University, ARC DECRA Fellow)

Panoramic view of the Southern Hex, after deployment in 2016. Credit – Kim Steele, Curtin University

Deployment of MWA long baseline tiles

Luke Horsley

Portable production line for assembling MWA dipole antennas at each remote tile location. Image Credit: Curtin University

In October 2017, the CIRA engineering team completed the deployment of 56 solar-powered long baseline tiles as the final installment of 'MWA Phase 2' (see the previous article). To deliver this project, Curtin staff teamed up with Geraldton-based company GCo in a six month long fieldwork effort.

The deployment began in April 2017, with the rollout of approximately 60km of fibre optic cable. To avoid damaging the environment with machinery, each cable was deployed by hand, requiring at least three people to drag each cable through the Murchison bushland.

Following the cable rollout, GCo developed a unique carrying jig to move the mesh ground plane of each tile hundreds of metres without further use of machinery. Limitations on the amount of mesh sheets this jig could carry meant the total distance walked each day was in excess of 15 km for the staff involved.

Wide angle view of GCo Electric running long (up to 2.6km) fibre cables out to distribution points, for the MWA Long Baseline tiles. Image Credit: Curtin University

Mesh carrying jig developed by GCo to transport MWA ground plane material long distances on foot. Image Credit: Curtin University

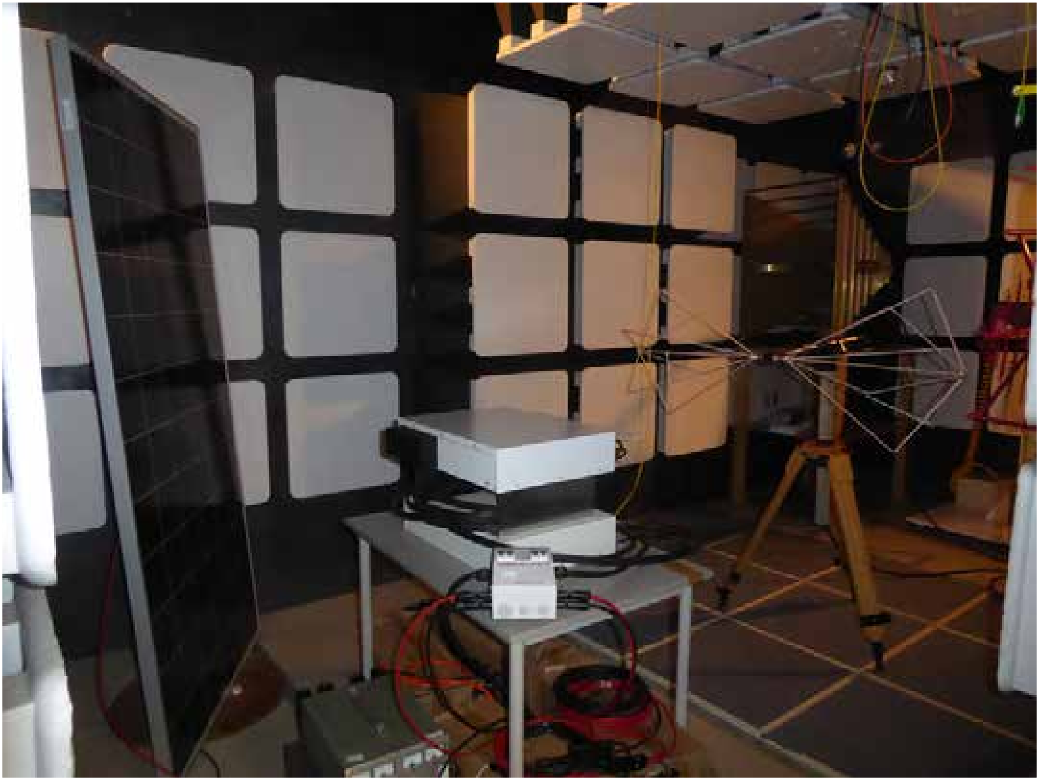
To construct the 896 dipoles required for the completion of MWA Phase 2, materials were taken to each tile site along with a portable work station. At each tile, a production chain was formed between GCo and Curtin staff to assemble, deploy, and connect each antenna.

Installation of the solar power system was the final step in deploying these new tiles. Four batteries totaling 160kg, along with 2 x 300 Watt solar panels provide enough backup power to keep these systems running and receiving signals for three days. A heavy-duty push-cart was built to carry enough batteries and materials required for each tile, but it was an enormous effort to transport this equipment to all long baseline sites without the aid of motor vehicles.

In summary, the deployment of these tiles saw GCo staff walking a combined distance of 700km, carrying a total of 25 000 kg of material between the 56 remote sites!

Design and development of a long baseline tile

David Kenney



Radio emissions testing of the Long Baseline system in the Curtin EMC chamber. Image Credit: D. Kenney, Curtin University

The requirement for 56 long baseline tiles for the Murchiso Widefield Array (MWA) Phase II upgrade presented the Curtin Engineering team with the challenge of how to power and communicate with a remote MWA tile, without affecting the radio quietness of the Murchison Radio Astronomy Observatory (MRO).

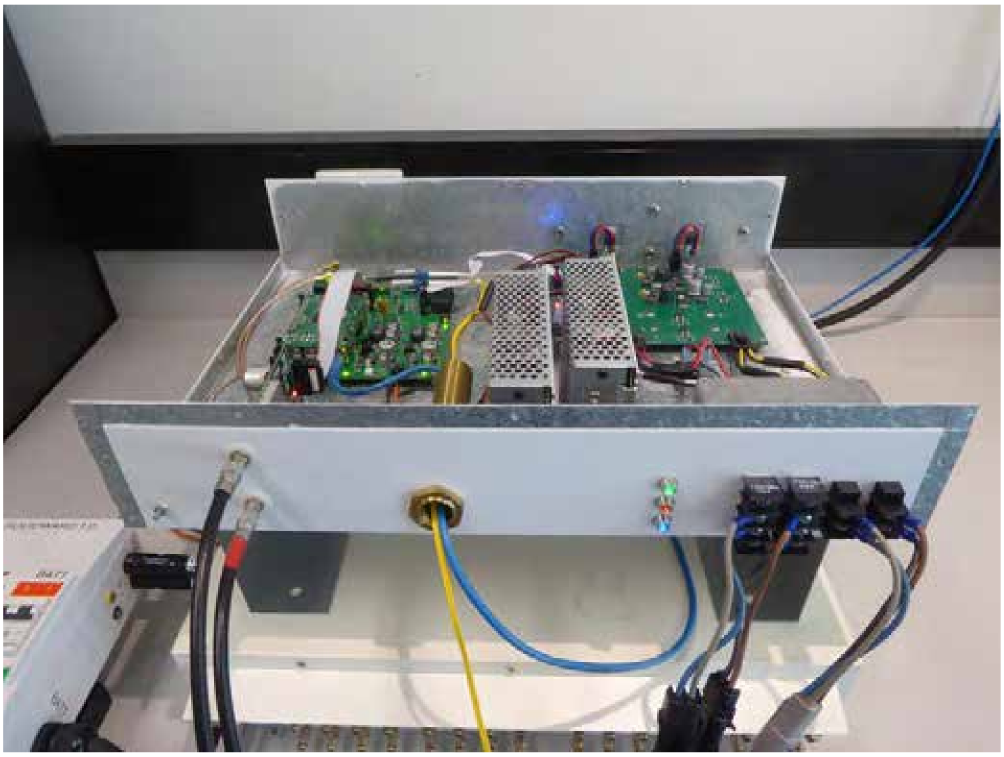
Until the long baseline tiles, radio signals detected by each tile were sent to a receiver over coaxial cables for further processing. The receiver also provided power and communications to the tile's beamformer via the coaxial cable pair. Power and signal losses of this cable limit how far away the tile can be positioned from the receiver. Practically this limit is 500 metres, and this has constrained the baselines of the telescope given the current receiver locations. With the requirement for baselines of several kilometers, a new way of remoting a tile was needed. Due to the bespoke nature of the telescope, an off-the-shelf solution to the problem was not an option. Instead, through drawing on prior experience, existing design solutions, new technologies, and industry assistance, a custom in-house solution was undertaken.

Having recently evaluated the performance and suitability of using optical methods for transporting analog RF signals, a technology known as Radio Frequency over Fibre (RFoF) provides the RF signal transport solution. An RFoF product from ASTRON, the Netherlands Institute for Radio Astronomy, was chosen. While the use of optics for transporting analog signals within the MWA is new technology, using optics for digital communication is not. By running additional fibres and using off-the-shelf media converters, tile communication for monitor and control functions can be achieved.

The Long Baseline system naturally divides into two submodules. The Solar Power Interface Unit (SPIU) provides solar power and battery management used to power the electronics. Solar energy is derived from two 24V, 315W solar panels which are used to charge two 24V, 150AH AGM battery banks. This system provides several days of online capacity and weeks of offline capacity in the case of low solar levels. The Beamformer Fibre Interface (BFIF) functions as a fibre to copper bridge, converting coaxial RF and Data-over-Coax communications from a standard MWA Beamformer to optical equivalents. These optical equivalents are transported over several kilometres via fibre optic cable to the receivers.

The hardware and software design of the system including both the BFIF and SPIU submodules was performed by CIRA Engineering. These designs leverage from working solutions of other on site instruments. Industry partners were used for printed circuit board fabrication, electronic component assembly, and metalwork fabrication. The system is designed to work in the harsh environment at the MRO, operating at temperatures of up to 70 degrees Celsius with passive cooling.

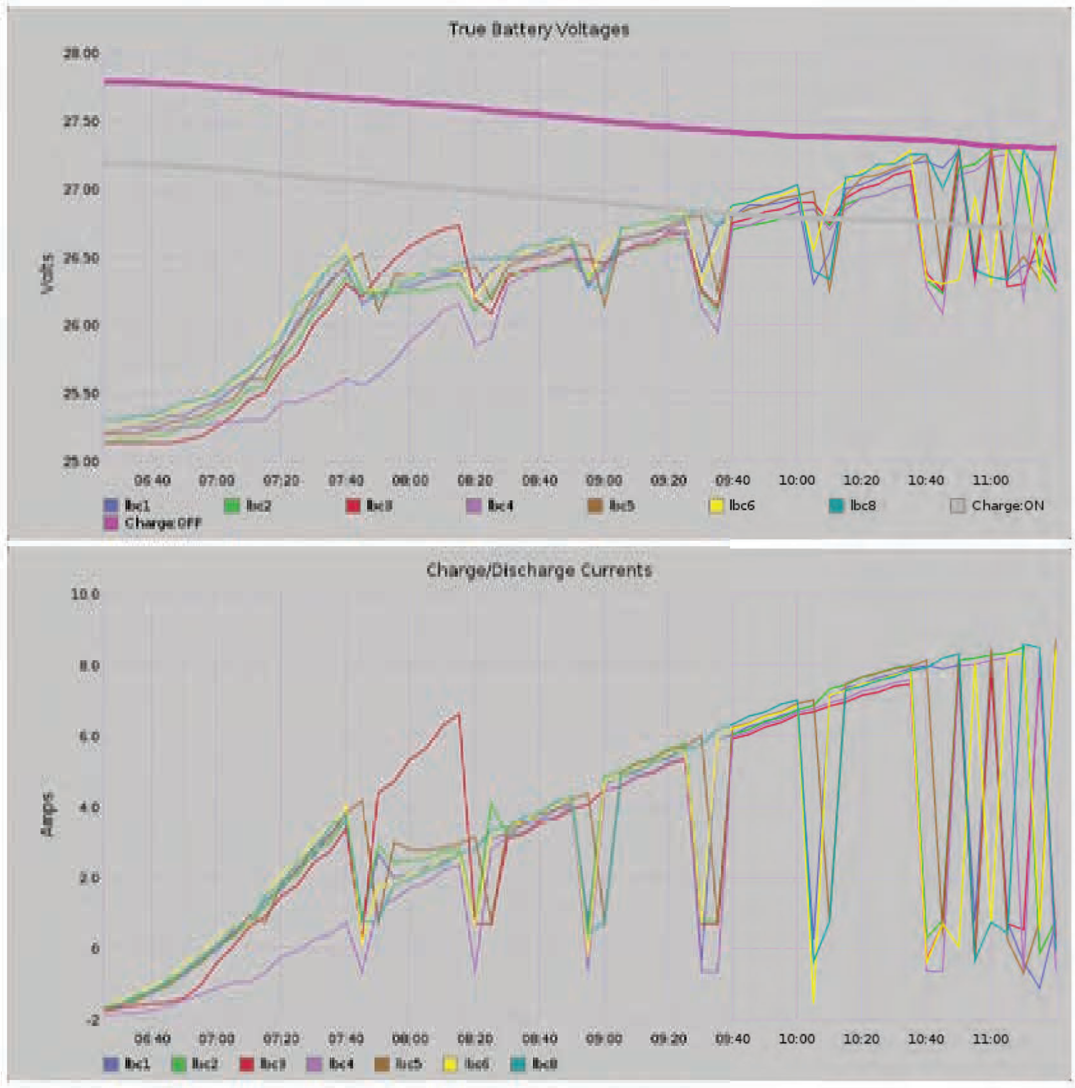
Due to the remote and mostly unmanned operation of the telescope, the system provides telemetry data to the operations team to assist operations, maintenance, and repair. As with all equipment deployed at the MRO the system must comply with stringent radio emissions requirements. Compliance with this requirement was performed within the Curtin University EMC chamber which is operated by the CIRA team.



Testing the control circuitry of a long baseline system. This box is referred to as the BFIF. although it contains both the custom BFIF and SPIU printed circuit assemblies. Image Credit: D. Kenney, Curtin University

Monitor and control for MWA long baselines

Andrew Williams



Graphs showing battery voltages and charging currents of each MWA tile in the 'C' group of long baselines, measured over five hours. This is an example of the data that are used to monitor the health of these remote tiles. Image Credit- Andrew Williams, Curtin University.

Rolling out the 56 new long-baseline tiles for the Phase II expansion of the Murchison Widefield Array (MWA) involved a significant amount of hardware and software development. Up until now, each of the MWA tiles sat at the end of a long dual coax cable, providing 48V DC power and serial communications signals (for pointing), and returning radio frequency signals in both X and Y polarizations. The data signals for pointing the tiles were provided by the receiver that the tile was connected to, via the receiver's Monitor and Control interface.

The new long-baseline tile controllers (described by David Kenney) are entirely self-contained, and consist of:

- A pair of solar panels.
- Four deep-cycle lead acid batteries, wired to give 300 Ah of storage at 24 V.
- A control box containing a single-board Linux host (a Raspberry Pi) to manage the battery charging, point the beamformer, convert the 24 V supply to 48 V to power the beamformer, and to convert the beamformer's RF signal to an analog optical signal over fibre.
- An ordinary, unmodified MWA beamformer connected to the control box via a few metres of dual coax cable.

The only link between the long-baseline tile and the MWA is a six core optical fibre cable run above ground through the bush. Two cores transmit the X and Y signals back to an MWA receiver enclosure, and two cores carry gigabit ethernet for communications with the Raspberry Pi.

The Raspberry Pi runs a daemon that manages the battery charging. Commercial solar charging systems would emit lots of radio frequency interference (RFI), as they switch the panels on and off at tens of kHz, varying the duty cycle to provide an optimum impedance load for the panels, at the same time as an optimum voltage/current supply for the battery. Instead, the new tile controller uses custom software to choose, depending on the panel voltage and the state of charge, whether to:

- connect both panels directly to the batteries in parallel,
- only connect one panel and leave the other switched off, or
- switch off both panels.

While this results in a less efficient charging system, RFI is minimised. The risk is that leaving panels directly connected to the batteries when the batteries are fully charged could physically destroy the batteries in a matter of minutes. A great deal of care was taken to reduce this risk, in both the hardware and the software design.

Pointing the tiles to the correct location for each observation presented another challenge, as the serial communication channel to the beamformer could not be carried over the 'RF-on-Fibre' link to the receiver. In fact, each receiver with long-baseline tiles connected generates errors at every new pointing (which need to be suppressed/overwritten later on), because it can't communicate with the tiles. Instead, the control software on each Raspberry Pi connects to a control daemon on a central server when it boots, and registers to be notified whenever that specific tile has a change in pointing direction.

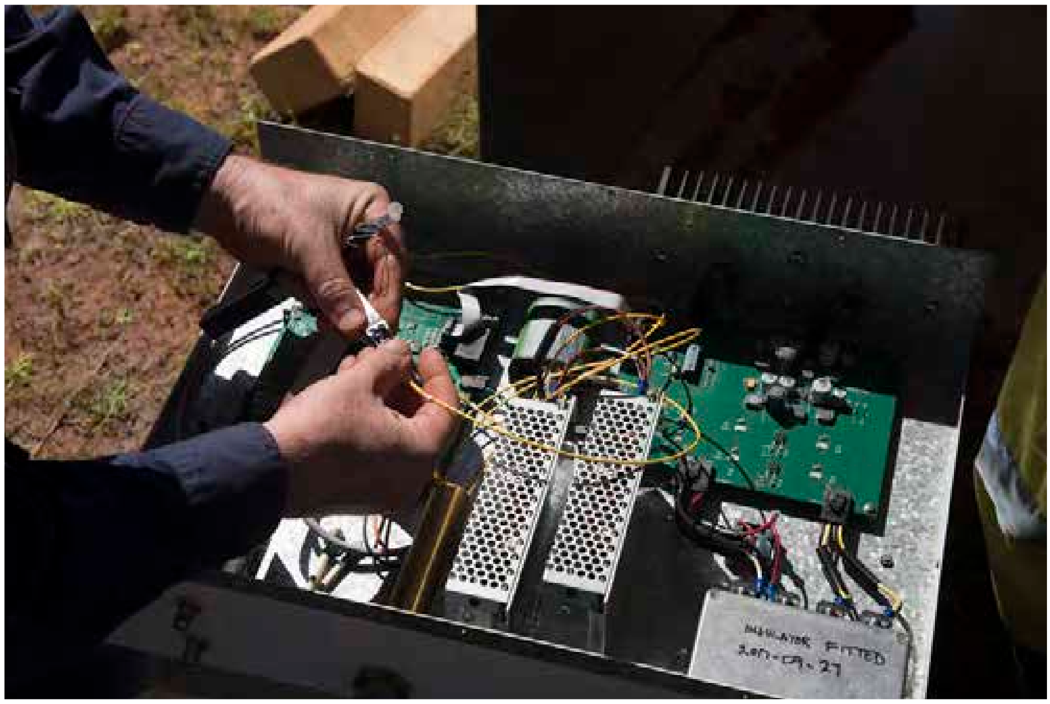
A few seconds before the start of each observation, the control daemon sends a message to each registered client that contains the new pointing data and the start time of the observation. At the instant the observation starts, the Raspberry Pi sends the new pointing delays to the beamformer over the dual-coax link. The results (success, or an error communicating with the beamformer) are returned to the control daemon and merged in with the status data from the other tiles, both original 128T and long baseline.

A separate communications channel allows the Raspberry Pi to send status data (temperatures, voltages, currents, charge state, etc) to the overall system monitoring package (icinga) to allow emailed alerts to be generated for critical errors, and to another system allowing the telemetry data to be graphed and analysed in an interactive online plotting package (graphite). It also allows manual control of beamformer power and battery charging via a remote command-line client. The above solutions have minimised RFI and provided effective monitor and control systems for the Phase II MWA.

The long baseline tile controller containing monitor and control equipment, sitting in place underneath the solar panels of a deployed tile. Image Credit: Curtin University.

RF signal transmission over fibre

David Emrich



Connecting optical cables to the Astron RFoF units, inside a control box adjacent to a long baseline tile. Image Credit: Curtin University.

In late 2015 the CIRA engineering group was tasked to design a means by which antenna tiles for the Murchison Widefield Array (MWA) could be placed further from receivers than the limit imposed by coaxial cables. Due to both direct current (DC) power loss and radio frequency (RF) signal loss considerations, this distance is a little over 500 metres when using high quality copper cables. In the implemented solution, as described in previous articles, each remote tile is connected to its own solar-powered, battery-backed supply within 10 metres of the tile, and the RF and control signals are carried via fibre-optic cable to receivers/digitisers that are up to 2.6 kilometres away.

The local power supply overcomes the DC losses in coaxial cables, and the fibre-optic cable drastically reduces the overall power loss and spectral “colouring” associated with coaxial cables, wherein the power loss is worse for higher frequency signals. Typical examples of RF loss measurements on 500m of coaxial cable at MWA frequencies range from 19 dB at 80 MHz, up to 38 dB at 300 MHz. This means that higher frequency signals, which are already naturally lower power ‘in the sky’, are more heavily attenuated over the long cables, by as much as 6300 times! In comparison, the optical cable loss is below one dB at lengths below 5 kilometres and is flat across the entire frequency range.

Several scientific and engineering groups around the globe use analogue signal transmission over fibre optic cables (“Radio Frequency over Fibre”, or RFoF) to send broadband radio frequency signals over distances varying from hundreds to tens of thousands of metres, and three groups that already had specific experience were approached to provide technical support and pricing quotations for our design.

After a suitable comparison study, ASTRON (the Netherlands Institute for Radio Astronomy) were selected since they had the closest fit of “off the shelf” RFoF hardware, which had been trialled in very similar conditions of operating frequency and distance when compared to the MWA radio-frequency environment.

One major difference between ASTRON and Curtin’s use of the RFoF solution lies in the environmental aspects; where ASTRON equipment typically operates up to a limit of around 35 degrees Celsius, the MWA telescope often sees temperatures over 50 degrees in the peak of summer. ASTRON and CIRA engineers were able to test the effects of the higher operating temperature on the optical link, as well as gather safe operating temperature limits that gave CIRA the confidence that the ASTRON modules would work under nearly all MWA operating conditions. If the operating limits were to be exceeded, we determined that the devices would remain undamaged even if they were not operating at their ideal performance.

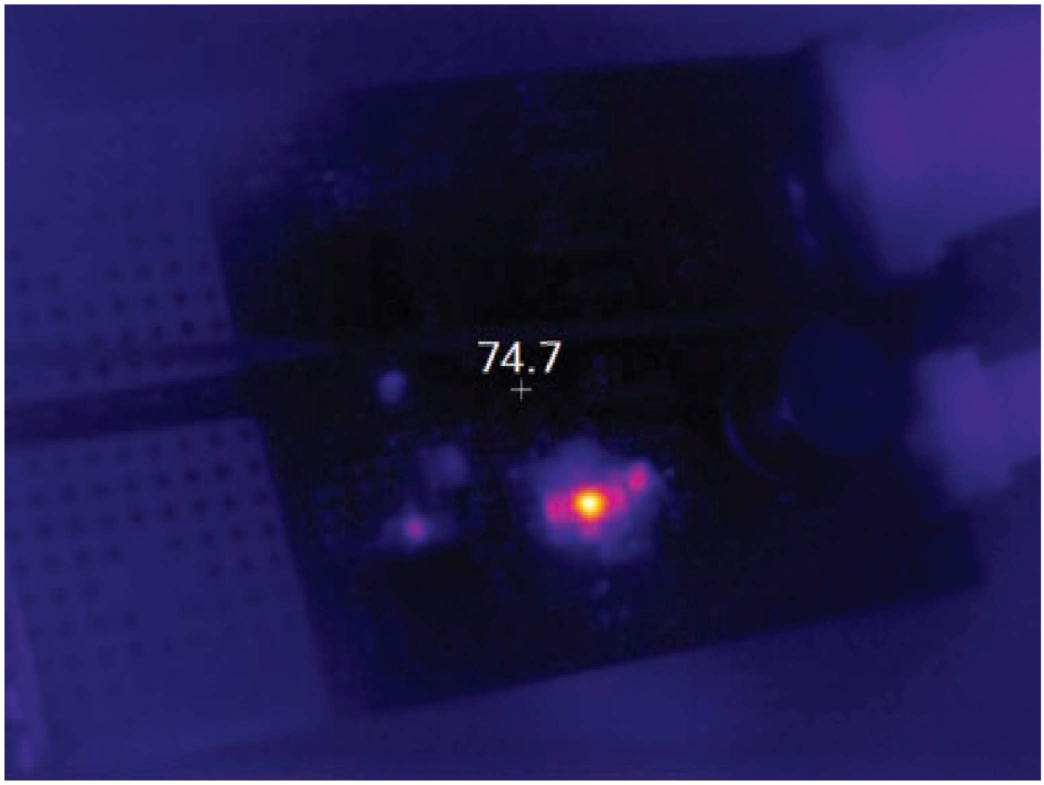
During the process of integrating and testing, a number of other small design issues were discovered which ASTRON and CIRA engineers were able to overcome due to the rapport that was established during the initial research phases.

The ASTRON RFoF modules have been in use since late June 2017 and have performed well during this time. They have allowed MWA Scientists to gather signals which will have a finer resolution on the sky than has previously been possible with the MWA.

A close-up view of the ASTRON RFOF modules, connected to optical fibre and USB inputs of the beamformer interface (BFIF) board. Image Credit: Curtin University.

Repairing MWA electronics

Malcolm Whinfield, Mia Walker



Thermal image of a faulty receiver data-over-coax board.
Image Credit: Curtin University

With the MWA telescope expanding during 2017, resources to service twice as many dipoles in the field became increasingly limited. It was necessary to repair and re-use as many parts as possible, but the Operations team had limited resources for providing maintenance during the intensive upgrade period. To fill the gap as electronics technicians, two Curtin University engineering students were brought into the team.

Malcolm Whinfield and Tim Bumbak were employed to provide support in the CIRA lab, and their duties were wide and varied. Initially the requirement was to repair most of the front-end equipment such as beamformers and receiver hardware, but later this included smaller electronics such as the low-noise amplifier (LNA) boards that sit in the hubs of the dipole antennas.

Repair work is usually prescriptive, and most common issues can be identified quickly with a combination of tools. The lab is equipped with a 'test' beamformer that runs a pseudo observation program that faulty equipment can be connected to, which allows the technician to probe voltages and radio signals along the circuitry for defects. Other methods to detect damage may include the use of a thermal imaging camera or simple visual inspection of components. After fault identification, replacement parts are soldered to the board, often with the use of a LIECA A60 microscope, and the board is then tested overnight to ensure it will operate smoothly back in the field.

For some components, the testing and fixing process was quite lengthy, and it became important to identify if it was more cost effective to completely replace these electronics. An example of this were LNAs with suspected electrostatic discharge damage, as repairs would mean the replacement of multiple field-effect transistors. The technicians also found new components to improve performance and replace obsolete parts in the beamformers.

In addition to servicing modules, a re-introduction of service history was implemented by the technicians to record and track equipment issues. Malcolm and Tim also carried out other tasks as required, such as equipment assembly and making cables for the Long Baseline tiles.

Providing repairs and support has given both Malcom and Tim a good grounding in the practical aspects of engineering, including extensive soldering practice in extremely small SMD components. This maintenance work has been vital in allowing CIRA field engineers to keep the telescope system fully operational, as well as allowing these Curtin University students to develop essential skills for future work as engineers.

Timothy Bumbak in the CIRA laboratory. Image Credit: Curtin University

Malcolm Whinfield using a Fieldfox analyser. Image Credit: Curtin University

Industry collaboration for MWA Phase III

Mia Walker

Image Credit: Curtin University

With the successful implementation of the MWA's Phase II long baseline tiles now behind us, the focus of the CIRA engineering research and development team has moved to Phase III. This involves the expansion of the array to a full 256 correlated tiles, requiring a new digitizing and correlating system that does not currently exist at the Murchison Radio Observatory. With the help of industry partners such as National Instruments, CIRA is working to make Phase III a reality.

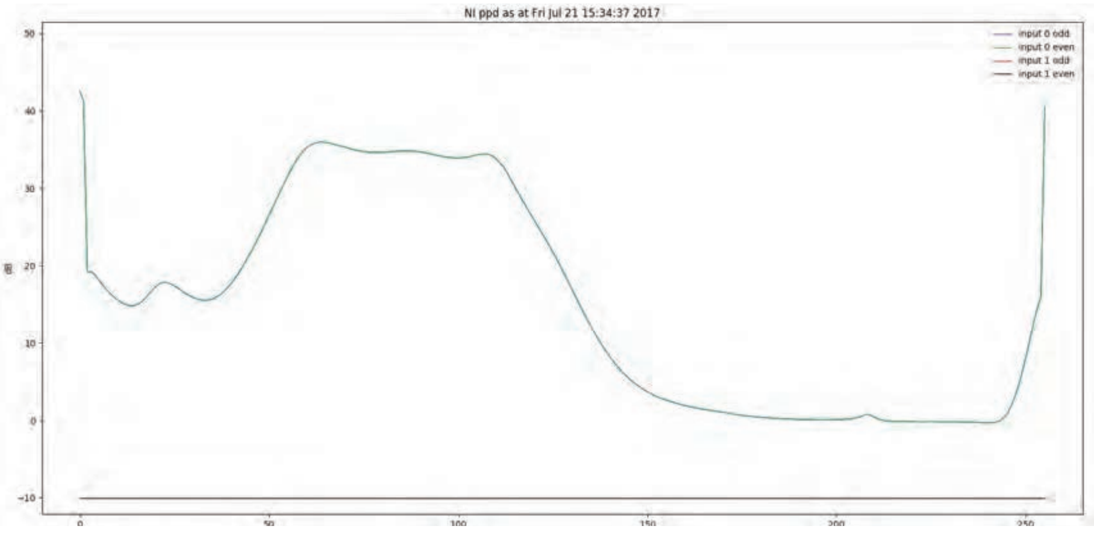
One of the key new developments is a receiver system which can accommodate wider bandwidth, and can provide higher frequency resolution and reduced channel aliasing. To achieve this, CIRA identified that a National Instruments (NI) FlexRIO sampler and controller could be modified to meet our system requirements. This demanded extensive FPGA coding to implement an oversampled polyphase filterbank, and the help of NI system engineers was critical to this process.

The FlexRIO was proposed as a potential solution candidate some years before Phase III would be implemented, which meant that the requirements were still in a state of flux. With no certainty on what equipment or format would support a 256 tile array, any hardware needed to be adaptable to changes in overall system design. This was one of the immediate advantages of the reprogrammable, commercial off-the-shelf NI FlexRIOs, instead of bespoke hardware that the MWA is built on. Obsolescence is a looming threat that is already evident in the current array system, but as a risk it can be minimised when planning for the future, by utilising state-of-the-art hardware. This concern becomes moot if the research and design stage outlasts the time it takes for new equipment to appear on the market that would do a better job for an equivalent price, so development needs to happen in a timely manner.

This may be further complicated, as it was in our case, by the physical separation distance and/or time difference that might exist between the system engineers working on development. Additionally, possible communication or language barriers need to be recognized. As the receiver project progressed, roles and responsibilities changed hands within CIRA and NI on multiple occasions, so sufficient documentation on the state of the code was important.

This common-sense approach to a collaborative project is always simpler in theory than it is in practice, but with NI we developed a strong working relationship for success. With the rapid development and deployment of Phase II, the Phase III receiver was low on the priority list, putting it at risk of the previously-discussed dangers of obsolescence. However, one of the advantages of programming within the LabView environment on an NI platform is that the FPGA and controller code is transferrable across their range of devices with minor edits. Coding is not limited to the NI engineers, and it can be performed by anyone with training in LabView, which NI readily made available for members of our team. Our own testing of the code was critical in ensuring that we as the end users would be proficient and relatively independent of NI during and after deployment of the FlexRIOs.

The NI platform allowed for the flexibility that our system required, and the NI engineers were accommodating with the chaotic process that can be a staple of research and development. Our experience in collaborating with this industry partner has therefore been extremely positive, and we hope to build on our relationship with NI in the future as we continue to design for change and success!



This image shows the first full bandpass we achieved of a simulated sky signal from an NI FlexRIO, programmed to act as a receiver. The signal data has been through an oversampled polyphase filter bank, resulting in smooth output power for 256 2 MHz wide coarse channels spanning 400MHz. Image Credit: Brian Crosse

Unlocking MWA Data through a virtual observatory

Greg Sleap

The ASVO consists of several data portals from Australian astronomical observatories, all with the common goal of making the data from Australian Government funded instruments available to the wider astronomical community. (http://www.asvo.org.au)

The All Sky Virtual Observatory interface described in this article can be found at https://asvo.mwatelescope.org

The Murchison Widefield Array (MWA) archive, located at the Pawsey Supercomputing Centre, has collected more than 18 PB of data since beginning science operations in mid-2013. Much of the data that has been collected is designated as available to the public. However, there has been no publicly accessible portal to provide access to researchers from outside of the MWA Collaboration.

In early 2017, ADACS (Astronomy Data and Computing Services) was awarded a contract by Astronomy Australia Limited (AAL) to design and develop a new pilot portal to allow Australian and international researchers to access raw, uncalibrated public data from the MWA archive. This project was led by Greg Sleap and Randall Wayth (CIRA), with systems and web programming work carried out by Dave Pallot from the University of Western Australia's Data Intensive Astronomy team.

The AAL had already been investing in data portals to provide researchers with astronomical data from various facilities around Australia. This initiative, known as the ASVO (the All Sky Virtual Observatory) already had two active "nodes" (the Theoretical Astrophysical Observatory [TAO] and Skymapper). The goal of the ASVO is to remove or reduce the barriers that researchers face when trying to access and use public astronomical data from various Government funded facilities in Australia. The MWA data portal would be the third node, known as the MWA-ASVO.

When scoping this pilot project, it was clear that there were many barriers researchers faced when trying to access and use MWA data. Firstly, the only tool available to download data (obsdownload) was restricted to active members of the MWA Collaboration. By definition, researchers should not need to be active members of the MWA Collaboration to access publicly available data, so it was clear we needed to provide a data portal that anyone in the world could access. In addition, if obsdownload was being used heavily, it could cause the system to become unstable, resulting in failed or incomplete downloads. Secondly, the raw, uncalibrated visibility data stored in the MWA archive was stored in a non-standard MWA-specific format. The tools needed to convert this data were also restricted to collaboration members only. Therefore, we needed to provide a way for the MWA ASVO to pre-process/convert the MWA data before downloading, which can then be used in many off-the-shelf astronomical packages. The third hurdle was that there was no way for researchers around the world to discover what MWA data exists.

With the scope defined, a clearer picture emerged of what it is we should build. As the project was funded and resourced as a pilot, we worked hard to keep the scope limited so that we can deliver a solution which addresses the largest hurdles for researchers accessing MWA data within the December 2017 deadline. The team divided the project into several deliverables: the MWA ASVO website, a standards-compliant metadata service, and a command-line client for submitting download jobs and downloading data.

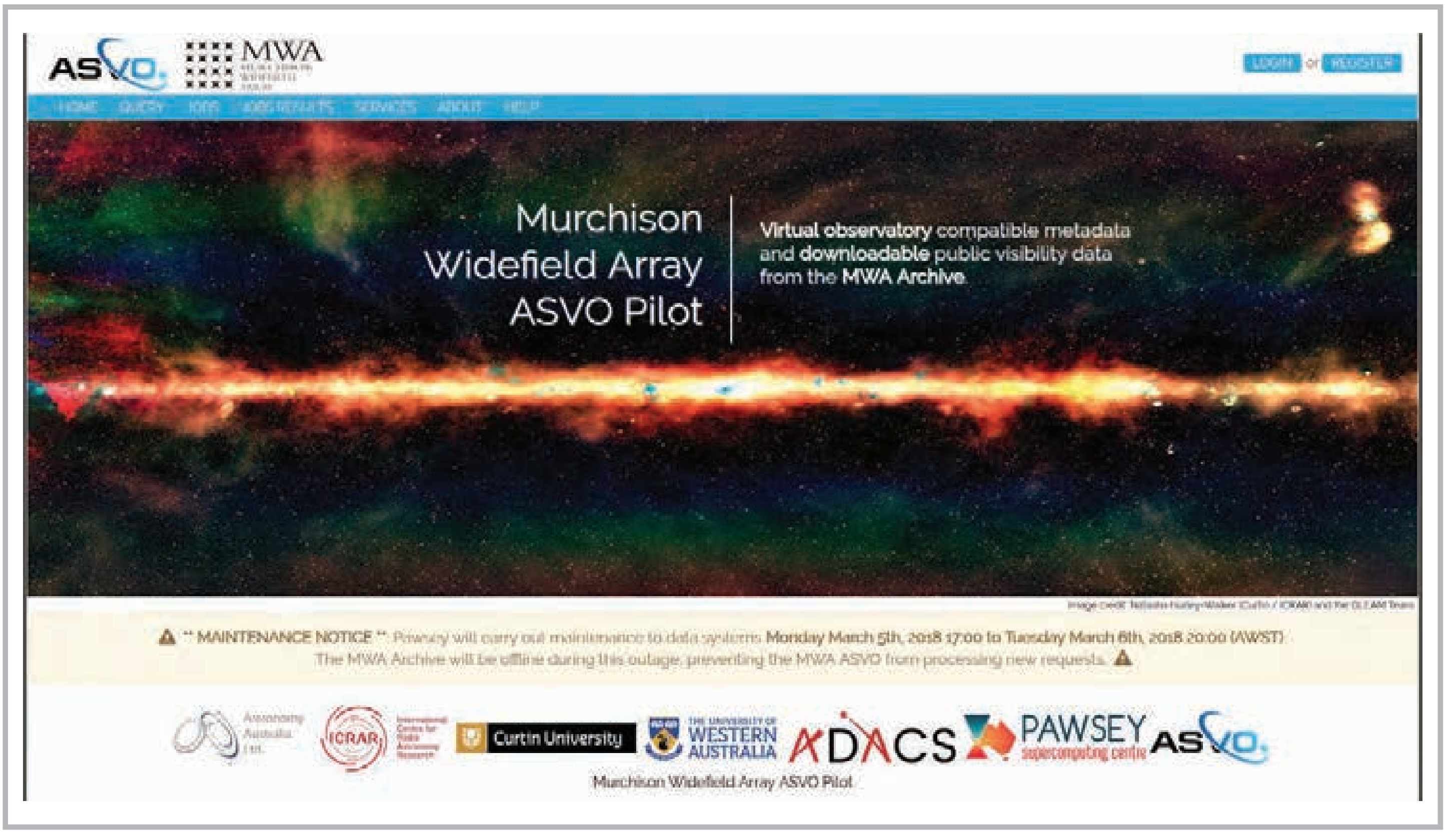
The front-end website allows researchers to register for a login, which they can then use to search for observations they are interested in. After having found an observation, they can then either submit a download job to download the raw data, or they can select various options to change the format of the data before downloading. These options include detecting radio frequency interference (RFI), averaging the data in time and/or frequency (which can be used to reduce the size of the data), and changing the format of the data to either uvfits or CASA measurement sets - two common, widely used radio astronomy data formats. Once download or conversion job is submitted, the status of the job can be viewed. Once compete, a hyperlink is provided to download the data product using any off-the-shelf download tools.

We also overcame another limitation where the MWA data was not generally discoverable via standard interfaces. So, an International Virtual Observatory Alliance (IVOA) compliant table access service (TAP) for MWA metadata was built. This service provides a standards-based interface that allows client tools (such as TOPCAT and many others) to query MWA observation information. The TAP service was provided courtesy of the CSIRO CASDA (CSIRO ASKAP Science Data Archive) team. The code to provide the TAP service is publicly available and we collaborated with their team to customize it to work with MWA data.

The third deliverable was to provide users with a command line tool to submit conversion or download jobs and to get the resulting dataset. Using the web front end to submit jobs and download data is not convenient when there is a lot of data to process, and often researchers will want to integrate the download and/or conversion steps as part of their pipelines on high performance computing platforms (such as Pawsey's Galaxy supercomputer). A command line client in python was built and released in a publicly available github repository. The client allows users to submit jobs in bulk and download the resulting data, all with a single command.

The system was designed to be distributed across various servers, including several MWA and Pawsey servers (including virtual servers on Pawsey's Nimbus Cloud), which allows for future scalability and flexibility. The conversion jobs that the MWA ASVO allows researchers to run can often be very computer intensive, so a robust work queue system that dynamically allocates resources to available servers is in place to ensure that jobs are efficiently allocated and that excessive demand from users cannot impact the MWA ASVO or Pawsey systems.

In late December 2017, the MWA ASVO Pilot project went live. With the Pilot project complete, the MWA ASVO team are looking at enhancing the MWA ASVO in 2018 with on-the-fly calibration (removing yet another hurdle for astronomers using MWA data), a federated authentication system (allowing users to log in via their own institution's credentials rather than having to remember yet another username and password), and many additional user interface and functionality enhancements.



Murchison Widefield Array ASVO Pilot

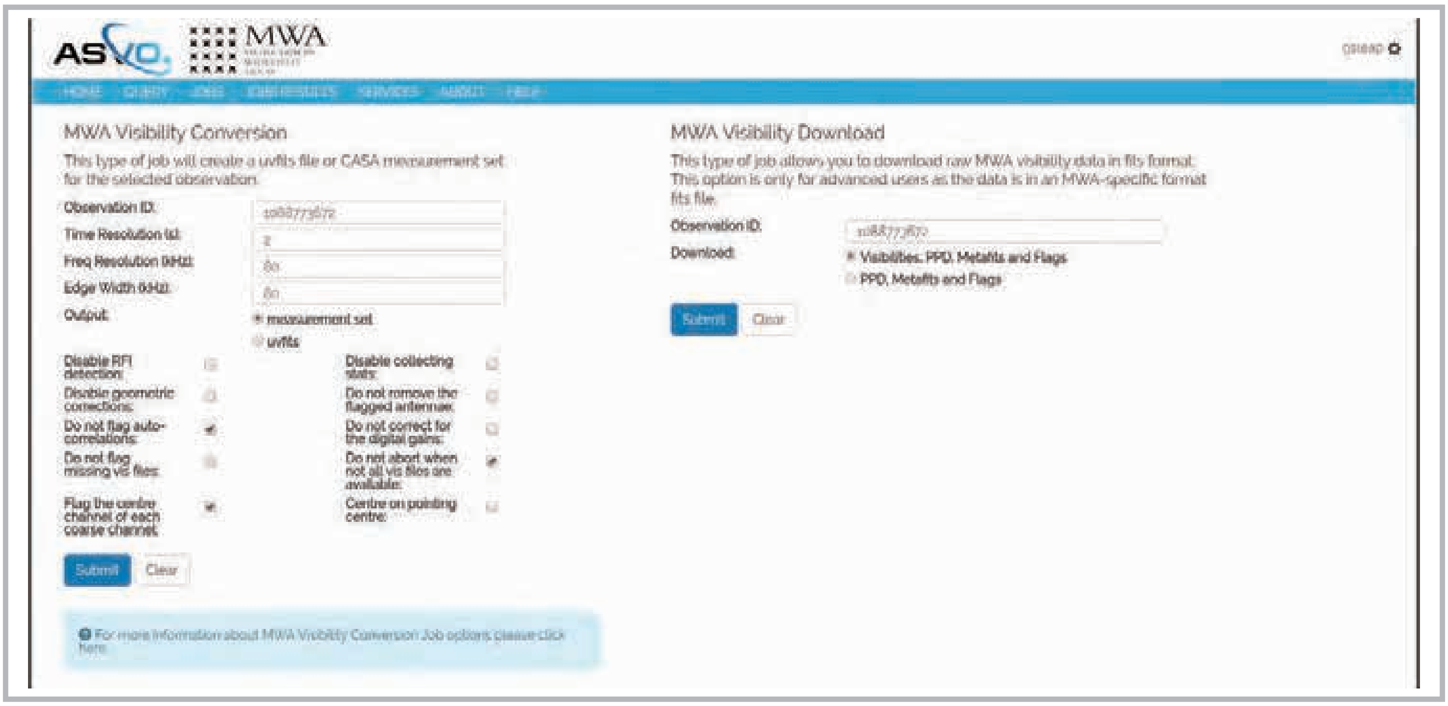
Virtual observatory compatible metadata and **downloadable** public visibility data from the **MWA Archive**

Image credit: Natasha Hurley-Walker (Curtin) / ICRAR and the GLEAM Team

⚠ ** MAINTENANCE NOTICE ** Pawsey will carry out maintenance to data systems **Monday March 5th, 2018 17:00 to Tuesday March 6th, 2018 20:00 (AWST)** The MWA Archive will be offline during this outage, preventing the MWA ASVO from processing new requests. ⚠

Murchison Widefield Array ASVO Pilot

The front page of the MWA ASVO pilot website (https://asvo.mwatelescope.org)



MWA Visibility Conversion

This type of job will create a uvfits file or CASA measurement set for the selected observation.

Observation ID: 1088773672
Time Resolution (s): 2
Freq Resolution (kHz): 80
Edge Width (kHz): 80
Output: ● measurement set ○ uvfits

Disable RFI detection: ☐
Disable geometric corrections: ☐
Do not flag auto-correlations: ☑
Do not flag missing vis files: ☐
Flag the centre channel of each coarse channel: ☑
Disable collecting stats: ☐
Do not remove the flagged antennae: ☐
Do not correct for the digital gains: ☐
Do not abort when not all vis files are available: ☑
Centre on pointing centre: ☐

For more information about MWA Visibility Conversion Job options please click here.

MWA Visibility Download

This type of job allows you to download raw MWA visibility data in fits format. This option is only for advanced users as the data is in an MWA-specific format fits file.

Observation ID: 1088773672
Download: ● Visibilities, PPD, Metafits and Flags ○ PPD, Metafits and Flags

The job submission interface on the MWA ASVO pilot website (https://asvo.mwatelescope.org)

CIRA

CURTIN INSTITUTE OF
RADIO ASTRONOMY

Characterising the MWA Engineering Development Array amplifiers

Daniel Ung

Application under test and attached LNA in the anechoic chamber for the direct measure method. Image Credit: Daniel Ung, Curtin University

In all active circuits, noise is present and causes signal distortion. To minimize the effects of noise, each component in a design must be carefully analyzed for its contribution to the overall system noise temperature.

Noise temperature of a device under test can be fully characterized using noise parameters that fully predict the noise temperature as a function of the source impedance at the input of the device. Traditionally, these parameters are provided by device manufacturers or measured using an impedance tuner. However due to size limitations, the availability of this information is often limited to higher frequencies (>500 MHz), and/or is limited to single-input single-output devices.

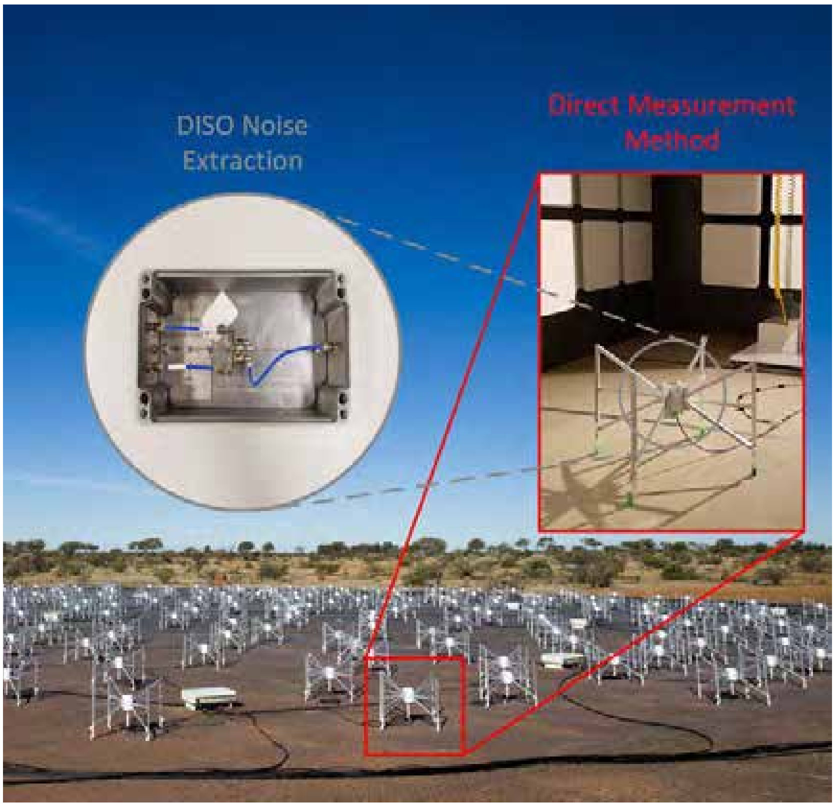
Extracting noise parameters at low-frequency radio astronomy bands where the Murchison Widefield Array (MWA) operates could be cost-prohibitive, as the cost of a single impedance tuner is in the $100k range. In addition, multiple impedance tuners may be required to cover the entire frequency band of interest or to characterise dual-input devices. An accepted engineering estimate in this case is to use simulation packages to extrapolate noise parameters provided by the manufacturer at higher frequencies to the low-frequency radio astronomy band. However, the accuracy of such an approach is uncertain.

To address these issues, CIRA engineers developed a cost-effective method of extracting noise parameters at low frequencies by using an open circuited coax cable acting as an impedance tuner. The proposed method also establishes a flexible framework of handling devices with two inputs. As a demonstration, the noise parameter of a differential-input single-output low-noise amplifier that is currently used in the MWA Engineering Development Array (EDA) was extracted.

For verification, the noise temperature of the low-noise amplifier obtained from the proposed method was compared to the direct measurement method and through astronomical observations. The direct measurement method involved placing the LNA attached to the antenna under test in an anechoic chamber and measuring the equivalent noise temperature via a well calibrated noise receiver. Astronomers also recovered the noise temperature of the EDA array through astronomical observations, allowing the sky to drift over the array.

The results validated with two independent methods were found to be in agreement within the estimated uncertainty bounds. Thus, the CIRA research engineers successfully demonstrated a cost-effective method of extracting the noise parameters of a differential-input single-output device. They also showed that simulation of noise temperature by means of extrapolation can indeed produce incorrect results. Our new technique has provided the engineering research team (and the wider radio engineering community) a new tool to characterize low-noise amplifiers, which will assist in the system design of low-frequency radio telescopes like the Square Kilometer Array (SKA).

A journal article entitled "Cold-Source Noise Measurement of a Differential Input Single-Ended Output Low-Noise Amplifier Connected to a Low-Frequency Radio Astronomy Antenna" has been submitted to IEEE Trans. Antennas Propagat. for publication. CIRA engineers who contributed to this experiment and paper are Daniel Ung, Adrian Sutinjo, Marcin Sokolowski, and Budi Juswardy.



Comparison of noise temperature of the EDA low-noise amplifier when connected to a Murchison Widefield Array (MWA) antenna. Uncertainties for direct measure method and differential-input single-output were estimated using Monte Carlo simulations. The 'obs' points are the estimated noise temperature of the EDA array through astronomical observation. Image Credit: Daniel Ung, Curtin University

The aperture array verification system

Tom Booler

The international AAVS crew celebrate the successful test of the first end-to-end AAVS1 signal path from an antenna in the field to the processing facility at the MRO. Image Credit: Curtin University

A member of the AAVS field crew implementing modifications to fielded antennas in July 2017. Image Credit: Curtin University

Moving out of the lab and into the field environment is a major step in the journey of every instrumentation project. This step was taken by the Aperture Array Design and Construct (AADC) Consortium (which includes CIRA) in 2017, as the Aperture Array Verification System 1 (AAVS1) took shape at the Murchison Radio-Astronomy Observatory (MRO).

CIRA is a member of the AADC Consortium—a collaboration of universities and research institutes designing the Low-Frequency Aperture Array (LFAA), the collecting element of the SKA_LOW telescope. CIRA's role in the Consortium includes design of the internal power and fibre distribution infrastructure to support the 131,000 LFAA antennas, planning the deployment of the antennas in the field, and coordination of the Consortium's MRO-based prototyping and test activities. CIRA conducts these activities in close collaboration with a number of industry partners, including leading contributions from West-Australian companies GCo Electrical and Balance Utility Solutions. Having built, operated, and performed world class science with the only SKA_LOW precursor instrument, the Murchison Widefield Array (MWA), CIRA and its industry partners are uniquely qualified to undertake and lead these important activities.

The first substantial deployment of AAVS1 hardware on the MRO took place in March 2017. The objective of the March campaign was to complete an entire station of 256 LFAA antennas. However, a significant number of the antennas deployed early in the campaign exhibited unexpected behavior that required analysis and investigation. In the end the activity saw CIRA and its international SKA partners deploy only 100 antennas. Not all of the objectives of the deployment were met, but, nonetheless, the activity was very successful in informing the next engineering design cycle.

During a site campaign in July 2017, CIRA engineers worked with colleagues from INAF to field and test a number of candidate solutions to address the issues that emerged during the March deployment. After settling on a combination of measures, the crew set about remediating as many antennas as possible with a view to assessing the stability of the fixes over time, remotely. Over the months that followed, the antennas that had the fixes implemented proved reliable, giving the AADC Consortium the confidence to plan a subsequent deployment to complete a full station of 256 LFAA antennas.

The full station of 256 SKALA antennas was finally deployed by the CIRA Engineering Team and colleagues from INAF and ASTRON in November 2017. The issues identified during the initial deployments appear to have been overcome and, at the time of writing in early-April 2018, the antenna array has now been functioning for more than 20 weeks without interruption. This has allowed significant amounts of data to be collected under a variety of environmental conditions, a critical step in progressing the 'upstream' digitisation, beamforming, and signal processing systems.

The deployment of AAVS1 through 2017 represented an important transition from small scale, institute-based production and quality control to a regime that is more applicable to Square Kilometre Array (SKA). The kinds production, transport, assembly, and installation procedures and techniques that will be required for SKA were exercised for the first time. It is not surprising then that a variety of issues emerged. The CIRA led team on the ground worked methodically to characterise and document a variety of issues that shaped subsequent engineering design iteration to improve the technical readiness level of the LFAA design.

Engineers and astronomers at CIRA will continue to play an important role in verifying AAVS performance through 2018, as the AADC Consortium incrementally releases signal processing functionality, and the SKA Project progresses through its Critical Design Review process.

100 completed LFAA antennas on the AAVS station with the international AAVS site crew in 2017. Image Credit: Curtin University

HIGHLIGHTS

TEACHING & OUTREACH

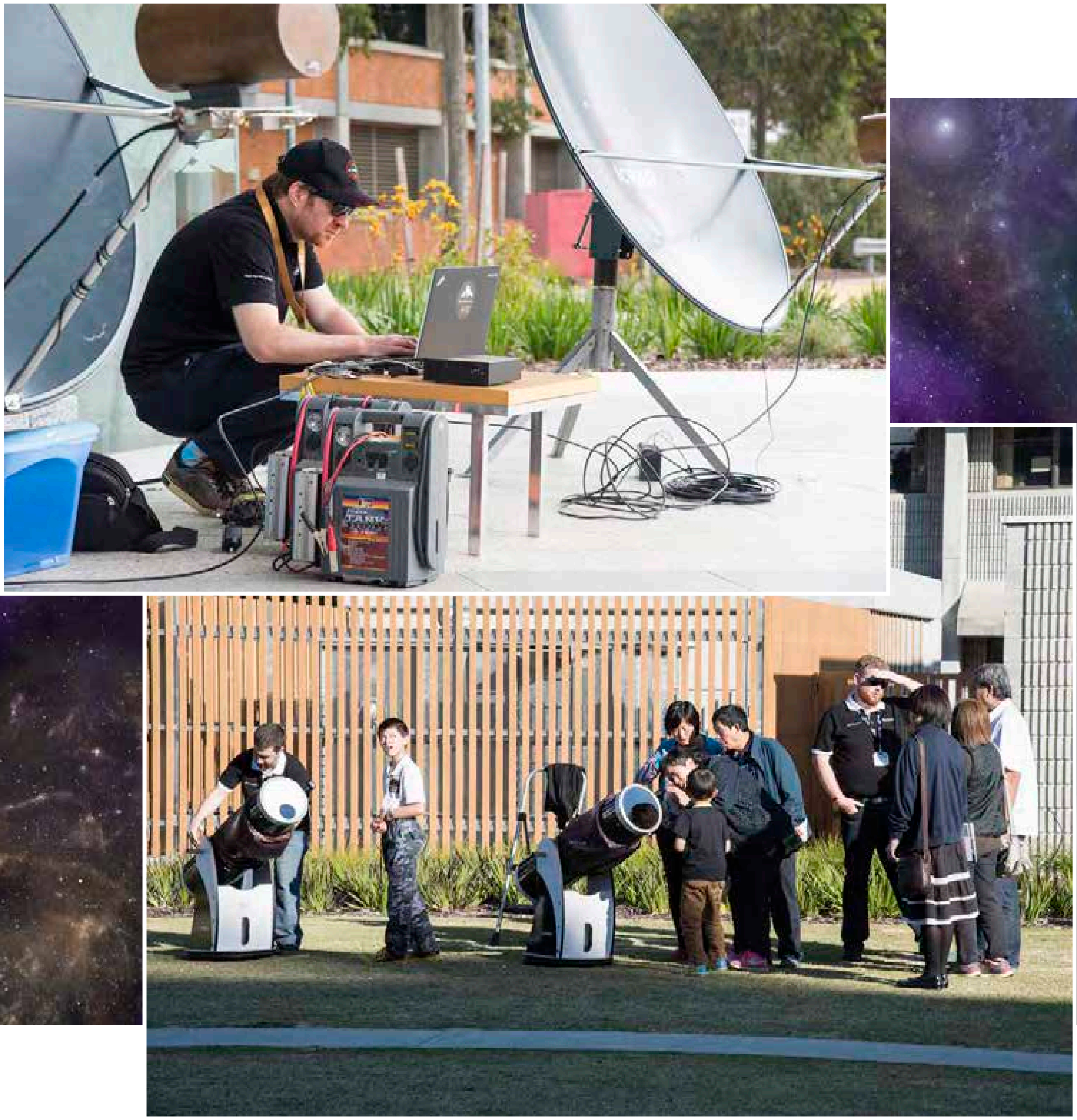


Image Credits: ICRAR

TEACHING & OUTREACH

Teaching 2017

Jean-Pierre Macquart, Paul Hancock

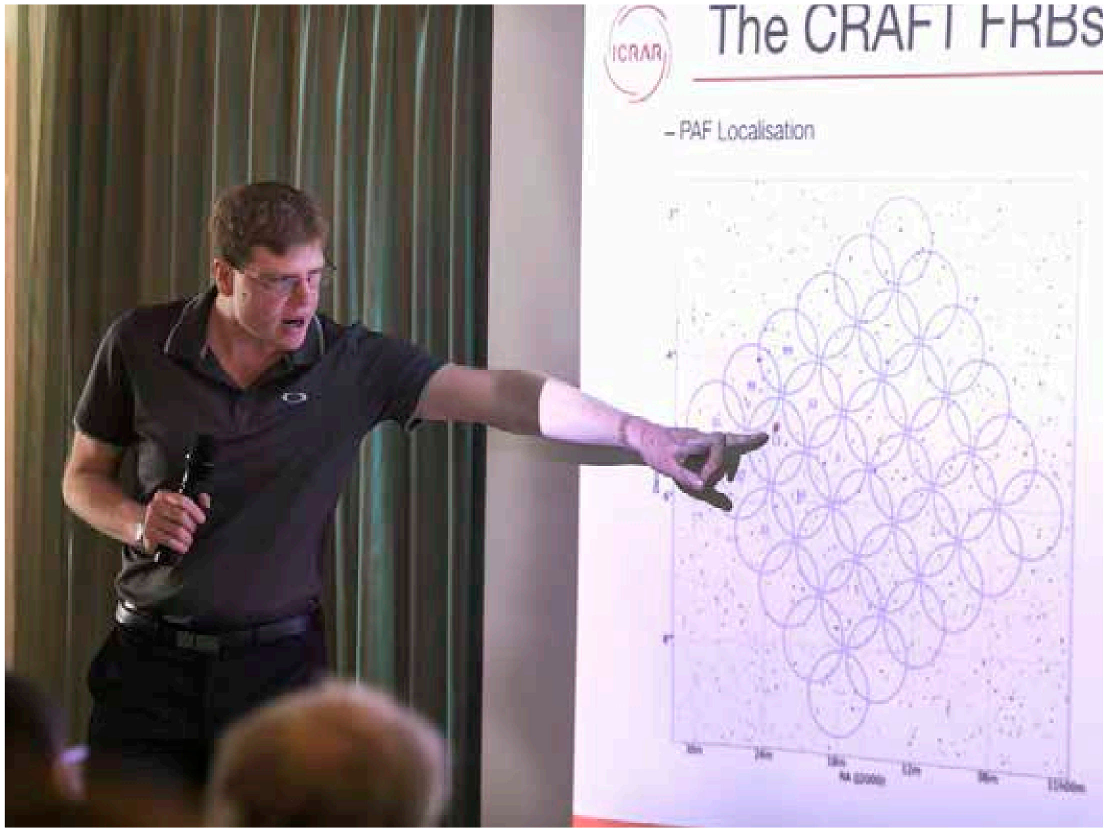


Image Credit: ICRAR

CIRA contributes strongly in the delivery of undergraduate units into the Physics and Engineering streams at all levels, in addition to supervision of undergraduate, Honours, Masters, and PhD projects. Paul Hancock and John Morgan provide our undergraduate cohort with their first exposure to CIRA, teaching first year Physics and the ever-popular Introduction to Astronomy course, respectively.

A large area of CIRA's teaching remains the Astrophysics stream, in which students can choose to specialise from the second year onwards. James Miller-Jones and Rich Plotkin provide a fleeting tour of all basic astrophysics in their second-year unit on the Physics of Stars and Galaxies. Ramesh Bhat and Ryan Shannon then cover Relativistic Astrophysics and Cosmology in the third year, and Nick Seymour rounds the experience by introducing the students to basic radio astronomy with his unit on Exploring the Radio Universe. Finally, several members of CIRA staff are responsible for modules of the fourth-year Honours course run jointly with the University of Western Australia, including Ramesh Bhat, James Miller-Jones, Jean-Pierre Macquart, Nick Seymour, and Cath Trott.

CIRA staff also taught other basic Physics units, including the second-year Statistical Mechanics and Thermodynamics unit (James Miller-Jones and Jean-Pierre Macquart), Electromagnetism (also co-taught by Jean-Pierre Macquart). CIRA staff also taught Engineering units, including Engineering Electromagnetics and Transmission Lines (Adrian Sutinjo, Franz Schlagenhufer, Mia Walker, Budi Juswardy, and Daniel Ung) and Mobile Radio Communications (Randall Wayth, Adrian Sutinjo, Mia Walker, Budi Juswardy, and Daniel Ung).

As in previous years, CIRA also ran our standard summer studentship program in 2017/18, aiming to engage with undergraduate students and expose them to the exciting research being done at CIRA. In addition to 10-week studentships funded by ICRAR and Pawsey, the Department of Physics and Astronomy funded additional six-week studentships for several Curtin undergraduates. The students worked on a range of science and engineering projects, from Fast Radio Bursts, to detections of transients with the Desert Fireball Network (a network of off the shelf cameras spread across the Western Australia Outback), to radio and X-ray studies of black holes and neutron stars. These hands on research experiences for undergraduates continue to provide stimulating learning experiences, that often serve as gateways for Curtin undergraduates to enter Honours and eventually PhD programs within CIRA.

Left to right: Erica Thygesen (Honours student), Elliott Charlton, Matthew Ryan, Ben Quici, and Jaiden Cook (3rd year students). Image Credit: Curtin University

Outreach 2017

John Morgan, Sarah White

Figure Caption: Photo from the Australian Teacher Astronomy Research Program, a two day training workshop during which the teachers learnt how broadband radio spectra allow us to investigate poorly-studied processes in bright, active galaxies. Their findings will be presented at the 2018 Astronomical Society of Australia Annual Scientific Meeting, and it is hoped that exposure to current research at an early stage will encourage more students to pursue physics or astronomy at university. Image credit: Robert Hollow, CSIRO

CIRA staff and students were involved in a wide range of face-to-face outreach events in 2017, including three Astrofests (Perth, Geraldton and Canarvon) and Curtin Open Day which include interactions with many hundreds of attendees (Perth astrofest alone attracted 3000 attendees). There was a particular focus on school incursions in 2017, in which over 300 students were reached over 10 visits. Other events ranged from participatation in the Indigenous Australian Engineering Summer School in January (Kim Steele, Ryan Urquhart, and Mia Walker), to CIRA scientists (Gemma Anderson and Charlotte Sobey) volunteering as mentors for the Innovators' Tea Party (an event designed to inspire female high school students to pursue careers in STEM fields), to CIRA representation at a booth at the WWW 2017 Expo in Perth, to numerous public talks throughout the year. A TED talk given by Natasha Hurley-Walker in 2016 on the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) Survey accrued over 1 million online views in 2017, and Dr Hurley-Walker was onstage to help open TEDx Perth 2017.

In addition, during the year over a hundred teachers were reached in events specifically targeted at science educators. In particular, 2017 saw the start of a new initiative known as the "Australian Teacher Astronomy Research Program (ATARP)", co-ordinated by Michael Fitzgerald at Edith Cowan University and Robert Hollow at CSIRO. As one of two Australia-based astronomers taking part in the program, Sarah White devised a research project that can be carried out by local secondary-school teachers and their students (see photo).

The big discovery of 2017 that garnered international media attention was the LIGO/Virgo detection of a neutron star merger. This discovery involved several instruments and institutions across Western Australia, with several CIRA staff and students being co-authors on the discovery paper(s). During 2017, CIRA staff and students, including James Miller-Jones and Randall Wayth gave interviews to The Australian and the West Australian respectively. The MWA upgrade continued to garner attention with MWA Director Randall Wayth giving interviews to ABC, The Australian, GWN7, The West Australian and Business News. Chenoa Tremblay also gave interviews on her work on Molecular lines with the MWA.

On a rather different note, Gemma Anderson represented the Astronomical Society of Australia as one of only 200 delegates at the annual Science Meets Parliament event in Canberra. Finally John Morgan, Rajan Chhetri, Paul Hancock, James Miller-Jones, Randall Wayth, and Andrew Williams, provided commentary to the media on various science and astronomy topics of general interest.

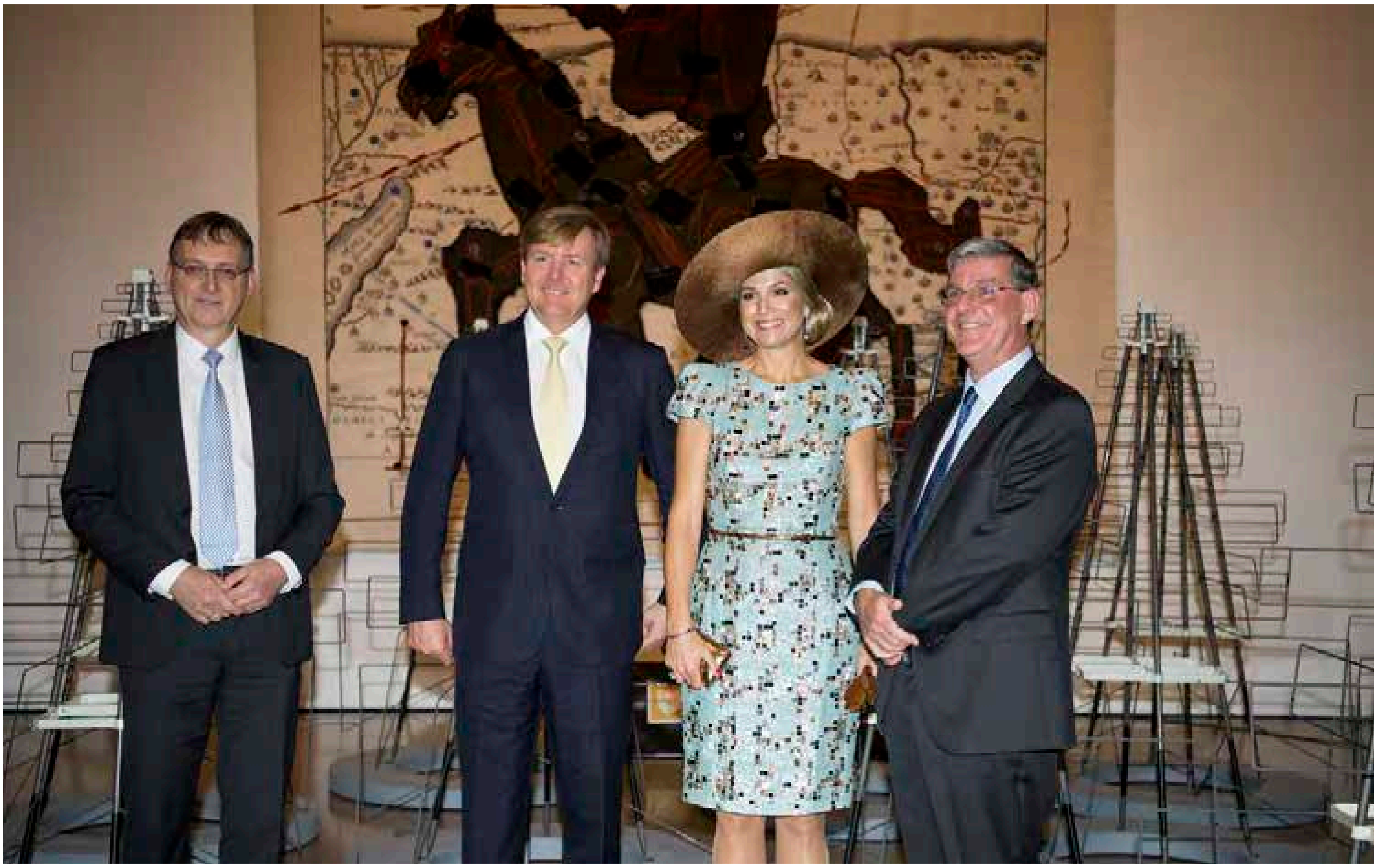
Image Credit: ICRAR

Dutch Royal Visit

Peter Hall

As 2016 turned into 2017, as what was designed by request as a low-key visit, King Willem Alexander and Queen Maxima visited Curtin University on November 1. As part of the visit, Their Majesties viewed a movie and heard a talk by Prof Peter Hall outlining the Square Kilometre Array (SKA) and the decades-old Dutch – Australian radio astronomy relationship. The King and Queen were well-informed about the SKA project and, in particular, articulated their understanding of radio-quietness as a key attribute of an Early Universe radio telescope. While important in cementing the place of SKA Low in Australian thinking, the visit was also significant to a Dutch science community seeking SKA construction contributions.

DUTCH ROYAL VISIT



Above: Their Majesties with Dr Michiel van Haarlem, ASTRON SKA Director and Prof Hall, in front of an SKA mini-station assembled using an advance shipment of AAVS1 antennas, fibre optic links and high-speed digital signal processors.
Below: Their majesties talking with Prof Ron Ekers and ICRAR/Curtin engineers and graduate students.

Image Credits: Curtin University

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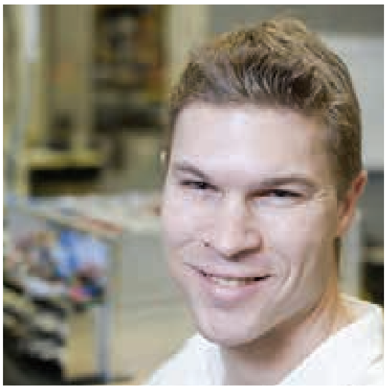

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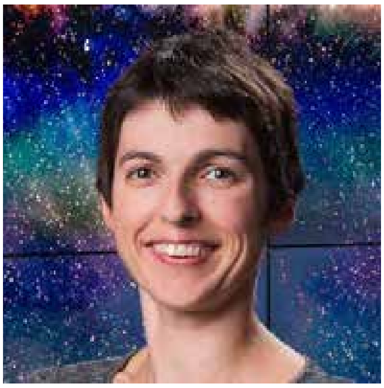
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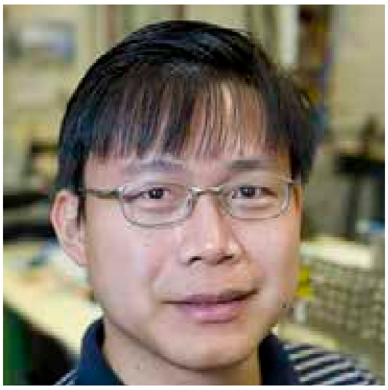
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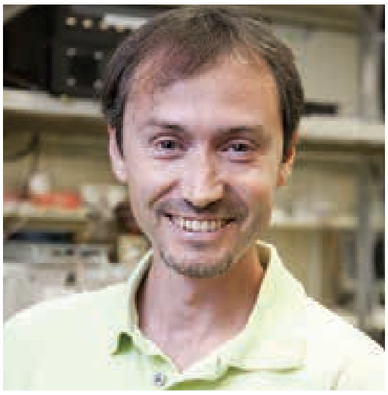
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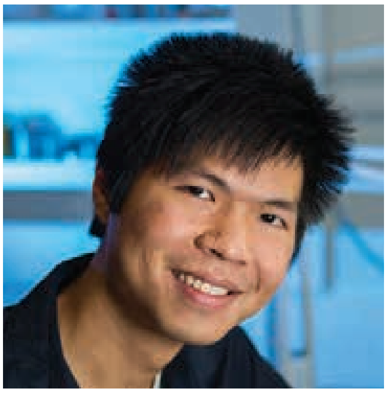
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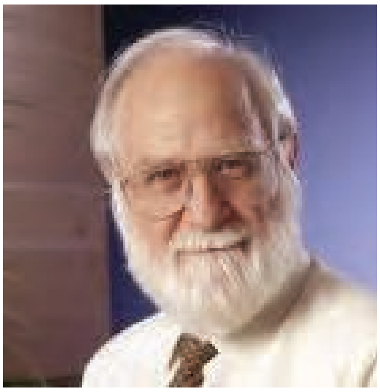

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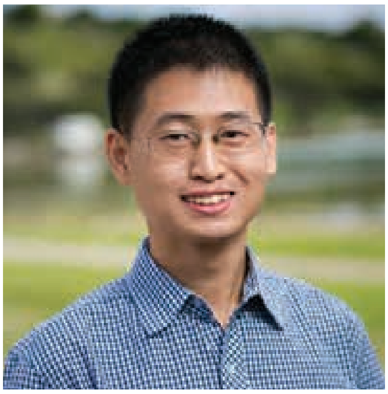

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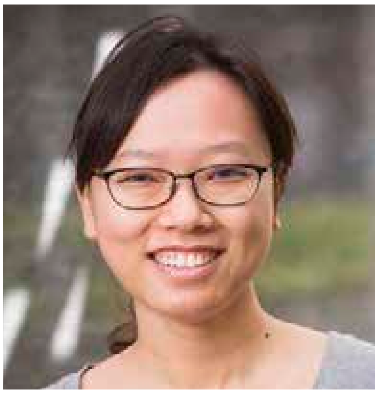

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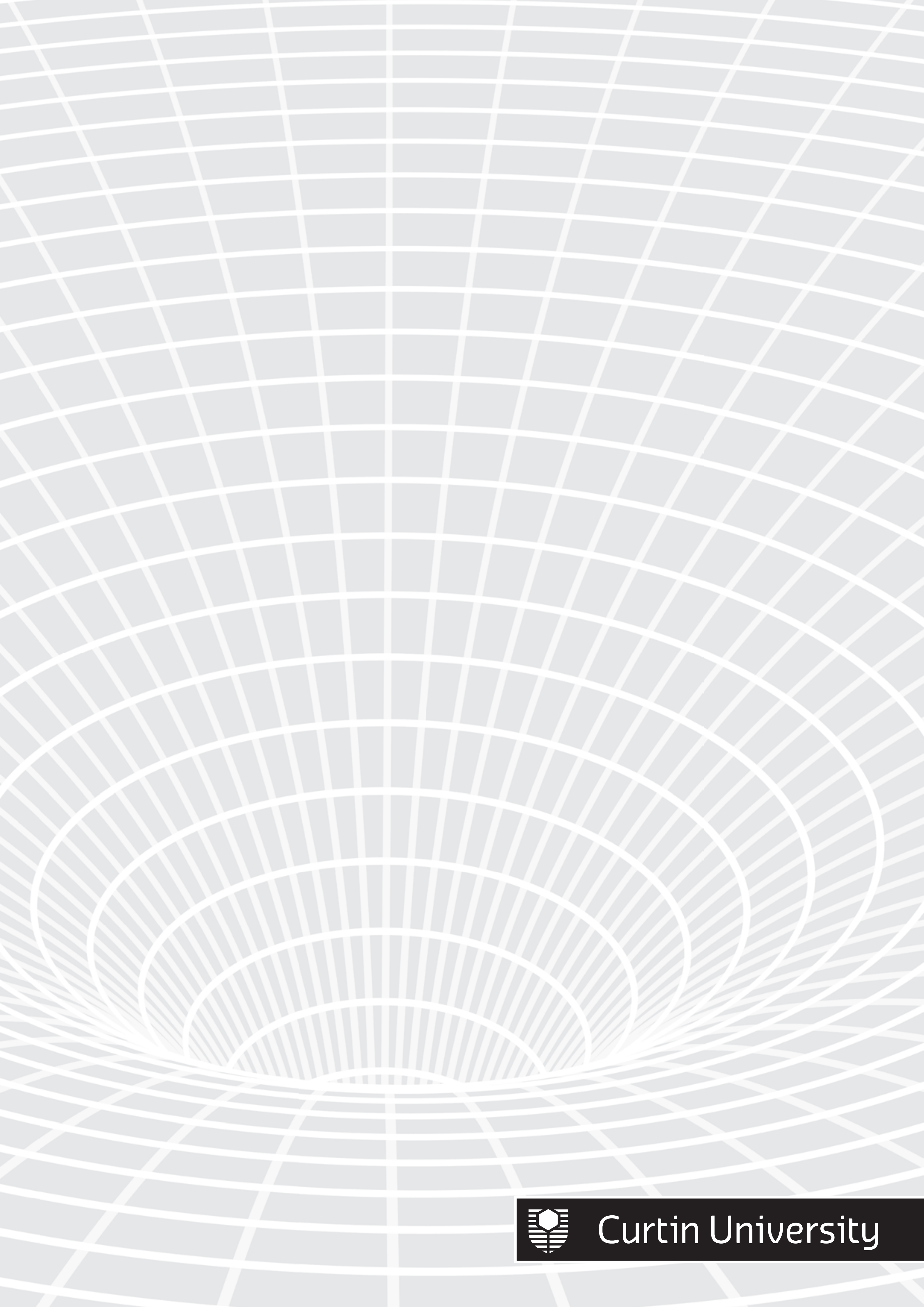

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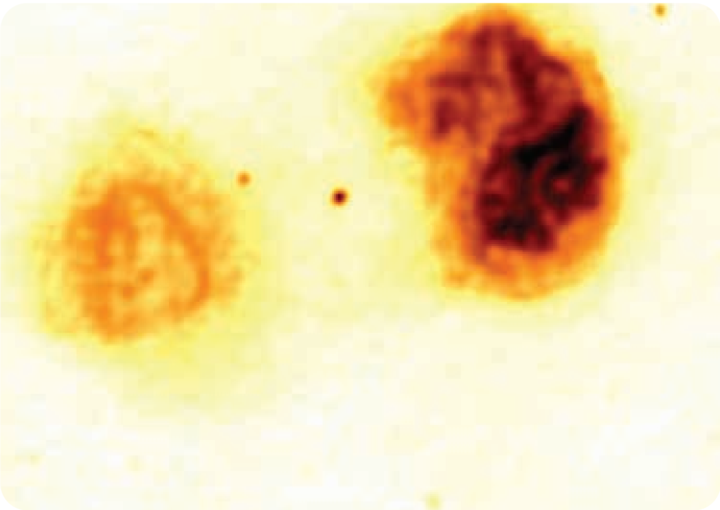

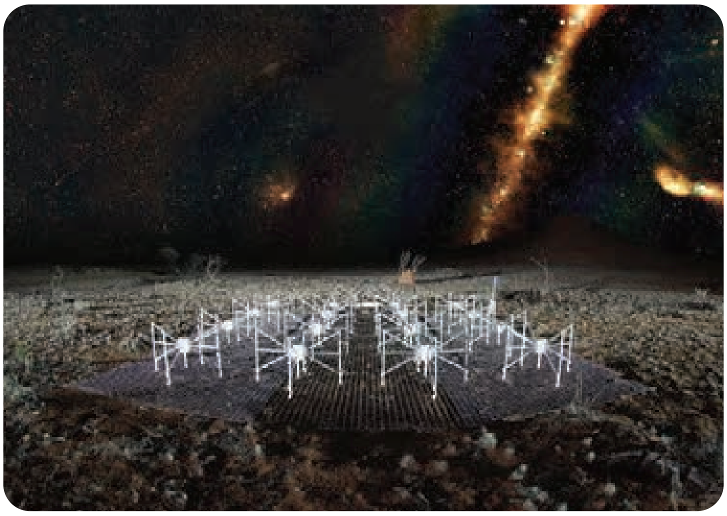

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