CIRA

CURTIN INSTITUTE OF
RADIO ASTRONOMY

2018

ANNUAL
REPORT

Curtin University

Curtin University

Contact Us:
Curtin Institute of Radio Astronomy
Curtin University.

Postal Address:
GPO Box U1987 Perth WA 6845
Tel: +61 8 9266 9899
Fax: +61 8 9266 9246
Email: cira@curtin.edu.au

Street Address:
Building 610 - 1 Turner Avenue,
Technology Park, Bentley WA 6102

http://www.astronomy.curtin.edu.au

CRICOS Provider Code 00301J

This annual report covers the calendar year 2018

Editors:
Mia Walker
Guillaume Drouart

Images on the front and back highlight CIRA activities in 2018

Front cover:

Top: The Torpedo star cluster imaged in radio, optical and X-ray wavelengths. Data taken using the Murchison Widefield Array telescope is shown in magenta. Credit: Zheng et al. 2018

Bottom: Artist's impression of a jet being emitted by the high-magnetic field neutron star system Swift J0243.6+6124. The neutron star is surrounded by an accretion disk, which is truncated by the strong magnetic field. Energetic jets are launched from close to the neutron star, possibly due to extraction of the neutron star's rotational energy. Credit: ICRAR/University of Amsterdam

Back cover:

Top: Showcasing 3D-printed antenna models at the 10th anniversary of Astrofest, Perth. Credit: ICRAR

Bottom: Prototype antennas for the low-frequency Square Kilometre Array radio telescope. Credit: ICRAR

CONTENTS

Annual Report 2018
Curtin Institute of Radio Astronomy

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 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. To minimise duplication in reporting, CIRA's programs are formally monitored and assessed via the ICRAR Executive and Board.

Steven Tingay

Director's Report

2018 was a year of transition and growth for the Curtin Institute of Radio Astronomy. At the start of the year, we welcomed two new Directors, Prof. David Davidson as Director of Engineering and Prof. Melanie Johnston-Hollitt as Director of the CIRA-hosted Murchison Widefield Array (MWA) project. In addition, Mr Tom Booler had earlier been appointed as Director of Operations and Assoc. Prof. James Miller-Jones as Director of Science. The new Executive team settled into its work very well over the course of 2018, guiding several big changes, such as to the management of the MWA and in preparation for the renewal of ICRAR funding beyond mid-2019. I would like to personally thank the CIRA Executive Team for our constructive and effective discussions and coordination, placing what is a large-scale and complex set of activities under the CIRA banner in a very good position at the close of 2018.

Our bid for renewed ICRAR funding, with our colleagues at The University of Western Australia, was enthusiastically received by the State Government of Western Australia and the two university partners and has resulted in approximately $28M being available at CIRA for ICRAR activities in the period mid-2019 to mid-2024. We greatly appreciate the support of Curtin University, through the Research Office at Curtin (ROC) and the Faculty of Science and Engineering, in making these substantial investments in CIRA. This new investment underpins all of our activities and allows us to successfully leverage resources from other sources to grow CIRA during the period that will see the commencement of construction for the Square Kilometre Array (SKA) in Western Australia. We look forward to working with our valued and long-term collaborators at UWA, and the State Government, in continuing ICRAR over the next five years.

Our footprint in the SKA project has grown substantially in the last 12 months. Our group is now at the centre of the final stages of design and prototyping for the low frequency SKA, with continued substantial funding from the Commonwealth. 2018 has been an intense year for the SKA for us and 2019 is shaping up to be at least as intense again. We are in an excellent position to participate in SKA construction and are held in high regard around the SKA project. This is a testament to our integrated team of engineers, scientists, and managers and our industry-facing attitude. We also greatly value the strategic partnership we have established with Italian colleagues in the SKA project, which is bearing fruit in these final stages of the SKA design process.

Beyond the SKA, CIRA has attracted very significant external funding in 2018 from the ARC, other Commonwealth government schemes, and international research funding schemes. This success in attracting the inputs for research (funding) is matched by our conversion of the inputs into outputs, high quality and high impact publications. In the pages of this annual report you will find a selection of this research described, across astrophysics and engineering, and, importantly, spanning both disciplines in a manner that is unique to CIRA within an Australian university setting and rare at an international level. The sum total of CIRA's outputs have allowed us to retain the maximum ranking of 5, "well above international standard", in the last ERA round and to make a substantial contribution to Curtin's improving ARWU ranking (and other institutional metrics).

I'm also very proud that all of this success is within the context of a group that pays close attention to the professional and personal welfare of its employees. At CIRA, we strive to align ourselves strongly with the strategic direction of Curtin University, to make sure staff and students have all the opportunities they require to prosper within a supportive environment, and that we uphold the highest measures of performance against international benchmarks within our fields of research. We have done this as an integrated team in 2018, as has been our strength for the last decade. This is the collective achievement of CIRA and the conditions appear favourable for this to continue into 2019 and beyond.

Several new large-scale initiatives are in the pipeline for CIRA over the coming 12 months and I hope to be able to report on their successful establishment in this introduction next year.

James Miller-Jones

Director's Report

SCIENCE

Following the transitional period of 2017, the CIRA science team settled into a new organisational structure over the past year, with a focus on closing out the ICRAR II science program by the middle of 2019. Strengthened by a significant cohort of staff arriving to join the Epoch of Reionisation (EoR) team as part of the ASTRO-3D ARC Centre of Excellence, CIRA maintained its impressive scientific output, with just under 100 papers published in 2018. Of particular note are the publication of the first high-profile results from the ASKAP CRAFT survey for Fast Radio Bursts, the development of the interplanetary scintillation technique for identifying compact radio sources, and the modelling of the radio emission and reflection from the Moon as part of the global EoR signal search.

One of the year's highest-profile astrophysical results came from the IceCube neutrino detector in Antarctica, which was able to associate a high-energy neutrino with an astrophysical source for the first time. The radio follow-up of this event led to one of several high-impact results involving CIRA staff that were published in the prestigious journals Nature and Science over the past year. These and a number of other publications generated significant media attention, demonstrating the public appeal of the work being done across the entirety of the CIRA science program.

As discussed elsewhere in this report, our staff and students engage with the public at a variety of levels, from school visits to work experience weeks and public lectures. The advent of the new ARC Engagement and Impact report for Universities underlines the importance of such programs, and it was therefore extremely heartening to see a number of CIRA staff recognised for their excellence in both research and scientific communication, from ARC Fellowships to prestigious state-based or national awards. It was also extremely pleasing to see the efforts of several of our staff being recognised internally, via success in the University's annual promotions process.

In closing, I would like to thank my fellow Directors for all their high-level strategic advice, the science group leads for the smooth running of their teams, and all of our science staff for their continued commitment to excellence and professionalism over the past year. I look forward to a successful close-out of our ICRAR II commitments in 2019, and a smooth transition into the third phase of the ICRAR program.

ENGINEERING

David Davidson

Director's Report

In January 2018, I arrived from South Africa, where I had held the SKA Research Chair at Stellenbosch University, to take up my position as the new Engineering Director and Professor of Radio Astronomy Engineering. Within a short period, I was heavily involved in our continuing work on SKA-LOW, planning for ICRAR-III, and managing new appointments in the engineering group.

The CIRA engineering group continued its tradition of high-impact work that I rapidly grew to appreciate as one of our hallmarks. The articles that follow showcase some of the highlights of the year, many of which span the Engineering, Operations and Science programs.

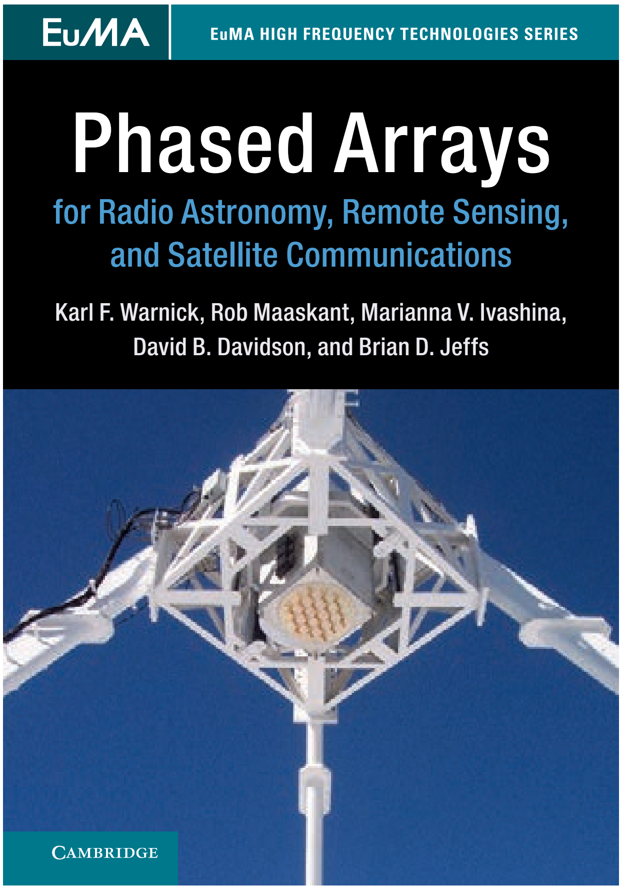
On the engineering front, the research program continued to produce quality publications rooted in CIRA's instrumentation programs and the field in general. I was delighted to be able to contribute to this via publication of a book on phased arrays, which I co-authored with colleagues in the USA and Europe. (The image shows the cover artwork). A considerable amount of our work was devoted to further commissioning of the SKA demonstration and test system Aperture Array Verification System 1 (AAVS1), deployed on the Murchison Radio-astronomy Observatory (MRO) during 2016 and 2017. I took the lead in writing the LFAA Demonstrator Test Report (SKA-TEL-LFAA-0800001), prepared for the SKA Low-Frequency Critical Design Review (which took place in December 2018); this represented a major collaborative effort by our group. This was a key document presented at the CDR, and led directly into our present work on the SKA-LOW Station Calibration bridging project, which started in November – before the CDR meeting had even taken place.

Operational responsibility for the Murchison Widefield Array (MWA) now resides with the new MWA Director, who also took up her role during 2018. However, work within the engineering group continued on a new software correlator for the MWA.

Several new appointments were made in the Engineering group. Dr Ian Morrison joined us mid-year from combined roles with Swinburne and Cisco; he is one of the main architects of the new MWA correlator. Dr Nipanjana Patra joined us later in the year from UC Berkeley; she is an expert in all-sky observations for 21cm cosmology. Finally, Dr Gregory Hellbourg joined us in November, also from UC Berkeley. He is an expert in the mitigation of radio frequency interference, in particular using spatial filtering.

On a personal note: I would like to acknowledge the contributions of my predecessor, Professor Peter Hall (a founding director of CIRA); he built up the very impressive engineering team which I have inherited. Special thanks to Tom Booler, who acted as Engineering and Operations Director in the period between Peter's retirement and my arrival, and kept me in the loop through some lengthy delays while visa issues were resolved. It has been a great pleasure working with Tom this year in his new position as CIRA Operations Director. Many thanks also to Prof Steven Tingay for his inspirational and visionary leadership as Executive Director of CIRA, and A/Prof James Miller-Jones, Science Director, with whom it has also been a great pleasure to work closely. Thanks also to A/Prof Randall Wayth and Dr Adrian Sutinjo for bringing me up to speed very quickly with the many complex activities underway at CIRA, and to the whole engineering team – and indeed the entire institute - for making me feel very rapidly an integral part of CIRA.

Finally, a note of heartfelt thanks to my wife and two teenage sons, who endured being uprooted from our home and extended family in the Western Cape and transplanted six times zones away to Western Australia.



OPERATIONS

Tom Booler

Director's Reports

CY2018 was all about the SKA Critical Design Review (CDR).

Early in the year CIRA and its industry collaborators contributed to a CDR readiness review as part of our participation in the SKA-preconstruction consortium charged with the design of the Low Frequency Aperture Array (LFAA) for SKA-Low. CIRA's complete and high quality submissions to this activity - on the LFAA Power and Signal Distribution sub-system, and LFAA deployment - stood apart in a Consortium return that was deemed insufficient overall by the external panel that undertook the review.

Following the negative outcome of the CDR readiness review, the SKA Office intervened directly in the management of the LFAA Consortium. The objective of the merged - SKA Office and LFAA Consortium - entity that emerged was to constrain the delay to LFAA CDR to 6-months, in order to limit the impact on the system-CDR timeline. CIRA personnel worked intensively with SKA and key LFAA consortium personnel to rationalise, and then compile the LFAA CDR submission. This effort culminated in late 2018 and was rewarded with a CDR pass, which allowed LFAA to transition to the next phase of activity. The efficiency with which the re-structured, collaborative, entity was able close the considerable gap in readiness is testament to both the shared positive intent of the merged team, and the inefficiencies inherent in the way the SKA pre-construction had been managed prior.

The CIRA Ops Team - including Admin and MWA/MRO/SKA personnel - play a critical role in CIRA's ongoing success and impact in SKA. The extraordinary effort and patience required to constantly respond to evolving circumstances cannot be overstated. The capability we have developed and the experiences that we have collectively gleaned stand us in extremely good stead as we look toward a phase of SKA where they will be to the fore.

Melanie Johnston-Hollitt

Director's Reports

2018 was a big year for the MWA with a number of significant milestones. Firstly, there were a number of management changes for the Project, with me stepping down as Chair of the Executive Board after 4 years and assuming the role of Director from A/Prof. Randall Wayth. I'd like to thank Randall for his tenure as Director and for allowing a very smooth transition. Randall has not strayed far from the MWA and retains his position as Principal Engineer. My move from MWA governance to operations has been an interesting exercise in which I have learnt and unlearnt many things, that it also coincided with my return to Australia after nearly a decade leading the SKA efforts in New Zealand, made it a very busy year. Beyond the change of Director we continue with an unchanged MWA Management Team with Tom Booler continuing as MWA Program Manager and Dr Adam Beardsley (Arizona State University) as Principal Scientist. The MWA Operations Team also saw some personnel changes with the departure of Luke Horsely and Kim Steele, and the arrival of our new Fieldwork Coordinator, Andrew McPhail. Andy arrived in August and joined Dave Emrich, Greg Sleap, Mia Walker, and Dr Andrew Williams to form the newly defined MWA Operations Team, which was separated as an independent unit within CIRA under the control of the MWA Director in September.

For the telescope itself April saw the official launch of Phase II with a celebration at the Curtin Hub for Immersive Visualisation and eResearch (HIVE). Phase II of the telescope is both an increase in the scientific capability of the instrument, and an expansion of the MWA collaboration to include 21 partner organisations across 6 countries. In a piece of precision timing, the official 'go' button was pressed simultaneously by Federal Minister for Jobs and Innovation, the Honourable Michaelia Cash, Parliamentary Secretary Chris Tallentire, Curtin Vice-chancellor Professor Deborah Terry and myself. However, for me the highlight of the event was the live stream to site with MWA Engineers Mia, Kim, and Luke 'hacking' a tile to connect to the HIVE during the ceremony (pictured). The process worked flawlessly and was the perfect example of the way that MWA staff are able to pragmatically and easily do spectacular technical things.

One of the great technical successes for the MWA was the completion of the trial of the MWA node of the Australian All Sky Virtual Observatory (ASVO) in December. The ASVO replaced the previous command line MWA data access protocol with a streamlined web-based interface, which has greatly improved accessibility of MWA data both within and outside of the MWA Collaboration. Additionally, the MWA became one of the few radio observatories to serve calibrated visibilities which we expect will greatly increase the return of papers utilising MWA data.

The output of the MWA collaboration is continuing to grow, and analysis of the metrics shows that a large proportion of the publication output for the telescope is driven by early career researchers (ECRs) many of whom are women and mostly Australian. In fact in 2018 76% of papers produced using MWA data were led by ECRs and 56% of the total publications were led by staff and students at CIRA. This highlights the important role CIRA plays in both supporting the telescope and that the MWA plays in the scientific output of the institute. Of course while MWA operations reside in CIRA and Curtin is the lead organisation playing a central role in both the operations and scientific exploration of the telescope, it is also important to note the international nature of the project. As of 2018 the MWA Collaboration boasted 270 individual members, up from 120 at the commencement of Phase I and 2018 saw a number of new MWA collaboration members from China and Japan visit CIRA and then publish papers with MWA data. This is great to see and with the signing of the recent MoU between Curtin and SHAO I look forward to seeing these collaborations expand and thrive.

In conclusion, 2018 has been a good year for the MWA and has set the stage for even bigger and better things in 2019, and I look forward to working with our staff, students, partners and supporters to take the MWA to even greater heights!

Diversity, Inclusion & Equity

The CIRA Development Committee

Mia Walker

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

DevCom Mission Statement

2018 was a very busy year for the CIRA Development Committee (DevCom), with a large number of events to support and increase diversity, inclusion and equity.

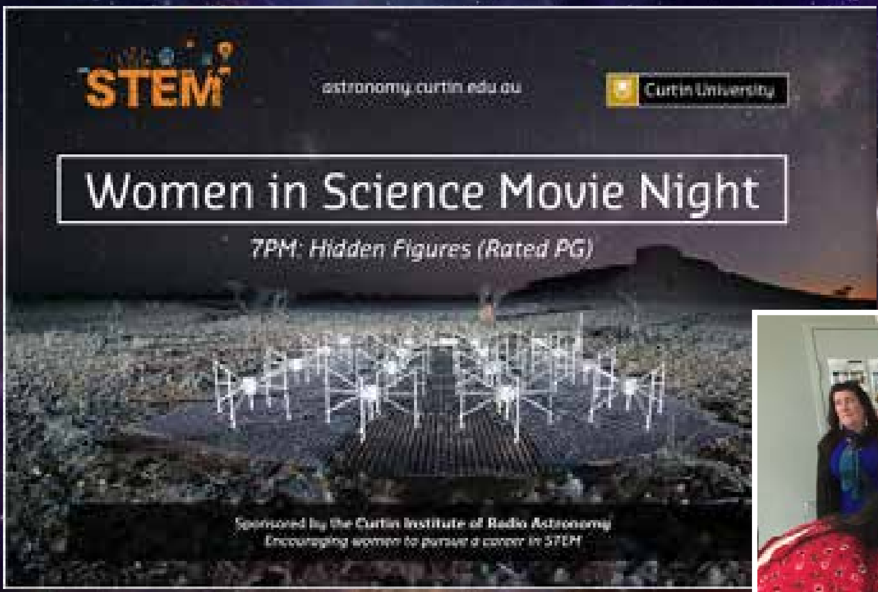
DevCom ran a new climate survey in 2018, to evaluate CIRA's improvement in the areas of gender equity, communication, family friendliness and cultural inclusiveness, in the period since CIRA's 2016 climate survey and Curtin's 2017 “Your Voice” survey. CIRA reported a lot of satisfaction across the board to the encouragement of DevCom, inspiring even more ideas and initiatives.

DevCom organised for Visiting Women's Fellow Anna Frebel to run a career development workshop for Early Career Researchers, and also for Jo Ward and Nicoleta Maynard (Curtin Athena SWAN leads) to give a colloquium on gender statistics at Curtin and the Athena SWAN initiative. DevCom also started maintaining a library of diversity and equity articles on the CIRA wiki, and ran a Women in STEM movie night on Curtin campus to encourage undergraduates (especially women) to consider careers in STEM fields, by showcasing powerful stories with female leads.

Cultural diversity was tackled in 2018 with a Cultural Intelligence workshop run by PRISMA, designed to help everyone acknowledge cultural differences and present tools for how to work most effectively and enjoyably with each other. Another very successful international lunch was also organised by DevCom, with staff and students bringing food to share that represents their cultural background.

DevCom and other CIRA staff and students were also the first to participate in an Inclusive Practice program developed by Curtin's Ethics Equity and Social Justice (EESJ) centre, which discussed important concepts such as implicit (sub/unconscious) bias and privilege.

In 2017 DevCom collaborated with CIRA Executive to create “cheat-sheets” of Curtin policies, to ensure an unbiased approach towards employee selection during the hiring process, and in 2018 added a new document related to gendered reference letter writing and preparing



Promotional image displayed at the DevCom Movie Night

International Lunch Day

job application materials. DevCom also prepared a work expectations document for current staff, and updated the wiki with information and resources for new staff and students.

DevCom has also improved their communication of objectives and activities to CIRA through regular updates at all-staff meetings, the circulation of DevCom meeting agendas and minutes, and the installation of a pin-up board. DevCom also led a CIRA-wide discussion of the importance of the annual performance and planning review process for maintaining workload "wellness" and work-life balance.

To endorse family friendliness at CIRA, DevCom promoted Curtin's policies regarding flexible working arrangements, and encouraged meetings to be scheduled during the family friendly core hours of 10am-3pm. Furthermore, DevCom organised for a room at CIRA to be upgraded with a privacy lock, table, and power point to assist breastfeeding parents.

In 2018, DevCom student representatives proposed that CIRA students would benefit from a direct channel of communication with the Director. As a result, a new student representative was established, who would be appointed by the CIRA student body and responsible for communicating student-identified issues directly to the CIRA Executive via regular meetings.

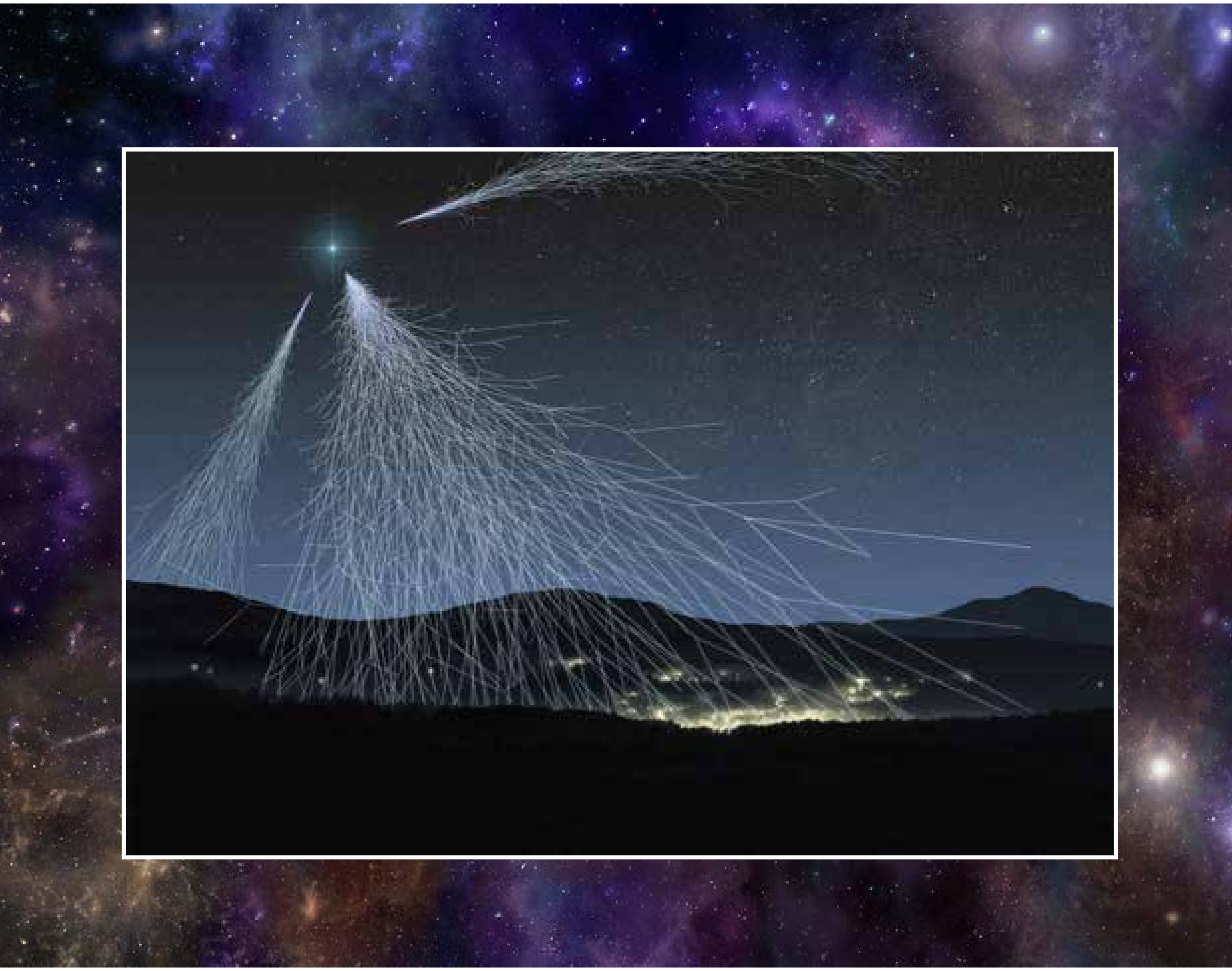
The actions of DevCom from 2016-2018 were presented in an application for a silver Pleiades award by the Astronomical Society of Australia (ASA), which would recognise CIRA as an organisation that takes active steps to advance the careers of women.

DevCom will continue to work with the CIRA Executive and Science in Australia Gender Equity (SAGE) to foster an equitable and inclusive culture within CIRA.

The 2018 CIRA Development Committee consisted of Rich Plotkin (Chair), Paul Hancock (Deputy Chair), Mia Walker (Scribe), Gemma Anderson (SAGE Liaison), Rajan Chhetri, Greg Sleap, Alex Williamson (student rep), and Pikky Atri (student rep).

HIGHLIGHTS

An artist's impression showing fast radio bursts in the sky above CSIRO's ASKAP radio telescope. Fast radio bursts come from all over the sky and last for just milliseconds. Researchers from CIRA were able to detect 23 of these elusive signals in 2017-2018 using ASKAP. ASKAP is located at the Murchison Radio-astronomy Observatory, the future site in Australia for the Square Kilometre Array (SKA). Credit: OzGrav, Swinburne University of Technology.



Artistic view of a cosmic ray shower. The origin of cosmic rays is unknown, but when one impacts the upper atmosphere, it produces an extensive air shower of secondary particles that emit bursts of radio waves. CIRA researchers deployed a prototype particle detector at the Murchison Radio-astronomy Observatory to trigger radio observations with the MWA telescope. Credit: ASPERA/Novapix/L.Bret.

Discovery of a new pulsar switching between accretion and pulsation

Arash Bahramian and James Miller-Jones

Image above: Star cluster Terzan 5 as seen by the Hubble space telescope. This cluster contains millions of stars and is host to dozens of accreting neutron stars. Credit: Hubble Space Telescope.

Pulsating neutron stars (pulsars) are the rotating hot remnant core of massive stars after death. Their magnetic poles are hotter and brighter than the rest of the surface, causing them to show radio pulsations as they rotate. Pulsars are expected to slowly lose energy over millions/billions of years, and slow down. However, there are numerous very old pulsars that have faster spin rates than typical new born pulsars. This indicates that these millisecond pulsars have been "spun up" by some source of energy. For years it has been speculated that the source of this energy is accretion from a companion star, where the pulsar is in a very tight binary system with a normal star and the strong gravity of the pulsar pulls matter from this companion star in the form of an accretion disk. Over millions of years, this process would deplete the companion star, and spin up the neutron star. Discovery of accreting neutron stars which show X-ray pulsations (pulsations caused by the accreted material falling onto the neutron star surface, as opposed to the rotation-powered pulsations in radio), supported this theory, and suggested that these accreting neutron stars might be progenitors of millisecond pulsars. However, the absence of radio rotation-power pulsations indicated there is a missing evolutionary step between accreting X-ray pulsars and radio millisecond pulsars.

The mystery of this missing link was solved by discovery of "transitional millisecond pulsars" (tMSPs) in 2013. These are pulsars in binary systems, which frequently switch between an accretion state in which they show accretion-powered X-ray pulsations and a pulsar state where they show rotation-powered radio pulsations.

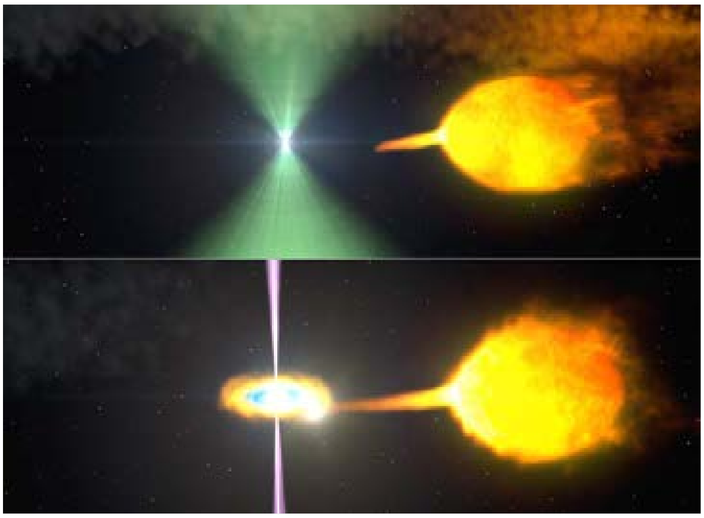
Studying common observational behaviors/patterns in these systems paves the path to better understanding them, their physics and the complete evolution from an accreting neutron star to a millisecond pulsar, but these studies are currently hampered by the fact that there are only a handful of these systems discovered so far. Expanding the sample size by searching for these systems would provide the ground work to better understand this evolution and what happens to neutron stars as they devour a companion star over billions of years.

For the last few years we have been surveying old Galactic star clusters (in radio and X-rays) to look for elusive yet energetic accreting systems like accreting neutron stars and black holes. Old star clusters contain some of the oldest stars in the Galaxy and thus host a high number of black holes and neutron stars. Our survey has led to discovery of unusual systems like a black hole-white dwarf binary system in star cluster 47 Tucanae.

In 2017 and 2018, as we continued our survey, we discovered a new candidate tMSP in one of the most massive star clusters in the Milky way. This old star cluster, known as Terzan 5, hosts dozens of old millisecond pulsars among many other unusual energetic systems. We took deep X-ray and radio observations of this cluster and also looked at older archival data of this fascinating cluster to study energetic systems like the pulsars it harbours. Our study revealed one of the brightest X-ray sources in this cluster has X-ray spectrum of an accreting neutron star, and shows bright radio emission consistent with pulsars. Both radio and X-rays vary over time in the same manner that transitional millisecond pulsars do. This system is the furthest discovered tMSP so far (19000 light years away) and the second one discovered in a dense star cluster.

Binary stars in tight orbits in star clusters are mostly formed as a result of one star getting trapped in another star's gravity field. This is different from the rest of the Galaxy where stars are too far apart to affected by each other's gravity field, and binary stars are simply born together. Thus, discovery of this tMSP in one of the densest star clusters in our Galaxy indicates a complicated evolutionary history, where the neutron star was formed billions of years ago as a young pulsar, and as it moved around in the cluster, it formed a binary with its current companion. Through accretion from this companion, it started to spin up and became the system we see today. It is also likely that other stars in the cluster passed close to the binary and impacted the binary orbit.

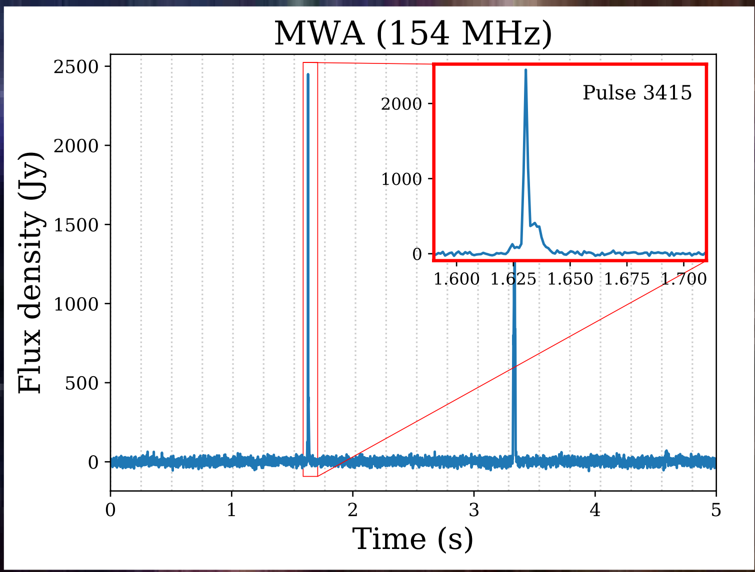
We are continuing our survey, with more results on the horizon. We hope that this survey helps us better understand how neutron stars and black holes evolve.



The two states in a transitional millisecond pulsar; a tMSP swings between a rotation-powered pulsating state (top) and an accretion-powered pulsating state (bottom). Credit: NASA's Goddard Space Flight Center.

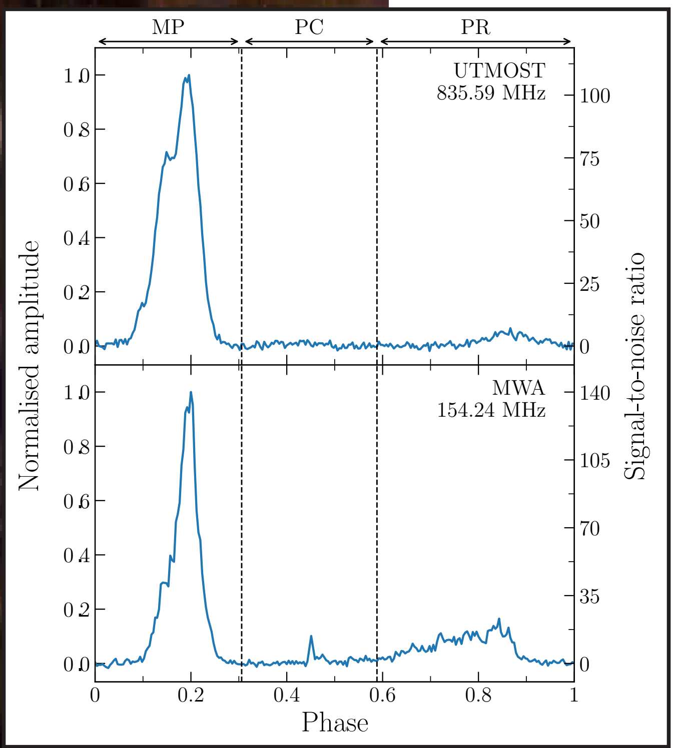
The first detection of low-frequency radio emission from a mostly-off pulsar

Bradley Meyers, Steven Tremblay and Ramesh Bhat



The integrated profile of PSR J1107-5907 constructed from the mean of all single pulses above our detection threshold. The profile is split into three regions: main pulse, postcursor and precursor. It is clear that emission occurs over a very large range of rotation phase, and that there are some differences between the profile shape and position of components.

A time series displaying 21 rotations of PSR J1107-5907 (separated by grey dotted lines). An example of the extreme emission this pulsar can produce is highlighted in the inset – a very bright (2.5 kJy) pulse observed with the MWA, with a relatively weak counterpart observed by UTMOST.



Pulsars exhibit a wide variety of emission phenomena, which makes understanding the physical processes responsible for producing said emission difficult. This is especially true for a relatively new class of pulsars, known as "intermittent" or "state switching" pulsars, which spend most of their time in the "off" state, during which no emission is detected. Ergo, these pulsars require extraordinary observing strategies to detect and characterise. Nevertheless, the effort is justified, as these pulsars may hold a vital clue to the underlying pulsar emission mechanism, and to why some pulsars are more "intermittent" than others.

Not surprisingly, only a handful of such objects are known; fewer than 10, out of more than 2700 pulsars, have been catalogued to date. However, there could be many more in our Galaxy that remain unfound by virtue of the inherent difficulty in their detection. Furthermore, no such pulsar has ever been detected at frequencies below 300 MHz, raising questions such as: Are they even detectable at low radio frequencies? How bright are they at these frequencies? Are low frequencies better suited to uncovering a larger population of such pulsars? Is their sporadic behaviour frequency-dependent? To pursue these questions, we made clever use of the Murchison Widefield Array (MWA, 154 MHz) and the refurbished Molonglo Synthesis Observatory Telescope (UTMOST, 835 MHz) to hunt for emission from PSR J1107-5907, a bright intermittent pulsar located in the southern sky that has three distinct emission states: "bright", "weak", and "off". This pulsar is located ~390 light-years from Earth, and is thus a relatively nearby object.

PSR J1107-5907 is inherently difficult to detect because it emits detectable, bright radio emission for only a small fraction of the time (<10%); and this bright state may only last from ~1 minute to ~45 minutes, with "off" gaps before and after lasting up to several hours. Given the observing limitations of the MWA's high time resolution data recording system (i.e. the Voltage Capture System, or VCS), traditional approaches and observing strategies are ineffective. We therefore undertook a concerted campaign, in coordination with UTMOST, whose real-time processing was leveraged to detect the pulsar and then "trigger" the MWA to record voltages simultaneously. This necessitated the development of a special VCS "voltage buffer" mode, whereby ~3 minutes of voltage data from the past are stored in memory, awaiting a trigger signal to dump them to disk. Even then, considering other limitations (e.g. the UTMOST's operation as a transit telescope), this approach demanded a high degree of perseverance, involving more than a dozen attempts spanning several months, before the pulsar was finally detected, albeit it in its weak state. This work demonstrated the voltage buffer mode's first scientific application, and highlighted other potential science opportunities such an observing mode provides, e.g. Fast Radio Burst (FRB), Gamma Ray Burst and Gravitational Wave triggers.

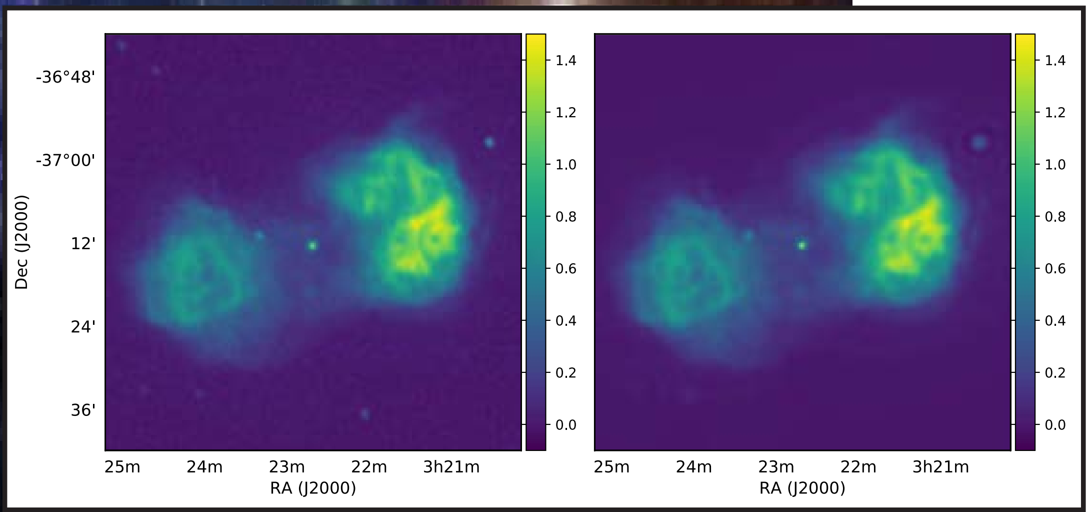
On 3 September 2017, we organised a standard 1.5-hour VCS observation to coincide with when PSR J1107-5907 would be within UTMOST's field of view and, serendipitously, detected the pulsar enter into its bright state for ~15 minutes before dropping to its weak or off state. This was the first detection of an intermittent pulsar below 300 MHz. The integrated pulse profile of PSR J1107-5907 (in its bright state) is complex, with three prominent features that contribute emission across the entire pulse profile, suggesting that the pulsar's rotation and magnetic axes are nearly aligned. We were able to make a more precise measurement of the pulsar's dispersion measure (DM), an indicator of its distance; and the rotation measure, an indicator of the Galactic magnetic field strength in the direction of the pulsar. Looking at the brightness of individual pulses, we measured the spectral index distribution to be a little steeper than the normal pulsar population (i.e. this pulsar appears even brighter at lower frequencies than would normally be expected). One notable example of extraordinary emission from this pulsar is the detection of a weak single pulse with UTMOST that had a counterpart at the MWA with a peak flux density of 2.5 kJy, which is more than 5 times brighter than its regular pulses, indicating an extremely steep spectrum. Normally, bright pulses at one frequency have a bright counterpart at the other.

The general emission characteristics of this pulsar seem to fit within the variance observed in the normal pulsar population. Under specific circumstances, PSR J1107-5907 could have instead been detected as a Rotating Radio Transient (another class of sporadically emitting pulsars that predominantly emit single pulses on time scales of minutes to hours), were it ~4 times more distant from Earth. This suggests that the different sporadically emitting pulsar sub-populations are linked, and that we do not necessarily need separate physics to describe them in the context of other pulsars. Furthermore, if the pulsar was to be placed ~100 times further from Earth, is it possible that the short duration (~3 ms) 2.5 kJy single pulse could have been detected as a low DM (i.e. relatively nearby), ~1 Jy ms FRB-like signal.

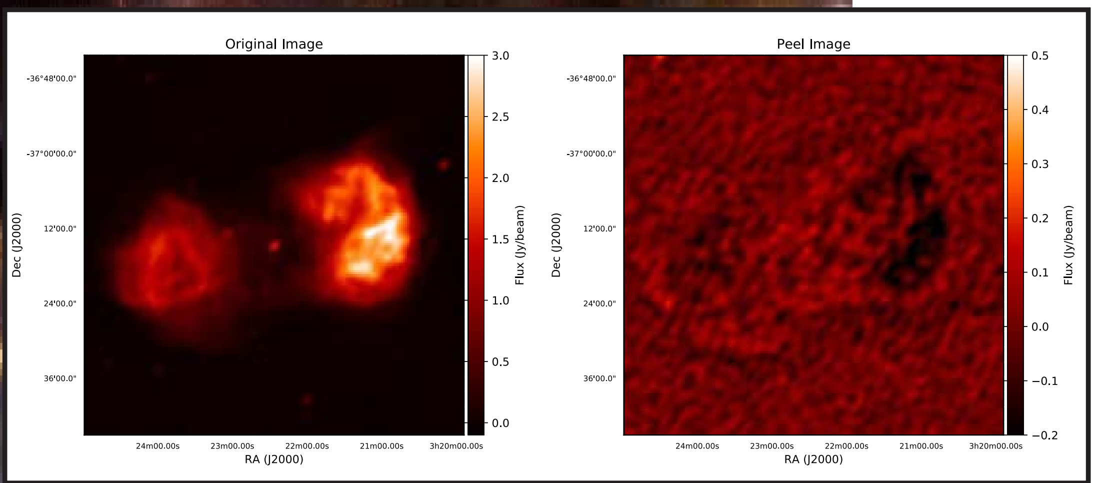
The next generation of radio telescopes, especially the Square Kilometre Array, present exciting opportunities to search for and study these rare pulsars. They offer the luxury of large fields of view and hence good prospects for large on-sky time. This unique combination, along with the steep spectral index, places these low frequency, wide field telescopes in an opportune position to uncover a larger population of pulsars like PSR J1107-5907.

Improving models of Fornax A for the Epoch of Reionisation Experiment

Jack Line, Christene Lynch and Ben McKinley



(Above, left) An image of Fornax A at 185 MHz created by B. McKinley using a joint deconvolution of MWA phase 1 and phase 2 (extended) data. (Above, right) A fitted shapelet model of the image shown on the left created by J. Line. The comparison shows how the shapelet model does an excellent job of reproducing the filamentary structure of the radio lobes.



(Above, left) An Image of Fornax A at 118 MHz created by C. Lynch using joint deconvolution of 10 minutes of MWA phase 2 extended array data. C. Lynch used this image to create a Gaussian model of Fornax A. (Above, right) An image of the residuals after peeling the Gaussian Fornax A model; the residuals are quite low, but it took a significant amount of time to complete this process.

The formation of the first luminous sources and their subsequent reionisation of the intergalactic medium, called the Epoch of Reionization (EoR), was a pivotal period in the history of the Universe. During this time astrophysical sources became the dominant influence on the conditions of the intergalactic medium and impacted all future generations of galaxy formation and evolution. Despite its importance, the EoR is one of the last uncharted eras in the history of the Universe.

The most promising method to observe the EoR is via tomography of the redshifted 21 cm line of neutral hydrogen. Due to the expansion of the Universe, 21 cm emission from the EoR redshifts to radio frequencies between 100 – 200 MHz. Detecting this cosmic signal is a goal for current and next generation low-frequency radio telescopes.

A significant challenge to radio EoR experiments is identifying and removing foreground emission produced by a variety of astronomical sources. The observing fields for the Murchison Widefield Array (MWA) EoR experiment were chosen based on their low sky temperature. However, the large field of view of the MWA, 40 degrees in the sidelobes, means that these fields still contain bright extended radio galaxies. This is particularly true for MWA EoR field 1 (centred at a right ascension of 4 hours and declination of -27 degrees) which includes the bright radio galaxy Fornax A; Fornax A is known to produce significant foreground contamination to the MWA EoR experiment. Over the last year, we have worked to improve the modelling of Fornax A so that we can more accurately remove its foreground emission from the MWA EoR data.

Improved MWA images of Fornax A were made possible in 2018 due to both the availability of new data with the phase 2 - extended configuration and new developments in the imaging software package WSClean. The extended array configuration effectively doubled the image resolution, resulting in the filamentary structures of the Fornax A lobes being captured in far greater detail than with phase 1. This increase in angular resolution, however, came at the cost of reduced sensitivity to larger-scale diffuse emission. This problem was rectified using an improved version of WSClean, which allowed the team to jointly deconvolve MWA phase 1 and phase 2 data simultaneously, taking into account the changing shape of the antenna primary beam.

WSClean improvements resulted from the work done by André Offringa during a highly-productive Astro-3D visitor scheme supported trip to Curtin in September. During this time Dr Offringa incorporated the image domain gridding (IDG) algorithm into WSClean. With IDG, the data are gridded in a computationally efficient manner that includes the primary beam shape each snapshot, therefore allowing an accurate combination of different MWA snapshot observations for joint deconvolution (as opposed to the previous method of combining images in image space post primary beam correction). IDG was also used to create an MWA phase 2 only image and model of Fornax A, at 118 MHz, to test the quality of the peeling process when trying to remove Fornax A from our MWA data.

Our main processing pipeline to measure the 21 cm emission from the EoR is to calibrate and remove sources using the Real Time System (RTS) and produce power spectrum estimates using The Cosmological HI Power Spectrum Estimator (CHIPS). Subtracting radio galaxies like Fornax A from the data is extremely computationally expensive, but required to feed data into CHIPS. To combat this computational burden, the RTS uses a set of basis functions known as 'shapelets' to model these huge radio galaxies. Traditionally, modelling consists of breaking the image down into pixels and fitting single points and elliptical Gaussians to them, resulting in 1000s of components for large galaxies. Shapelets are extended across the sky, and so can build up an image of a galaxy with less computational expense. In early testing of the speed, we've found shapelets to be of order 20 times faster in source subtraction with the RTS than more traditional point source and Gaussian fitting techniques. Given it typically takes longer to calibrate and process than it does to produce the data with the MWA, and to get a detection we need around 1000 hours of data, any speed up we can create is welcome.

Cosmic ray detection at the MWA

Clancy James

Deployment of the cosmic ray detector at the Murchison Radio-Astronomy Observatory.

SCIENCE

Cosmic rays are high-energy particles – mostly protons and atomic nuclei – bombarding the Earth from outside our solar system. The best candidate for the origin – supernova remnants – can't explain the highest-energy cosmic rays, which can reach 10^{20} eV, more than 10 million times the energy of particles produced at the Large Hadron Collider.

In 1965, it was discovered that cosmic ray extensive air showers (EAS - cascades of secondary particles produced by cosmic rays hitting the upper atmosphere) emitted radio-wave radiation. The radiation was known to peak in strength near 50 MHz, and be dominated by interactions between the secondary particles and the Earth's magnetic field.

It wasn't until the modern era of digital radio astronomy in the early 2000s however that the LOPES and CODALEMA experiments in Germany and France measured in detail the nanosecond-scale bursts of radio emission produced by cosmic rays.

Advances in the theory of radio emission in 2011 allowed accurate predictions of the complex ground pattern of radio emission. Using particle detectors at ground level to trigger buffered voltage data when a cosmic ray interaction occurred, the Dutch radio telescope LOFAR was able to detect this ground pattern. The dense clustering of LOFAR antennas in the core meant this data provided the most accurate method for measuring certain cosmic ray properties, placing new constraints on the cosmic ray spectrum, and thereby the cosmic ray origin.

Understanding cosmic ray radio emission however requires simultaneously modelling particle interactions at energies that cannot be studied in a laboratory, and solving for the spectrum of primary cosmic rays themselves. To untangle these uncertainties requires a better resolution on the structure of cosmic ray cascades, which necessarily means moving to frequencies above the 50 MHz at which radio emission is coherent over their entire length.

The Murchison Widefield Array offers the best chance of such improved resolution. Ideas for cosmic ray detection at the MWA began as early as 2010, as an offshoot of the LUNASKA project that looked for even higher-energy particles hitting the Moon. However, it was not until the formation of the SKA's High Energy Cosmic Particles Focus Group in 2015 that momentum began to build for the project.

A team of researchers led by Dr Clancy James (ICRAR/Curtin) and Dr Justin Bray (U. Manchester, UK), have collaborated with the MWA Operations Team to build, test, and deploy a prototype radio-quiet particle detector in the MWA core region in November 2018.

Affectionately known as the 'pizza box', the detector uses silicon photomultipliers to detect light from cosmic ray secondary particles passing through a block of plastic scintillator. The detector runs at low voltages, and passed all requisite RFI checks at the Curtin anechoic chamber. Simulations by an ICRAR summer student, Jesse Schelfhout, have shown it is detecting cosmic ray muons at the expected rate. A planned array of 8 such detectors will allow the rapid identification of energetic cosmic ray cascades to trigger the capture of MWA voltages.

Simultaneously, a PhD student, Mr Alex Williamson, has been investigating how to use MWA data to study cosmic ray signals. The Pulsar group have already developed a pipeline to convert fine channel data (20kHz, resolution) from the Voltage Capture System back to coarse channel resolution (1.28 MHz). Supervised by Prof. Steven Tingay and Dr. Clancy James, Alex has developed a fast code to synthesise the MWA coarse filterbank and obtain data at the full time resolution provided by the bandwidth. The resolution can be up to 27 ns for the maximum 24 1.28 MHz coarse channels.

The goal is to use the higher resolution afforded by the MWA core to determine the longitudinal structure of cosmic ray cascades. In particular, interference between the emission mechanisms (geomagnetic and Askaryan mechanisms) is expected to encode new information via the changing polarization structure of the radio ground pattern. Studies of this structure will inform high-energy particle physics models, and models of cosmic ray sources both within and beyond the Milky Way.

CRAM: The Central Redundant Array Megatile for EoR Science

Cathryn Trott, Randall Wayth and Gurashish Singh Bhatia

Photograph of the CRAM, a new 8x8 dipole tile sitting within the centre of the southern hexagonal subarray of the MWA.

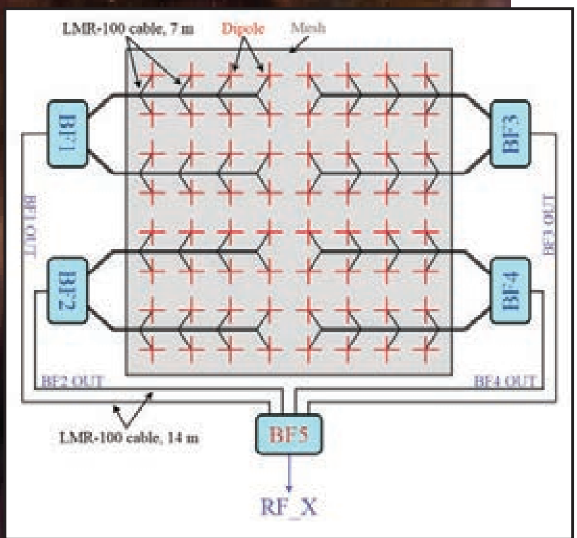


Diagram of the CRAM's layout. Credit: Bhatia

The Epoch of Reionisation (EoR) science program with the Murchison Widefield Array (MWA) aims to detect temperature fluctuations in the brightness of primordial hydrogen in the first billion years of the Universe. The spatial distribution of these fluctuations encodes information about the birth and death of the first stars and galaxies in the Universe. The signal is extremely weak, and is masked by the brighter and closer radio galaxies and Active Galactic Nuclei (AGN) observed with our radio telescopes from the 12 billion years between the EoR and the present day.

These radio galaxies can be isolated in our data due to their different properties in frequency compared with the hydrogen signal, but this isolation is limited by the observing constraints of our telescopes --- finite bandwidth and field-of-view on the sky --- where a larger field-of-view can cause additional unwanted contamination of the data. The field-of-view is set by the physical size of the observing tile, and the observing frequency. Limiting the field-of-view in post-processing is possible, but does not remove all of the influence of emission from near to the horizon, where the Galaxy and other galaxies can cause the largest problems.

To address this problem, we conceived of the CRAM --- the Central Redundant Array Megatile --- a large-sized MWA tile that resides in the empty centre of one of the MWA Phase II hexagonal sub-arrays. The hexagonal sub-arrays are two purpose-designed 36-tile sections of the MWA laid-out in a hexagonal pattern, motivated by two primary EoR-related goals: (1) providing copies of the same sampling of the sky to gain EoR signal rapidly, and (2) providing redundant measurements for improved calibration of the telescope. Although they can strictly fit 37 tiles into the space, they do not have a central tile due to the signal processing chain being able to only efficiently handle 36 tiles. In the southern of the two hexes, this leaves a space of 24m x 24m available for another tile. The CRAM, as an 8x8 dipole tile, fits well within this space, with a footprint of 8m x 8m (see image of the CRAM sitting within the southern hex).

The CRAM, with its larger footprint, and smaller field-of-view, sees much reduced signal from near the horizon, providing a signal path with lower contamination. When combined with the existing MWA tiles, these measurements provide more information about the signal coming from the field centre, versus the horizon. Combined with the redundancy in the hexagonal sub-arrays, where the same measurements can be copied, this provides a direct data comparison where the CRAM measurements can be used to excise contamination.

Design work for the CRAM signal chain was undertaken by Gurashish Singh Bhatia as part of his Engineering Honours work at the University of Western Australia, including a cost-benefit analysis of various architectural and hardware options.

The CRAM tile is unique and as such has its own unique signal chain. Signals from all 64 dipoles are combined in a 2-stage beamforming hierarchy. The full 8x8 megatile is divided into four 4x4 sub-tiles, each the size of a regular MWA tile. Each sub-tile is beamformed with a custom-built zenith-pointing beamformer, the output of which goes to a nearby second-stage beamformer, which combines the signals from all four sub-tiles.

Inside the second-stage beamformer, the signal is amplified and converted to an optical "RF over fibre" (RFoF) signal, which is sent to receiver hardware inside the MWA equipment hut.

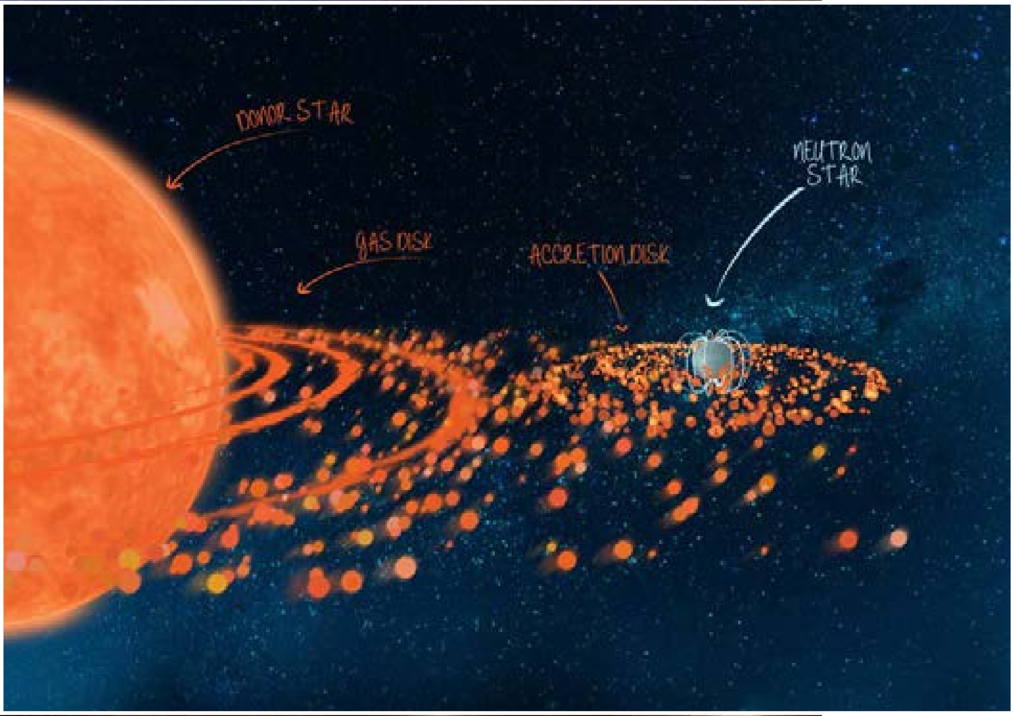
The RFoF signal from the CRAM travels via optical fibre approximately 200 metres to the MWA equipment hut where it is converted back to an electrical signal, amplified, filtered and digitized using the observatory clock.

The digitised signals are suitable for science data processing, including using the CRAM in a standalone mode, and also by incorporating the signals from the CRAM into the MWA datastream for cross-correlation with the full MWA array. This is achieved using a system that is very similar to what was used for the Engineering Development Array 1 (EDA1).

The CRAM was successfully deployed in April 2019 by two of us (Bhatia and Wayth) with help from the CIRA Engineering team and MWA Operations team. At the time of writing, the dipoles, beamformers, optical hardware and power supplies had been successfully commissioned, with further commissioning work to be done on the digital systems in the near future. The full CRAM system is scheduled to be operational for the 2019 EoR observing season on the MWA.

Jets from an unlikely source: radio emission from a high magnetic-field neutron star

James Miller-Jones



Artist's impression of the neutron star X-ray binary system Swift J0243.6+6124. A neutron star is in a 27-day orbit with a more massive, rapidly rotating companion, and accretes gas every time it passes through the disk of material flung off by the rapidly-rotating donor star. Credit: ICRAR/University of Amsterdam

Almost anywhere that we see gas falling onto a massive central object in our Universe, we also see outflows, either in the form of fast, narrowly-focussed jets, or as slower, more uniform winds. These outflows of mass and kinetic energy are an important channel for dense stellar corpses such as black holes and neutron stars to provide feedback to the surrounding interstellar medium.

For a similar accretion rate (as determined from the X-ray luminosity of the inflow), black hole jets tend to be significantly radio-brighter than those from their neutron star analogues. For this reason, it had been significantly harder to study neutron star jets prior to the recent sensitivity upgrades to both the Karl G. Jansky Very Large Array (VLA) in New Mexico and the Australia Telescope Compact Array (ATCA) in New South Wales. Nonetheless, while previous studies had detected radio emission from the jets of low-magnetic field neutron stars (field strengths up to about a billion times that of the Sun), jets had been thought to be absent in neutron stars with much stronger magnetic fields. Theoretically, it was believed that the magnetic pressure around a strong-field neutron star would truncate the accretion disk some way from the stellar surface, and hence prevent the formation of jets.

Using the enhanced sensitivity of the upgraded ATCA radio telescope, our team (led by PhD student Jakob van den Eijnden from the University of Amsterdam, who visited CIRA for a month in June 2017) searched for radio emission from high magnetic-field neutron stars, making two detections, in the systems Hercules X-1 (van den Eijnden et al. 2018, MNRAS, 473, L141) and GX1+4 (van den Eijnden et al. 2018, MNRAS, 474, L91). In both cases, the neutron star's magnetic field strength was estimated to be over a trillion times that of our Sun. What was unclear, however, was whether the radio emission arose from jets, or from a different mechanism.

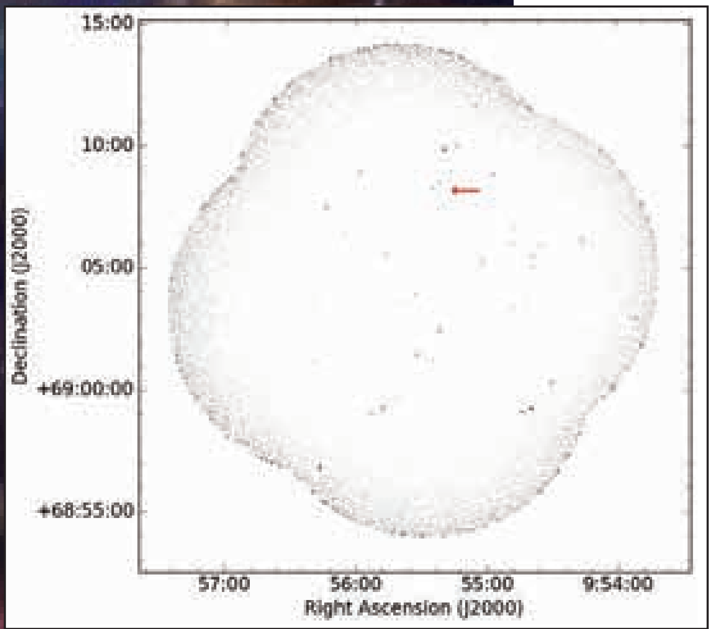
An extremely luminous outburst of a previously-undiscovered neutron star binary system in October 2017 presented the perfect opportunity to tackle this question and identify the source of the radio emission. This system, known as Swift J0243.6+6124, consists of a neutron star accreting material from a disk of matter blown off the surface of a rapidly-rotating Be-type companion star that is a few times the mass of our Sun.

During its 2017 outburst this system reached the theoretical maximum luminosity for an accreting object, known as the Eddington luminosity. At this point, the outward force of radiation overcomes gravity and prevents further infall of gas. Our team tracked the radio and X-ray emission during the outburst, and found that the radio light curves and spectra evolved in much the same way as those from known jet-producing neutron stars with lower magnetic field strengths – only at radio luminosities about a hundred times lower. This led us to conclude that jets were indeed responsible for the detected radio emission in this system.

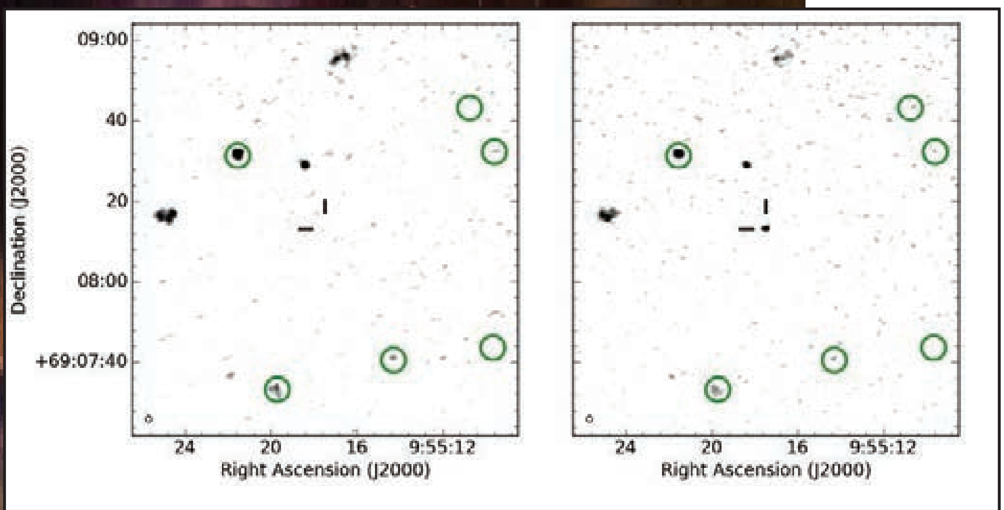
This study, published in Nature (van den Eijnden et al., 2018, Nature, 562, 233), showed us that while strong magnetic fields may suppress jet emission to some extent, they do not completely prevent jet formation, in contrast to what had previously been believed. Recent theoretical work suggests that under some circumstances, it may be possible to power jets by extracting some of the neutron star's rotational energy. In this case, that process may have been enabled by the very high rate at which matter was falling onto the neutron star. Regardless, this work has opened up a new window on jets, allowing us to study jet launching in high magnetic field systems, and enabling us to begin to quantify the effect of magnetic field strength on jet formation.

Discovery of an unusual radio transient in the nearby spiral galaxy M81

Gemma Anderson



VLA radio image of M81. The radio transient is indicated by the red arrow.



Close-up radio images of the M81 transient. It was undetected during the January 2014 observation (left) but then detected in early 2015 (right). The position of the nearby X-ray sources are indicated by green circles, none of which are coincident with the M81 transient.

Transients are astronomical objects in our Universe that explode, outburst or flare. These could include the small, red dwarf stars that produce flares 10,000 times more powerful than our Sun, the explosion of massive stars known as supernovae, and black holes that go into outburst. Studies of transients using radio telescopes is extremely important as such observations allow us to study the total energy released during the event and the acceleration of particles up to relativistic speeds. We can also use radio light to probe magnetic fields and the impact of these explosions on the surrounding galactic environment.

We know from observing stellar mass black holes in the Milky Way that as their gravity pulls material off their companion star, this material begins to spiral in towards the black hole in what we call an accretion disk, causing it to periodically go into outburst. During outbursts, these black holes launch powerful, relativistic jets, which produce bright radio light that is detectable by radio telescopes.

We recently conducted a radio survey using the Karl G. Jansky Very Large Array (VLA) of the nearby, spiral galaxy M81. The aim was to try and discover stellar mass black holes that produce more powerful radio jets than those we see in the Milky Way. This radio survey took place over 2 years, with the VLA observing the four quadrants of M81 a total of 12 times (one of the final radio images of M81 can be found in Figure 1).

On 2 Jan 2015, we detected a bright radio transient that had not been detected a year earlier (see Figure 2), which lasted for a least 2 months, and was located within one of the spiral arms of M81 (see Figure 3). There were no other reports of a transient at this position and we found no steady optical or X-ray counterpart in archival observations of M81. While extremely radio luminous and energetic, the M81 transient did not behave like any known Galactic or extragalactic black hole as the radio emission showed no short timescale variability, which is typical of jetted ejecta. However, this transient was also too faint and evolved too slowly to be identified as most kinds of radio-detected supernova.

The properties of this transient more closely resemble another radio transient found in the nearby, starburst galaxy M82, which has been suggested to be a radio nebula associated with an accreting black hole. There are some black holes that are so powerful that they accrete material from their companion star at a rate that almost violates the laws of physics. As a result, they have extremely energetic outflows, either from relativistic jets or accretion disk winds, which are too faint for our radio telescopes to detect but are constantly injecting energy into the surrounding interstellar and intergalactic media. Such outflows can power a large radio nebula that cocoons the black hole and therefore often referred to as a "bubble". But what if a black hole was only accreting at these rates for a short time (months-years) rather than continuously? Could such a black hole inflate a short-lived bubble that could appear as a transient in our radio VLA observations? We suggest that both the new M81 transient, and also the M82 transient are the birth of a short-lived radio bubble that are associated with a black hole that underwent a short-lived, yet powerful outburst.

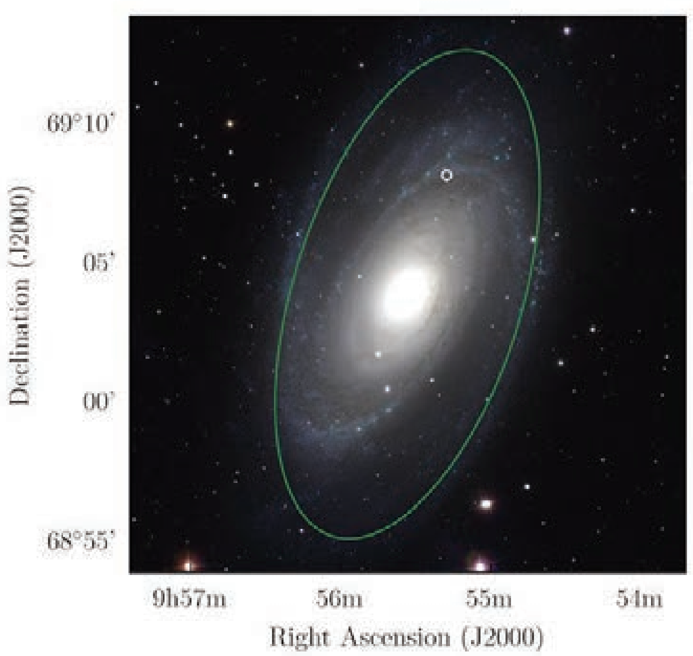
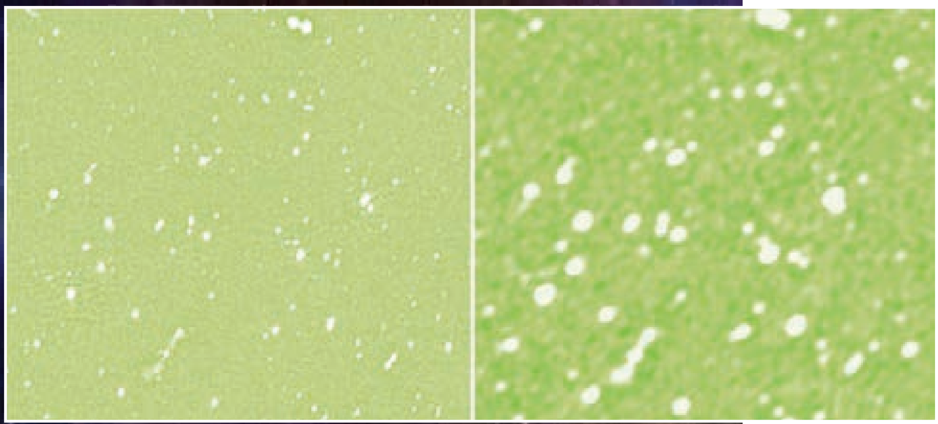


Figure 3 caption: Optical image of M81 using data from the Sloan Digital Sky Survey. The white circle shows the position of the radio transient within one of the spiral arms of M81 and the green ellipse indicates the extent of the galaxy to aid the eye.

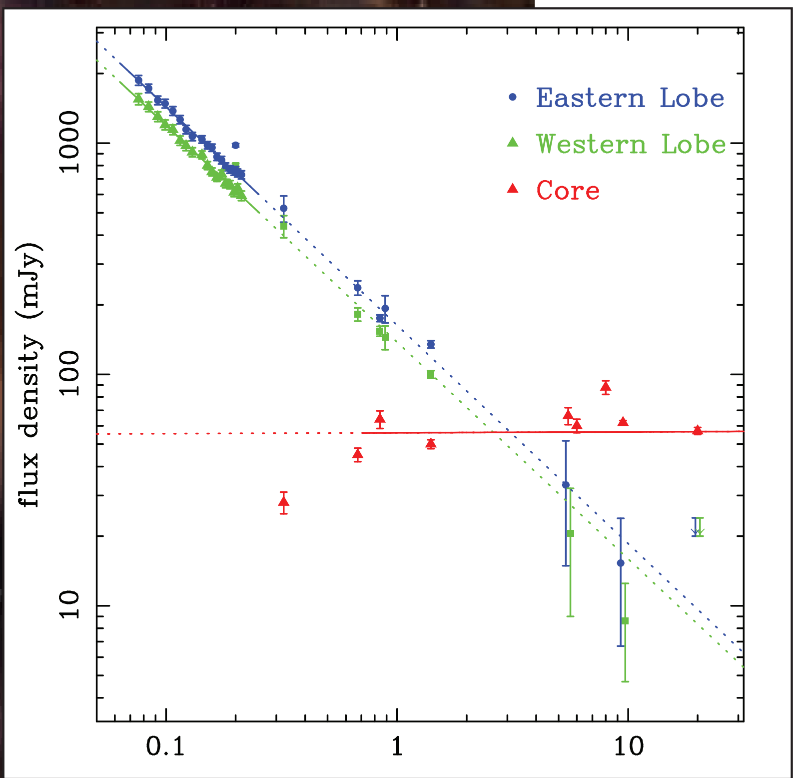
Higher, Further, Faster with MWA Phase II

Nick Seymour



Comparison between GLEAM year 2 image (Franzen et al. in prep) and a deep MIDAS of part of the GAMA23 field (Seymour et al., in prep). Both images are at 200-230 MHz. The improved resolution and ability to image more deeply with MWA phase 2 is clear.

The 0.07-20 GHz radio spectral energy (SED) distribution of giant radio galaxy PKS 2250-351 which lies in the GAMA 23 region from Seymour et al. in prep. PKS 2250-351 lies in the cluster Abell 3936 at a distance of around 1000 megaparsecs with the eastern lobe pointing roughly towards the cluster centre. The SED is decomposed into the two lobes and the core which each show typical slopes (negatively steep and flat, respectively). Of most significance is the fact that the western lobe remains around 30% less luminous across the whole frequency range. This is consistent with the western lobe expanding adiabatically into a less dense region away from the cluster centre.



SCIENCE

Phase 2 of the Murchison Widefield Array allows us to probe far further into the distant Universe than was possible before. The long baseline configuration of phase 2, going out to 5.5 km, provides us with a resolution twice as good as phase 1. This improved resolution dramatically improves our ability to make deep, sensitive images at these low radio frequencies by greatly reducing the so-called `confusion' noise.

This `confusion' noise is created by the many faint sources below the detection limit beginning to over-lap at fainter flux densities. At some point these faint, undetected sources fill in all the space between all the brighter sources making it impossible to image more deeply. A simple doubling of the maximum baseline length decreases the confusion noise by more than an order of magnitude. This makes it possible to conduct observations far more deeply than was possible in phase 1. Indeed, the GLEAM survey was about as deep as we could go.

There are now several efforts to conduct deeper surveys with MWA phase 2. GLEAM-X is an effort to repeat the successful GLEAM survey but with the greater sensitivity and resolution. There are numerous small projects targeting various sources of interest. Most ambitiously, the MWA Interestingly Deep Astrophysical (MIDAS) survey is targeting six of the prime extra-galactic survey fields in the southern hemisphere. These include the five GAMA survey fields and the South Pole Telescope deep field.

The aim of MIDAS is to observe each of these fields across 70-230 MHz (like GLEAM) and to reach a sensitivity around an order of magnitude deeper than GLEAM. We shall be able to detect significantly more radio sources per sky area, probing both more distant and less luminous radio sources. We will find many more radio galaxies (powered by black holes) and far more star forming galaxies. The improved resolution will help de-blend radio sources close together as well as allowing us to more easily cross-identify the MIDAS sources with those at other wavelengths. This last step is crucial so that that the distance to the radio galaxy may be determined.

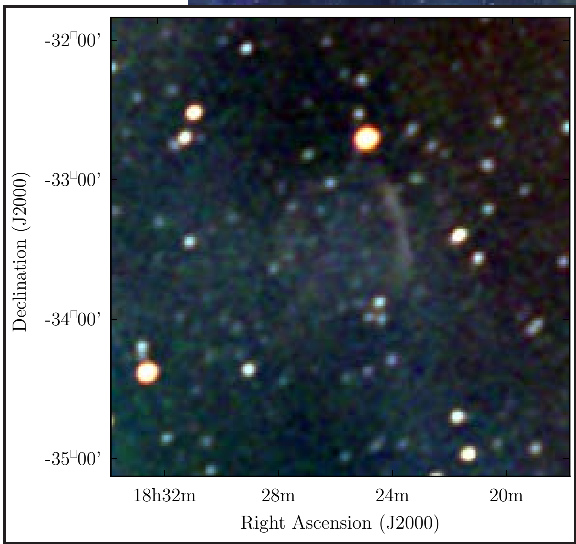
The GAMA 23 survey region is the field of choice in the southern hemisphere. It is very close to zenith making observations easier and is also fortuitously devoid of bright, confusing radio sources. The GAMA survey provides federated imaging and catalogues from the ultra-violet to near-infrared over 60 deg^2 as well as over 48,000 spectroscopic redshifts. This data complements the unparalleled broad-band radio data that has been put together from MIDAS (70-230 MHz), uGMRT (250-700 MHz), ASKAP (0.7-1.8 GHz) and the GLASS survey (4.5-10.5 GHz). This radio data will allow us to accurately measure the jet-power of vast number of radio galaxies across a wide range of distance and environment for the first time. Such a data set will ultimately provide us with great insights into the evolution and origin of the powerful radio emission from these galaxies, an out-standing mystery in modern radio astronomy.

Early work on the MIDAS survey has proved fruitful. The GLEAM survey has been very useful for calibration of phase 2 data despite the difference of resolution. Furthermore, as we are in Solar minimum at present, the ionosphere is very quiet and does not disrupt the observations. Indeed, day time observations have been possible with the Sun carefully positioned into a null of the primary beam. In the top frequency band of MIDAS (200-230 MHz) we are able to obtain a resolution of less than an arcminute and RMS sensitivities of 5-6 mJy/beam.

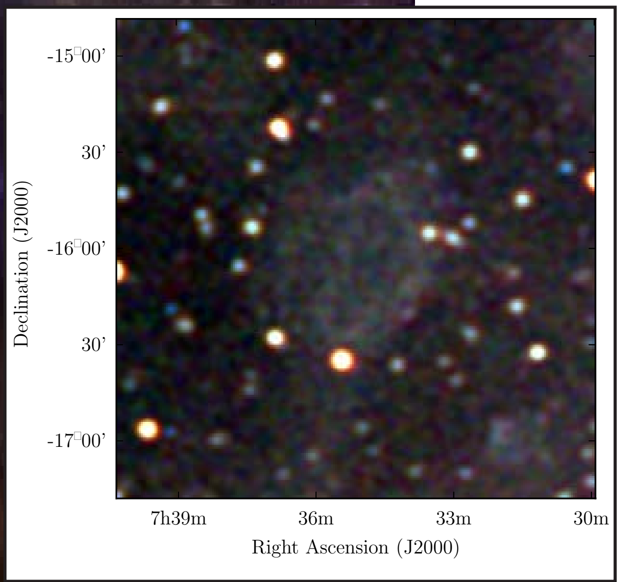
Our current best MIDAS image at 200-230 MHz (see figure) reaches an RMS sensitivity of ~0.8mJy/beam derived from mosaicking 54 two minute snapshots together. At this sensitivity we can detect ~60 radio sources per square degree compared to ~15 per square degree from GLEAM over the same part of the sky. As an example of the type of science we can do we present the broad-band 0.07-20 GHz radio spectral energy distribution of the giant radio galaxy PKS 2250-351.

26 Newly-Detected Supernova Remnants with the MWA

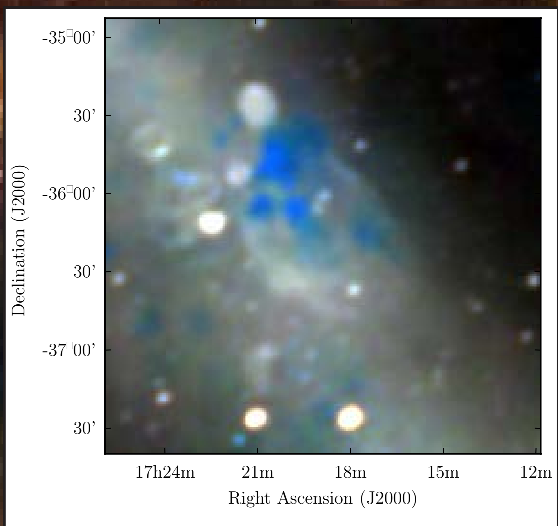
Natasha Hurley-Walker



Supernova remnant 0.2-9.7, imaged with the MWA.



Supernova remnant G232.2+2.1 , imaged with the MWA.



Supernova remnant G350.8+0.7, imaged with the MWA.

SCIENCE

Supernovae are enormously powerful explosions caused when large stars run out of hydrogen fuel, and rapidly collapse. These explosions are how all heavy elements in the Universe were formed, making possible planet formation, chemistry, and life. For a few months, an individual supernova outshines its host galaxy, and in this time can be detected across cosmic distances. Once the initial explosion has cooled, a shell of expanding material propagates into space at thousands of kilometers per second, sweeping up and accumulating into a supernova remnant (SNR). Since these shells are highly ionised and magnetised, they emit synchrotron radiation, and are visible in gamma ray, X-ray, and radio observations, for up to millions of years after the initial supernova.

A longstanding puzzle in Galactic astrophysics is the discrepancy between the predicted number of supernova remnants and that which we observe. The brightest and bluest stars, O- and B-type, end their lives in supernovae, and white dwarfs accreting material from companion stars can also generate supernovae. Given the large number of these types of stars in the Galaxy, and the typical lifetimes of the largest stars and SNRs themselves, we expect to see around 3,000 SNRs when we examine our own Milky Way. However, we see only around 300, an order of magnitude of difference.

A widely held view in astronomy is that the discrepancy is mainly down to selection effects from existing surveys; while radio wavelengths are very useful for detecting SNRs, single dish radio telescopes have poor resolution, and tend to confuse SNRs with the surrounding Galactic background. Conversely, traditional radio interferometers, such as the Very Large Array, "resolve out" the diffuse emission of larger SNRs, as they lack the short baselines to detect large-scale emission. SNRs are also brightest at low frequencies, at which ionospheric effects are strongest, and sky noise the highest.

The Murchison Widefield Array is a low-frequency radio telescope and its original configuration possessed both short and long baselines, ideal for finding SNRs on 5-arcminute to 5-degree scales. The GaLactic and Extragalactic All-sky MWA (GLEAM) survey observed the entire sky across 72 to 231 MHz over 2013--2014, and I performed high-quality imaging of the Galactic Plane in 2017. In 2018, I searched the images for the faint circular shells which might indicate the presence of supernova remnants. I was successful in finding 26 new SNRs, increasing the number known by about 10%.

The figures to the left highlight some of the most interesting objects, using the wide bandwidth of GLEAM to display RGB images, where R = 72-103MHz, G = 103-134 MHz, and B = 137-170MHz.

SNR G0.2-9.7 is the faintest SNR ever detected, and appears as a filled ellipse with a single bright edge. At its centre is the rotating radio transient PSR J1825-33, a neutron star with a powerful magnetic field and intermittent radio emission, spinning just over once per second. As SNR G0.2-9.7 lies 10 degrees from the Galactic plane, there are very few other pulsars nearby, so we are confident that this is the remaining core of the supernova progenitor star. Using the distance of the pulsar and the size of the SNR, I calculated that this supernova occured less than 9,000 years ago, and would likely have been visible to everyone in the Southern hemisphere at that time.

SNR G350.8+0.7 demonstrates why the wide bandwidth of the MWA is particularly useful in detecting SNRs against the confusing background of the Galactic Plane. Highly ionised regions around very bright stars, also known as HII regions, have rising (thermal) spectra, so appear as bright blue areas in this field, while the falling (non-thermal) spectrum of G 350.8 + 0.7 gives it a pale peach colour. Previous surveys have missed this object due to its large size and the complicated foreground HII regions.

SNR G232.2+2.1 is an unusual object as it is far from any distinct regions of massive star formation, and is one of two objects discovered in this area of the sky, previously thought not to host supernova remnants. It is probably around 200,000 years old, and has poorly-defined edges, potentially indicating that it is beginning to merge with the surrounding interstellar medium, a rare chance to spot a fading SNR near the end of its life. This sample is more sensitive to these older SNRs, and helps us understand the life cycle of stars in our Galaxy.

SCIENCE

Revealing the low-frequency emission signatures of fast-spinning radio pulsars

Ramesh Bhat

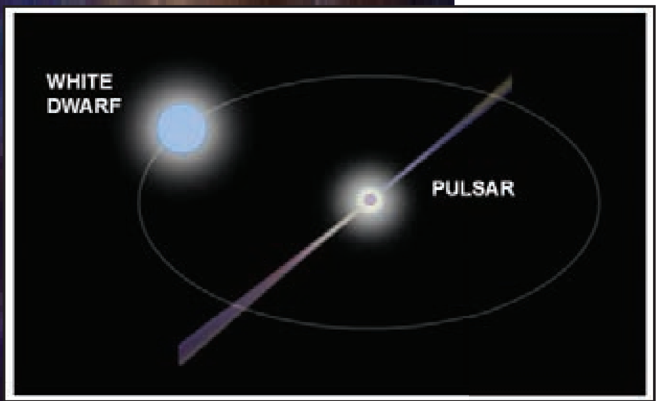


Figure 1: An illustration of a millisecond pulsar in binary orbit with a white-dwarf companion star, whose mass is typically ~10-50% of the Sun. Such systems are well-suited for high-precision timing applications such as pulsar timing-array experiments. Credit: Phys.org/Thomas Tauris

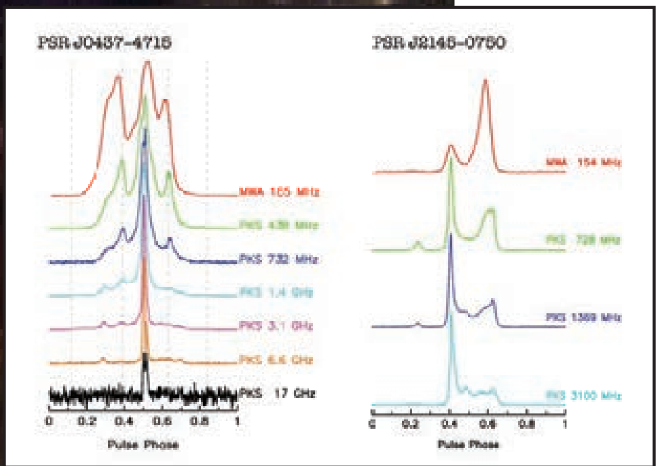


Figure 2: Integrated pulse profiles of millisecond pulsars J0437-4715 (left) and J2145-0750 (right), at radio frequencies from ~100 MHz to several GHz. These represent the strength of average emission from pulsars against its rotation phase. The complexity in the temporal structure and the remarkable changes with frequency can be reconciled in terms of a complex spectral evolution that appears to be a characteristic of millisecond pulsars.

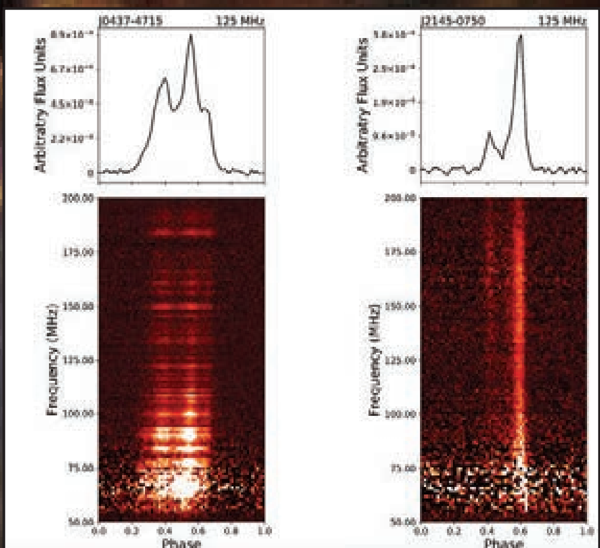


Figure 3: Millisecond pulsar detections with the Engineering Development Array that was constructed using MWA technologies. The strength of pulsar emission is shown against the pulsar's rotation phase and radio frequency, simultaneously sampling the \ ~50 to 200 MHz range in a single observation.

Over the past five decades, pulsars have successfully established themselves as Nature's premier laboratories for extreme physics. These compact, city-sized (~30 km), super-dense objects continue to enable us to push the boundaries of fundamental physics and astrophysics. With applications from probing the state of ultra-dense matter where densities reach over 100 billion kilograms per cubic centimetre, to serving as Galactic-scale gravitational-wave detectors in the pursuit of searching for ultra-low frequency gravitational waves produced by supermassive black-hole mergers, these fascinating celestial objects enable us to probe physics from nuclear scales to cosmological scales. They can be best described as the Universe's gift to mankind; and they allow us to explore new vistas in physics, and probe extreme physical environments that cannot be replicated on Earth, or found elsewhere in the Universe.

The rotation periods of pulsars can range from tens of seconds to one-thousandth of a second; those that spin very fast are called millisecond pulsars, and they are amongst the highly sought after ones. The fastest one spins at a rate of over 700 times per second, which is equivalent to more than 40,000 revolutions per minute, i.e. even faster than a kitchen blender! Yet, their rotational stability is astonishingly high, and it takes billions of years for these cosmic clocks to drift by even a millisecond, making them the most accurate clocks in the Universe. Finding more millisecond pulsars can thus enrich a wide-ranging science, including understanding complex stellar evolutionary scenarios and testing the theories of gravity, and the prospective detection of an all-sky signature of gravitational-wave background produced by millions of black-hole mergers as galaxies formed and evolved in the early history of the Universe.

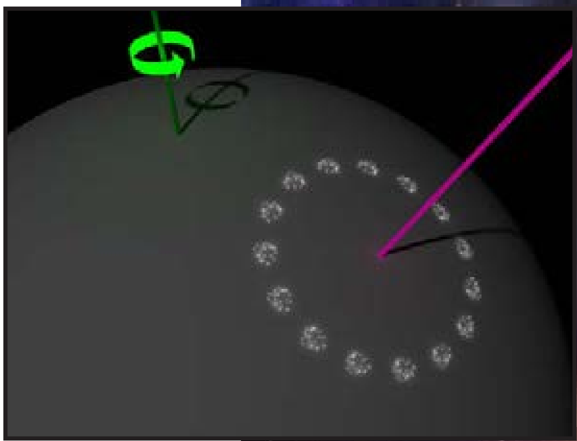
However, for more than two decades, their scientific exploration was largely limited to relatively high radio frequencies, ~1 GHz and above, where interstellar distortion to their temporal signature becomes affordably smaller, and the high sensitivities of large single-dish telescopes, such as the Parkes radio telescope in NSW, can be leveraged to compensate for their reduced brightness at those frequencies. This has been particularly the case for pulsars located in the southern sky, many of which have been discovered and studied exclusively at high frequencies. The advent of the Murchison Widefield Array (MWA) has changed that. The MWA is also Australia's official Precursor for the low-frequency Square Kilometre Array, or SKA-Low, and has even led to the construction of the Engineering Development Array (SKA) for critically-important prototyping and verification purposes. In combination with the voltage capture system that allows data recording at very high time and frequency resolutions, the advanced software instrumentation we have developed, and a flexible selection of frequency bands built into the MWA's signal path, it has become possible to make impressively high-quality detections of these intriguing objects at uncommonly observed frequencies, down to ~50 MHz, i.e. wavelengths up to several metres. This has enabled a multitude of science relating to the intervening interstellar medium, and taking a first look at their emission signatures at very low frequencies. For instance, in the direction of the pulsar PSR J0437-4715, the nearest and brightest millisecond pulsar located at ~490 light years away, observations with the MWA allowed us to pinpoint the location of the plasma layer responsible for deflecting pulsar radiation to an impressive precision of the order of a few light years.

Our analysis also revealed another intriguing property of these objects. Unlike most garden-variety pulsars (with spin periods of the order of a second), the fast-spinning ones tend to show a much higher degree of complexity in their emission signatures, typically characterised as the strength of average emission against the pulsar's rotation phase, i.e. the so-called integrated pulse profile (Figures 2 and 3). This is something that is unique to a pulsar, like its fingerprint. Our analysis confirms that observed emission signatures across the ~100 to 3000 MHz range can be meaningfully, and consistently, reconciled in terms of a complex spectral evolution, thereby confirming Parkes results from decade-long observations. Our analysis further reveals remarkable changes in the emission signatures with radio frequency – a complexity that can be possibly, and justifiably, attributed to the fact that the magnetospheres of these fast spinning pulsars are highly-compressed, only ~100 km in extent compared to ~100,000 km of their longer-period counterparts.

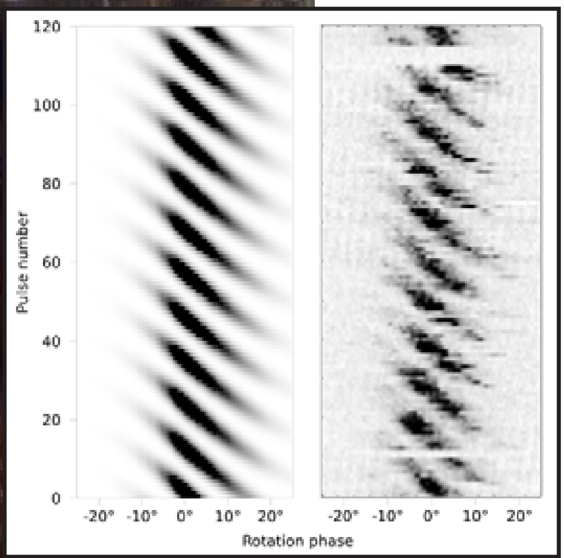
Our analysis further suggests that the brightness of these objects steadily increases at low radio frequencies. This is encouraging, both for their detailed studies, as well as finding new ones, using next-generation low-frequency telescopes such as the MWA, and eventually the low-frequency SKA, which will be built in Australia. SKA-Low is slated to be the most efficient pulsar finding machine to be ever built, and the MWA, as a crucial pathfinder telescope, presents the perfect platform to prepare and move forward in the direction. The future thus looks bright and promising for unconstrained exploration of these amazingly tiny but scientifically precious objects.

Simulating spark events and carousel structures in pulsar magnetospheres

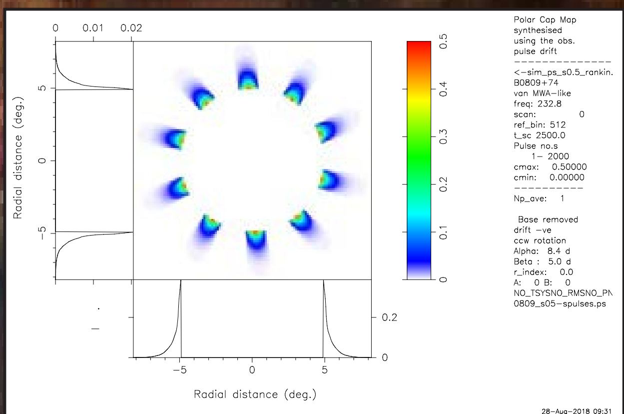
Sam McSweeney



A cartoon of the localised spark events near the surface of a pulsar, surrounding the magnetic axis (magenta line). The green line represents the pulsar's rotation axis.



A simulation of drift bands generated by PSRGEOM (left), showing very similar features (spacing, curvature) to the true drift bands of PSR B0809+74 (right).



A simulated pulsar signal which has been transformed back into an image of the original emission beam shape.

SCIENCE

We have developed new software for simulating realistic signals from pulsars (rapidly-rotating neutron stars) that includes both the wide-spread phenomenon of subpulse drifting and the Special Relativistic effects of rotation.

Pulsars, or neutron stars, are the compact remnants of massive stars that have exhausted their fuel and gone supernova. As the debris settles after the explosion, the nascent pulsars are spun up to impressive rotational speeds. Isolated pulsars typically rotate about once every second, while those that are in binary systems extract angular momentum from their companions by accreting matter onto the surface, resulting in rotation speeds up to once every few milliseconds!

Neutron stars were originally not expected to give off any detectable radiation, but in 1967, a series of regular pulses with a period of a little over 1 second was detected from an astronomical source, and quickly identified as a rotating neutron star. Since then, thousands of pulsars have been discovered, each with their own unique characteristic signal.

Fifty years on, we know a lot about pulsars, but the mechanism that produces the bright radio emission is still hotly debated. One model ascribes the radio beam to dense bunches of electrons and positrons travelling at relativistic speeds along magnetic field lines like beads on a wire. All charged particles emit radiation when accelerated, and in this model, the acceleration comes from the curvature of the field lines. However, not all magnetic field lines are “active” at the same time. At the place where the field lines intersect the pulsar’s surface (the so-called “footpoint”) regions starved of charged particles can grow and consequently huge voltage differences can develop over very short distances. When the voltage gap reaches the order of 10^12 V, charges are ripped from the surface in a catastrophic avalanche called a “spark event”.

In this model, localised spark events do not necessarily occur randomly. Instead, they arrange themselves in a circular pattern around the magnetic axis and rotate around it by means of electrical and magnetic forces. This “carousel” rotation is vital for explaining the phenomenon of subpulse drifting, which is where individual subpulses march regularly in time from pulse to pulse. Each rotation of the pulsar presents a slightly different carousel configuration to the observer, resulting in a beautiful sequence of “drift bands”.

Modelling the drift bands for any one pulsar is not a trivial exercise. One not only has to know the number of sparks in the carousel and its rotation rate, but also the radial size of the carousel, the angle between the pulsar’s rotation and magnetic axes, and how those axes relate to the direction of the line of sight. These parameters are usually poorly constrained, and it is often simpler (both computationally and conceptually!) to guess their values first and work out what kind of drifting pattern would be seen by an Earth-bound observer. If the simulated drift bands resemble the observed drift bands, our confidence in the correctness of the assumed parameters increases.

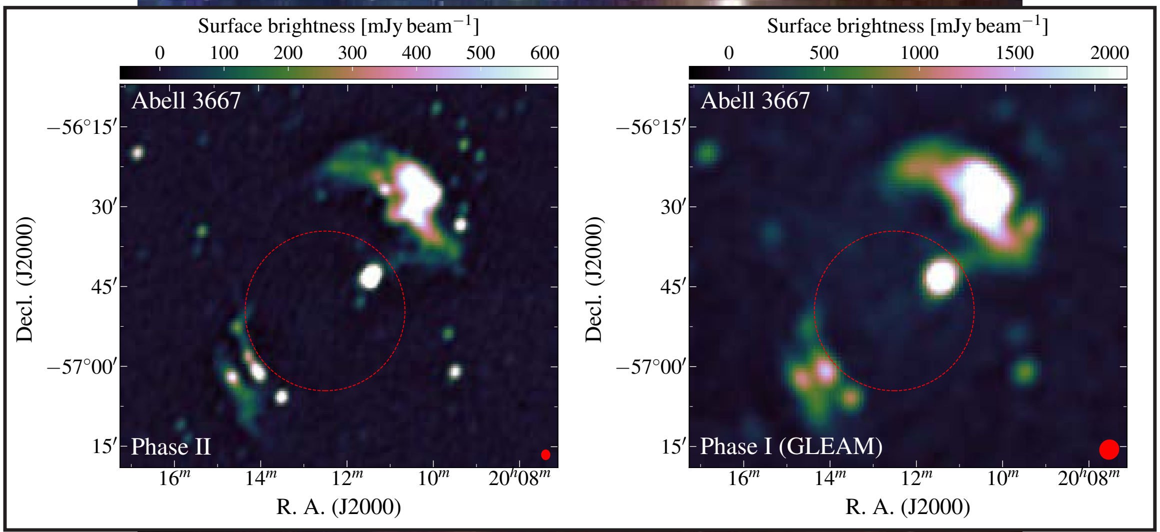
Although such methods have been around for a long time, they usually work out the shape of the emission beam as it would look in a reference frame that is corotating with the pulsar. Switching from a corotating frame to an inertial (non-rotating) frame involves the computation of a Special Relativistic effect called “aberration”, analogous to the apparent shift of stars’ positions due to the motion of the Earth about the Sun. In the pulsar case, the net effect of aberration is that emission is observed slightly earlier than expected, shifted forward in time by an amount that depends on the height of the emitting particle bunch above the pulsar’s surface. This can result in distortions of the drift bands that could belie the true nature of the underlying carousel!

To address this issue, we have developed a computer code, named PSRGEOM, which simulates drift bands in the observer’s reference frame, taking into account the effect of aberration as well as other effects relating to Special Relativity and the finite speed of light. The signals output by PSRGEOM can then be directly compared with observation, and once the carousel parameters have been thus determined, a further transformation can be used to reveal the original emission beam structure.

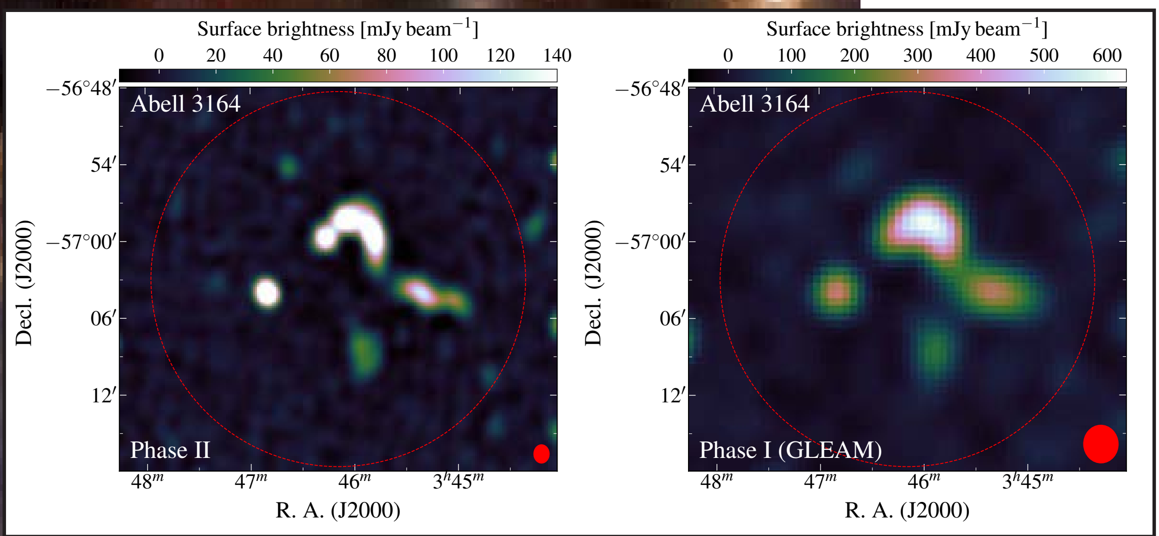
It is anticipated that PSRGEOM will pave the way for the correct identification of the carousel parameters for large numbers of pulsars that exhibit the phenomenon of subpulse drifting. This is vital for understanding why different pulsars’ carousels have different numbers of sparks and rotate at different speeds, and how the carousel changes its behaviour even for a single pulsar (which it is known to do in many cases). The paper describing the algorithms of PSRGEOM was published in ApJ, and the code itself is available for download and use from GitHub.

An MWA Phase II follow-up of diffuse, non-thermal galaxy cluster emission

Stefan Duchesne, Melanie Johnston-Hollitt,
Randall Wayth and Torrance Hodgson



Radio emission in and around Abell 3667 shown in false colour at 118 MHz from the (left) new MWA Phase II data and (right) the Phase I GLEAM survey. The red, dashed circle has a 1 Mpc radius at the redshift of the cluster, and the solid, red ellipses are the resolution elements for each image. The colourscale has a linear stretch between -10 and 100 times the local noise. The twin relics are the extended structures at the bottom left and top right.



As with the other figure, but for Abell 3164 at 154 MHz with a colourscale stretch between -5 and 50 times the local noise. The main source of interest is the faint emission towards the lower portion of the cluster region.

Galaxy clusters are the largest gravitationally bound structures in the Universe, and they are thought to form hierarchically through highly energetic merger events. Clusters are found to host large-scale magnetic fields on the order of 1-10 mirco-Gauss, which can be detected through Faraday rotation of radio emission from background radio sources. Within clusters, large, mega-parsec scale, diffuse, non-thermal synchrotron emission has been detected without clear optical hosts. The emission is thought to be associated with the intra-cluster medium (ICM) rather than any particular object.

This type of emission comes in a number of flavours, namely the centrally located radio halos and peripheral radio relics. The exact origin of these sources is not clear, but there is evidence to suggest that the mergers of galaxy clusters can trigger the emission when turbulence and shocks pass through a population of electrons residing within the ICM. This is often considered a re-acceleration process as the synchrotron-emitting particles are effectively shocked back to life by the cluster-wide shocks and turbulence in the ICM.

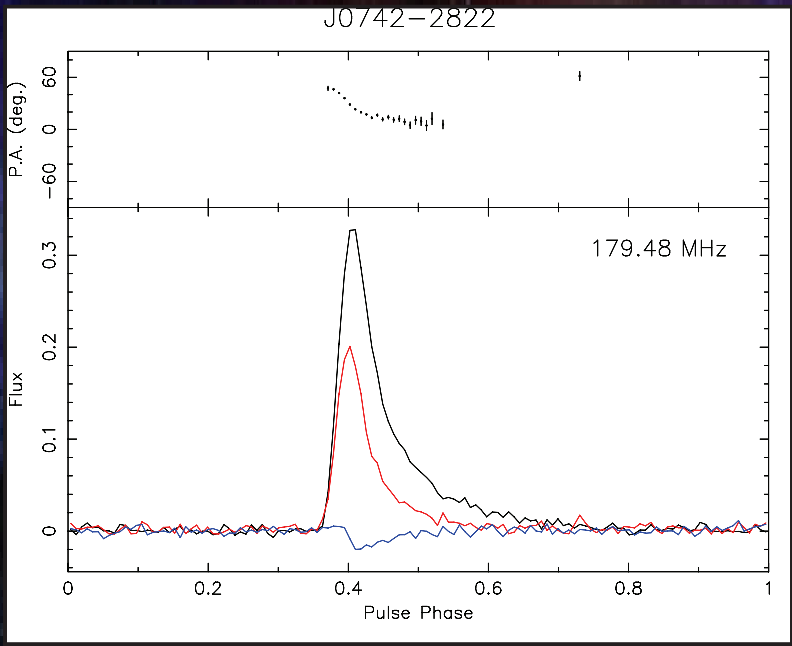
At present, there are less than 100 of each type of source published in the literature. Their steep synchrotron spectra and low-surface brightness make detection and characterisation difficult at multiple frequencies, rendering them virtually undetectable by many radio interferometers. One such instrument that has the required surface-brightness sensitivity is the Murchison Widefield Array (MWA); with its many short baselines and low-frequency coverage we have identified around 200 new candidate halos, relics, and similar cluster-based emission. However, these possible detections were made using the Phase I of the MWA, and the resolution is one of the major limiting factors of the instrument (with resolutions of ~5-1.5 arc-minutes for 88-216 MHz). This leads to potentially misidentifying, for example, faint blended point sources as extended structures.

With the upgrade to Phase II and its long-baseline configuration, we have observed a number of these candidate diffuse sources in clusters at a sensitivity level better than the upcoming Phase II all-sky survey. With these observations we have resolutions of ~2-0.75 arc-minutes for 88-216 MHz. For a majority of 2018 work has been done to process these data to a high, science-ready quality. Data processing follows very similarly to the processing of the Galactic and Extragalactic All-sky MWA survey (GLEAM), though with specific improvements to imaging, calibration, and the MWA primary beam model. Namely, with the GLEAM extragalactic catalogue, we can utilise infield calibration which is easier for processing reasons, but also allows each 2-minute snapshot to use calibration solutions at the time of observation rather than some calibrator source observed up to a few hours ago. Additionally, the imaging software we use (WSClean) has a number of small improvements that improve speed, which, with the new Phase II data, is important as imaging requires images with (at least) 4 times as many pixels for the same field of view of the telescope at any given frequency. A new data-reduction pipeline has been developed for this work, which starts with pre-processed visibility data (i.e., flagged of RFI and converted from raw telescope data) and returns flux- and astrometry-corrected snapshot images for use in stacking. Images are stacked, and we are (or will be) left with 10 fields of interest with around 30-40 interesting clusters and cluster-based emission within them.

Some of the more notable clusters included in these fields are Abell 3667, a relatively nearby cluster hosting a pair of relics, and Abell 3164, a system hosting a number of relic-like sources with additional uncharacterised steep-spectrum emission throughout the system. While these are some of the more spectacular examples, the comparison of the Phase I and Phase II data does well to illustrate the additional information provided by the higher resolution Phase II data. The higher resolution Phase II data are required in many cases to confirm the nature of the candidate object; incorporating relics and halos from this list of candidates into the known sample will better our understanding of the origin of not only the emission itself, but the electron population responsible.

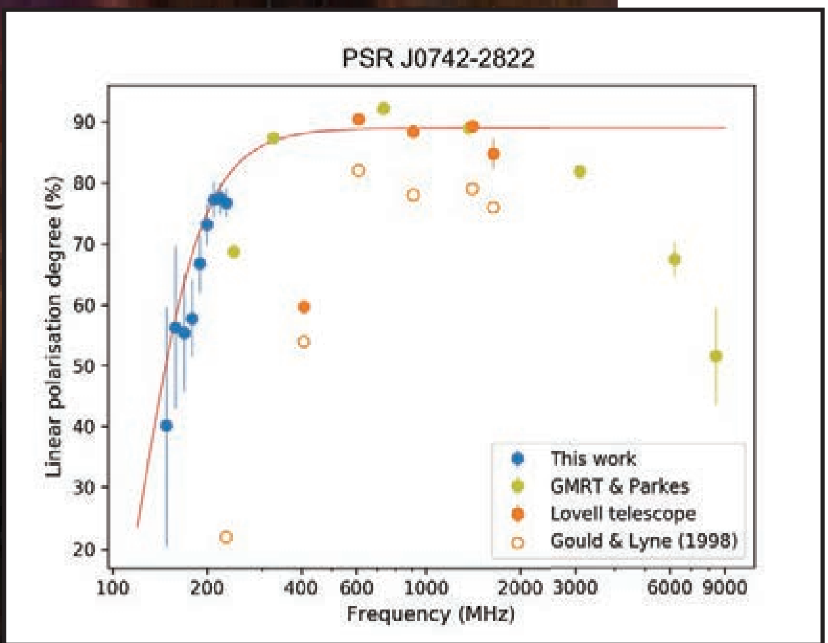
Gearing up the MWA for pulsar polarimetry

Mengyao Xue



The first low frequency polarimetric profile of PSR J0742–2822, a bright pulsar in the Southern sky. The lower panel shows the average pulsar emission against the rotation phase of the pulsar and the upper panel shows the position angle curve. The black, red, and blue lines indicate the total intensity, linear polarisation, and circular polarisation, respectively.

Degree of linear polarisation as a function of frequency for PSR J0742–2822. At frequencies above 400 MHz, the degree of linear polarisation decreases with an increase in observing frequency. This is possibly caused by propagation of pulsar radiation through a large, relatively old, supernova remnant in the general direction of the pulsar.



With the development and verification completed for performing full polarimetric studies with the Murchison Widefield Array (MWA), a new window has opened up for low-frequency pulsar astronomy in the Southern hemisphere.

Pulsars are rapidly-rotating, highly-magnetised neutron stars. Often referred to as cosmic lighthouses, they emit beams of radiation from their magnetic axis, which is offset from their rotation axis, so that we observe them as pulses when their emission sweeps through our line of sight. Their extremely strong magnetic field (several hundred billions of times greater than the geomagnetic field) results in the emitted electromagnetic radiation to be highly polarised, where it often oscillates preferentially along certain planes (linear polarisation), or certain preferred orientation (circular polarisation).

The radio emission from pulsars is broadly thought to originate within the open magnetic field lines near the magnetic axis of the magnetosphere. Consequently, the linear polarisation position angle will be determined by the direction of the magnetic field line as it sweeps across our line-of-sight. The trace of position angle against pulsar's rotational phase, referred to as the PA curve, can be used to infer the pulsar's geometry – the emission beam size and the inclination angle of the magnetic axis with respect to the rotation axis.

Polarimetric studies at multiple frequencies can also be used to study magnetospheric emission mechanism. Moreover, the intervening magneto-ionic interstellar medium can rotate the PA of the pulsar signal as it propagates through it – this is known as Faraday rotation. The amount of rotation scales as the square of the wavelength, and is quantified by the Faraday rotation measure (RM), which is a measure of the electron column density and the magnetic field strength along the line-of-sight.

Historically, most pulsar polarimetric studies have been performed using either large single dish telescopes (e.g. the Parkes radio telescope in NSW), or interferometric telescopes comprised of a modest number of parabolic dishes. Next-generation low-frequency telescopes – aperture arrays, such as the MWA, are promising in pulsar polarimetric studies. However, for aperture arrays, accurate polarimetric calibration is much more complex since its polarimetric response is a strong function of the observing frequency and direction. Thus, developing a suitable calibration strategy and verifying that it is satisfactorily robust and reliable is an essential prerequisite for performing any polarimetric pulsar work with these new generation radio arrays.

We carried out an empirical examination of the MWA's polarimetric response using a series of carefully designed observations of two bright southern pulsars (PSRs J0742–2822 and J1752–2806). Our analysis shows that the polarimetric response of the MWA is reliable in the domain where the analytical beam model is a good approximation to reality. This is currently the case at observing frequencies less than 270 MHz and at zenith angles less than 45 degrees. As expected, observations closest to the zenith provide the highest quality pulse detections.

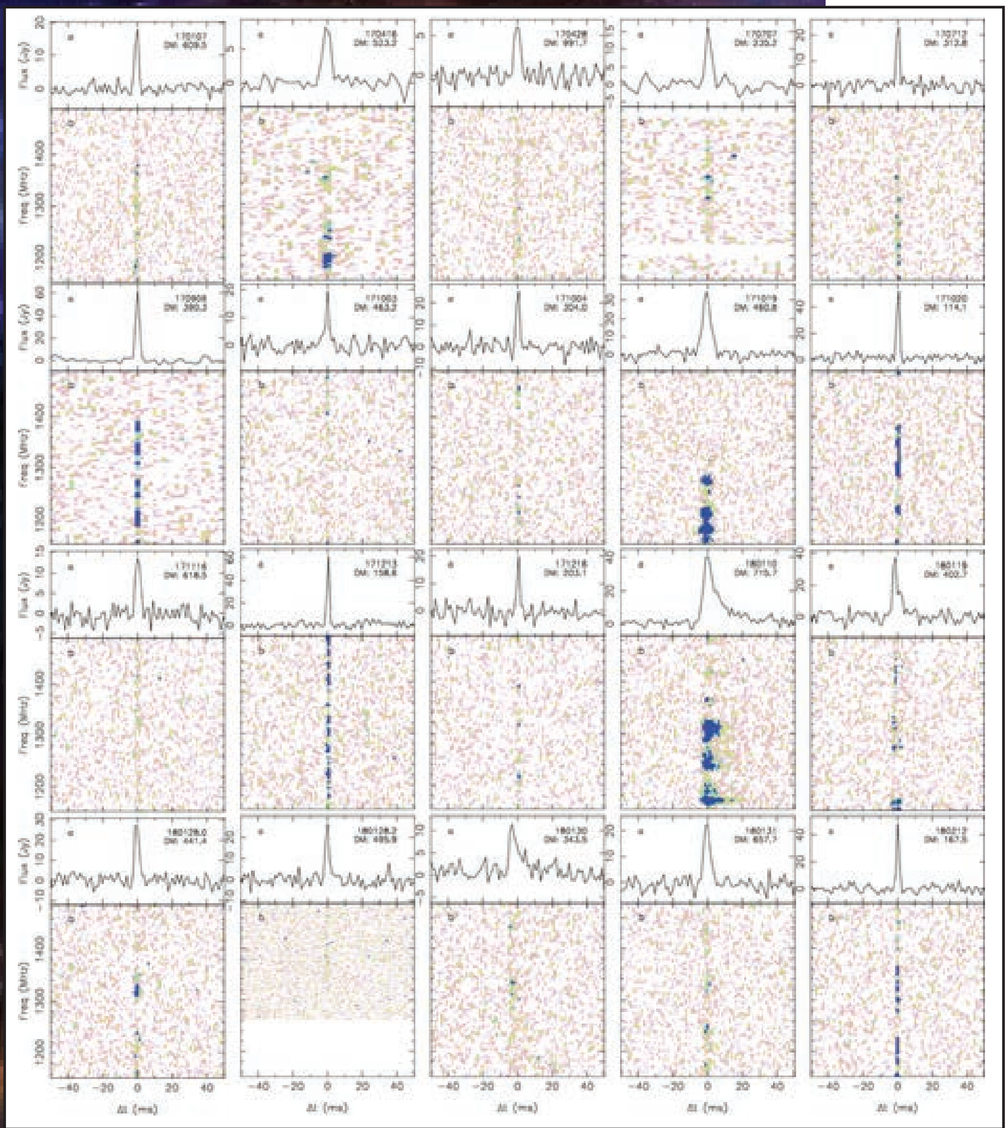
The work not only provides a verification of the polarimetric performance of the MWA but also interesting science results. For the two pulsars, this produced first full polarimetric profiles low radio frequencies. We also studied the polarimetric pulse profile evolution over a large frequency range (~100–230 MHz) using the MWA's large (non-contiguous) fractional bandwidth and compared our results with the published work from higher frequency observations (up to ~8.4 GHz). For PSR J0742–2822, the measured degree of linear polarisation shows a rapid decrease at low frequencies, which is in contrast with the generally expected trend for pulsar emission. One of the possible explanations for this is stochastic Faraday rotation when the pulsar signal propagates through turbulent plasma components in the interstellar medium that are irregularly magnetised. We are now investigating this effect in more detail using a larger sample of pulsars.

This study opens a new window into the polarimetric properties of Southern pulsars at low radio frequencies and will stimulate further research in this area. Obtaining polarimetric profiles for a large sample of Southern pulsars using future MWA observations will allow us to continue to use them as a tool to study the pulsar emission mechanism, geometry and the interstellar medium.

A record haul of Fast Radio Bursts

Jean-Pierre Macquart

with Ryan Shannon, Clancy James, Ron Ekers, Mawson Sammons, Marcin Sokolowski and Ramesh Bhat



For each burst, the top panels show what the FRB signal looks like when averaged over all frequencies. The bottom panels show how the brightness of the burst changes with frequency. The bursts are vertical because they have been corrected for dispersion. Credit: Ryan Shannon and the CRAFT collaboration.

Discovered in 2007, the origin of the millisecond-timescale events known as Fast Radio Bursts remains a mystery to this day. Using the Australian SKA Pathfinder, the CRAFT collaboration has netted a record haul of these elusive events, and discovered that the most events occur at cosmological distances. That is, many of these cosmic events occurred several billion years ago, and some when the Universe was only half its present age. This makes their extremely bright emission even more energetic than previously supposed, and deepens the riddle of what generates them.

Fast radio bursts come from all over the sky, but their fleeting existence - mere milliseconds - and the randomness of their occurrence times makes them hard to find.

You don't know where one will occur or when. The only sure way to find these bursts, in sufficient numbers to measure the properties of the population as a whole, is to use a telescope with a large instantaneous field of view and keeping looking for as long as possible. The more sky you look at and the longer you look at it, the more chance you have of capturing a burst.

This was exactly the strategy used by our survey team in 2017 and much of 2018. Our CRAFT collaboration (CRAFT is the team undertaking the Commensal Real-time ASKAP Fast Transients survey) decided to employ an unusual strategy to capture as many extremely bright fast radio bursts as possible. Our goal was to detect as many bursts with ASKAP in a year than had been detected by all the world's other radio telescopes in the previous decade. We would use a small collection of 6-10 antennas in the Australian SKA Pathfinder, ASKAP, while undergoing engineering commissioning to its full 36-antenna size, to undertake an extremely wide-field survey. Each telescope, each with a 30 square degree field of view, would be pointed in a different direction, allowing us to search for fast radio bursts over an enormous 180-300 square degree field of view at once. With only a single antenna detecting each event, this survey would only detect the very brightest of bursts but it would, for the first time, capture enough events to make a number of definitive statements about the fast radio burst population.

Central to the success of the survey was the phased-array feed technology that gives these ASKAP antennas their large field of view. To cover such a wide area, each phased array comprises 36 independent "beams", each covering about one square degree, and each pointing in a slightly different direction. Phased array feeds pack a hefty punch in the fast radio burst game, and not just because their field of view is sixty times that of the Parkes radio telescope, the instrument which made the first detection of a fast radio burst.

Unlike the 13-beam multibeam receiver on the venerable Parkes telescope, the beams on a phased array are spaced closely together, so that the signal from any detected burst is recorded simultaneously in many independent beams. By measuring the strength of the signal in each beam, it is possible to determine where the burst occurred to a region much smaller than the square-degree footprint of an individual beam.

This is a huge advantage. Once you know where the burst occurred relative to the pointing direction of phased array beam, you can obtain a much more accurate measurement of its true brightness, and its spectrum. If you can do this, you obtain a much better estimate of the true event rate of fast radio bursts, a quantity which had proven remarkably tricky to pin down. Thus, the phased array feed technology on ASKAP automatically overcame a number of limitations that had bedevilled measurements of fundamental fast radio burst properties on previous-generation telescopes.

This meant that every burst detection with ASKAP contained better and more reliable information about the burst than had previously been possible to measure with other telescopes. The figure opposite displays a gallery of 20 of the bursts detected by the CRAFT survey team on ASKAP. For each burst, we obtained a burst position to within about 6 x 6 arcminutes, a reliable spectrum and an estimate of the burst fluence to 10% accuracy. (Fluence is the total amount of energy received by the telescope over the burst duration.) Compare this to previous Parkes detections, where the burst fluence is typically not known to within a factor of several, the position is generally not known to better than 20 x 20 arcminutes, which in turn makes it impossible to correct the observed spectrum for telescope chromaticity effects (which require you to know where in the beam the event occurred).

The 23 burst detections from the CRAFT fly's-eye survey allowed us to reliably measure a number of fundamental properties of the fast radio burst population for the first time. One of the most basic quantities is the apparent brightness of each burst, and how many are detected as a function of brightness. This is possible once you have accurate measurements of the burst brightness.

This quantity is surprisingly useful because you can use it to determine how far away the bursts are coming from. It was already known that the bursts had to be generated well outside our own Galaxy, the Milky Way. The big question is whether the bursts we detect are generated in relatively nearby galaxies, or they are instead generated at cosmological distances, and their radiation has traversed a large fraction of the observable cosmos!

If the bursts we detected were all nearby, the number we would detect above a certain brightness B would scale like $B^{-3/2}$. So for every burst you detect above some brightness level, you should detect eight if you are able to detect bursts four times fainter. This result arises because, although you don't know the distance to any given burst, you do know that, whatever its distance, its brightness will decrease with the square of the distance (hence the -1/2 power). And if the bursts are distributed homogeneously in the survey volume, the number of bursts out to a given distance increase with the cube of that distance (hence the 3 power, giving -1/2 x 3, hence $B^{-3/2}$). But this is only true if the bursts are so close that their distribution is homogeneous within the survey volume. It won't be true in general, because any events that are detected at extremely large (cosmic) distances will have been emitted several billions of years ago, a timescale over which the abundance of many populations of objects in the Universe changes drastically. If the abundance of the population changes, the number of events within the survey volume will not quite scale with distance-cubed, and the slope of the brightness distribution will be different.

We used the CRAFT fly's-eye data to show that the fast radio burst distribution is inconsistent with that expected for a nearby population. The events ASKAP detected, though extremely bright, were coming from distances so large that their radiation was indeed emitted billions of years ago. In short, we have proven that these bursts are coming from the other side of the Universe rather than our own galactic neighbourhood!

We were also able to compare the CRAFT bursts against the sample of those previously detected by Parkes. Although we do not know the true apparent brightness of any one of the Parkes-detected bursts, we do know that the Parkes survey was at least fifty times more sensitive than the CRAFT fly's-eye survey. Significantly, we found that the dispersion measures of the Parkes bursts — the amount of matter that the burst travelled through on its journey to Earth, imprinted in the signature of each burst — were on average twice as large as for the CRAFT bursts! In other words, we found that the burst dispersion measures are correlated with their apparent brightness.

This is striking, because such a relation would not exist if the bursts were coming from nearby, because then the amount of matter a burst propagated through would not relate to its distance. In this case, there would be no correlation between a burst's apparent brightness and its dispersion measure. The fact that such a relation does exist means the amount of matter a burst has propagated through does relate to its distance, and this must mean that the dispersion measures of the bursts is dominated by the only component of matter that relates to its distance: the Interagalactic Medium.

In other words, each fast radio burst contains an imprint of the all the intergalactic matter it has propagated through in its journey through the cosmos. Because we've shown that fast radio bursts come from far away, we can use them to detect all the missing matter located in the space between galaxies. This is an exciting discovery. It paves the way for using fast radio bursts as a sort of cosmic weighbridges that are distributed along the intergalactic highway. We can use them to weigh the Universe!

The survey made a number of other remarkable discoveries. It discovered the brightest burst yet measured: it must have involved incredible energy—releasing in a millisecond the amount of energy released by the Sun in 80 years. (The Lorimer burst, the first discovered burst, may have been brighter, but its detection with Parkes makes it impossible to measure exactly how bright it was.)

The CRAFT fly's-eye survey also discovered the burst with the lowest dispersion measure yet, indicating that this particular event likely came from a very nearby galaxy. We think we know exactly which galaxy it was — a large galaxy only 120 million light years from Earth — but it's impossible to be 100% sure.

We were also able to measure the spectral properties of our bursts with a high degree of confidence. We found that nearly all our bursts have highly patchy spectra, consisting of bright “islands” of emission at some frequencies, but with virtually no detectable emission at other frequencies. The spectral variations look quite random, and might be caused by propagation effects, such as scintillation. However, we can still measure the average spectrum of our population. Interestingly, we find that this very closely resembles the spectral shape of rotation powered pulsars in our own Galaxy. Is there a connection between the emission of pulsars and fast radio bursts? If so, how do fast radio bursts generate emission that is a trillion times more luminous?

We now know that fast radio bursts originate from about halfway across the Universe but we still don’t know what causes them or which galaxies they come from.

The CRAFT team’s next challenge is to pinpoint the locations of bursts on the sky. Instead of using ASKAP in fly’s-eye mode, our next project is to turn all its antennas to point to a single, common 30 square degree field, and operate ASKAP as it was intended to be operated: as an interferometer. With this, we will be able to localise each burst we detect to better than a thousandth of a degree, a figure out exactly which galaxies harbour fast radio bursts.

Whatever may cause fast radio bursts, we are certain that their study has a bright future.

These results were published in a succession of articles centred around the letter in Nature on 10th October 2018, “The dispersion-brightness relation for fast radio bursts from a wide-field survey”, by Ryan Shannon, Jean-Pierre Macquart et al. The publication contained contributions from 5 Curtin-affiliated authors: Ryan Shannon, Jean-Pierre Macquart, Ron Ekers, Clancy James and Curtin 3rd year student, Mawson Sammons.

Macquart and Shannon are both co-PIs of the CRAFT survey team.

ASKAP is located at CSIRO’s Murchison Radio-astronomy Observatory (MRO) in Western Australia, and is a precursor for the future Square Kilometre Array (SKA) telescope.

Other publications associated with this work:

Macquart, J.-P., Shannon, R.M., Bannister, K.W., James, C.W., Ekers, R.D. & Bunton, J.D., The spectral properties of the bright FRB population, ApJ Letters, 872, L19

Mahony, E., Ekers, R.D., Macquart, J.-P., Sadler, E.M., Bannister, K.W., et al. A search for the host galaxy of FRB 171020, ApJ Letters, 867, L10 (2018)

Sokolowski, M., Bhat, N.D.R., Macquart, J.-P., Shannon, R.M., Bannister, K.W., Ekers, R.D. et al., No low-frequency emission from extremely bright Fast Radio Bursts, ApJ Letters, 867, L12 (2018) This work is discussed in a separate article in the CIRA 2018 Annual Report

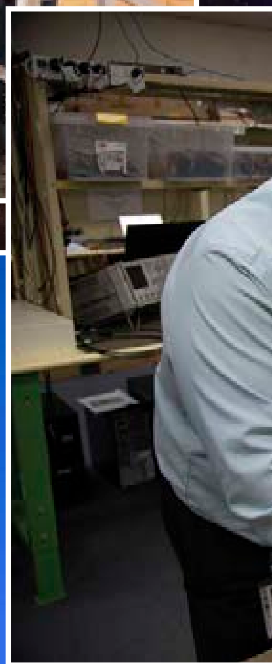
James, C.W., Ekers, R.D., Macquart, J.-P., Bannister, K.W. & Shannon, R.M., The slope of the source-count distribution for fast radio bursts, MNRAS, 483, 1342 (2019)

James, C.W., et al., The Performance and Calibration of the CRAFT Fly’s Eye Fast Radio Burst Survey, PASA, 36, 9 (2019)

An artist’s impression of CSIRO’s ASKAP radio telescope detecting a fast radio burst (FRB). Scientists don’t know what causes FRBs but it must involve incredible energy - equivalent to the amount released by the Sun in 80 years. Credit: OzGrav, Swinburne University of Technology.

HIGHLIGHTS

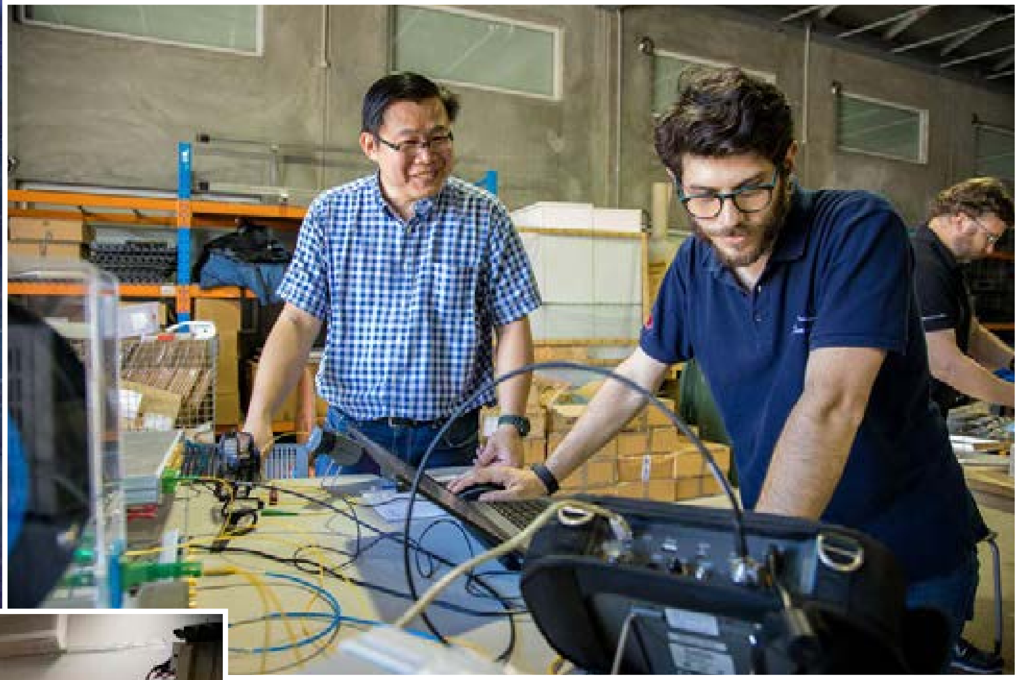
Below: MWA Operations Team members Kim Steele, Mia Walker and Luke Horsley attending the Phase II launch from a remote antenna tile.



Above: SKA engineer Mark Waterson deploying the latest SKA-LOW antenna.

ENGINEERING & OPERATIONS

Right: Curtin and INAF engineers working on new SMART box technology.

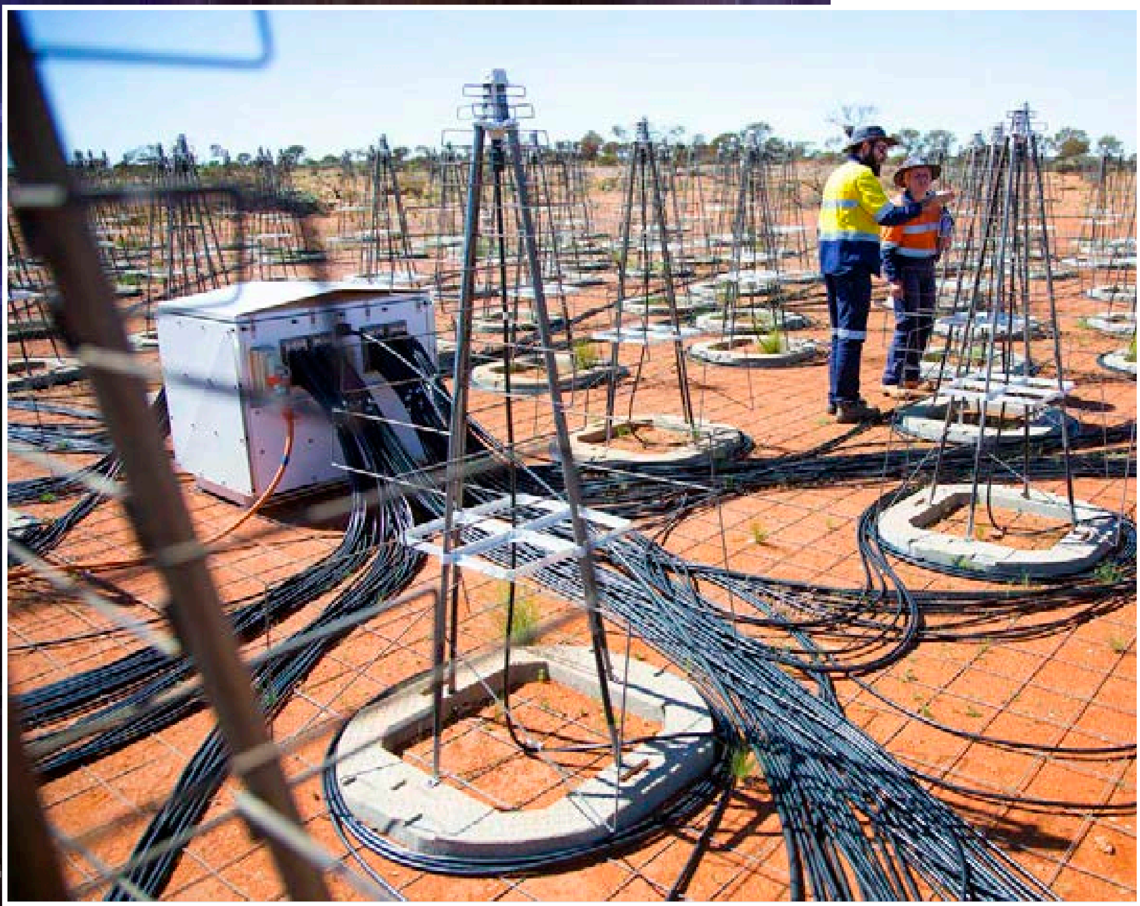


Below: Curtin student engineer Malcolm Whinfield in the lab.

Above: The MWA Operations Team were runners-up in the 2018 VC awards for excellence in leadership.

Getting to the pointy end of the SKA – Critical Design Review and beyond

Tom Booler



Inspecting SKA-LOW antennas deployed at the Murchison.

The technical and scientific ambition of SKA is unprecedented. Add to this the myriad challenges inherent in a large and highly distributed collaboration and it's easy to imagine any number of factors that might impede progress. It's not surprising then that the SKA Project has seen a number of false dawns on its multi-decade journey. A lot of things have to go right, and a lot of compromises have to be struck on the way to making the dream a reality.

CY2018 witnessed a number of key milestones—including the successful completion of element level Critical Design Reviews (CDR), and commitment of the international membership to the nascent Inter-Governmental Organisation—that mark this episode in SKA's history as a critical tipping point. The project now has sufficient momentum to carry it through the all-important transition from design to delivery.

CIRA's mode of engagement with the SKA-LOW design process, and the project at large, has evolved considerably through the current 'pre-construction' design phase, which commenced in CY2013 and will conclude with the system level CDR late in CY2019. When we originally enrolled in the Aperture Array Design and Construct Consortium (AADC Consortium)—formed to design the Low Frequency Aperture Array (LFAA) for SKA-LOW—it was with a narrow, tightly defined, scope focussed on managing the Consortium's on-site prototype and test activities and managing the design (by industry partners) of the power and fibre distribution system(s) within LFAA stations. However when, in late 2013, the SKAO identified the deployment of the 230,000 antennas (then) slated for Stage 1 of SKA-LOW—an undertaking without precedent in the history of research infrastructure—as the biggest risk to the success of the project, CIRA was recruited to place realistic bounds on its cost and schedule. The SKAO's desire to have CIRA lead this important work was a reflection of our reputation as having a realistic and pragmatic approach to planning, and a strong track record of delivery.

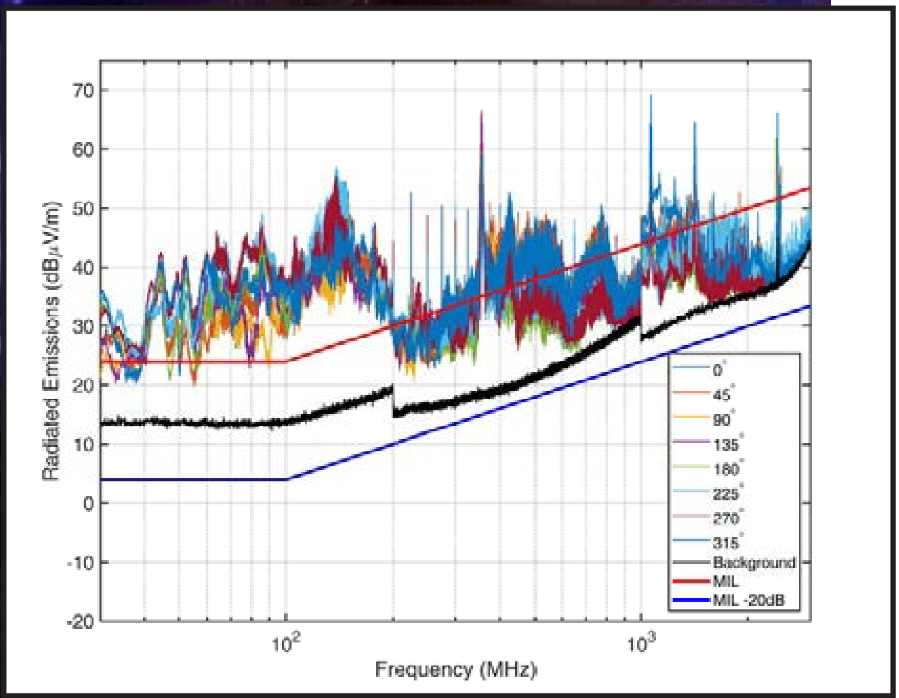
In the years since 2013 CIRA's footprint in and influence on SKA pre-construction has continued to evolve and grow. CIRA's core strengths—antenna and array design and characterisation; processing and scientific exploitation of instrumental data; and the commissioning, operation and maintenance of radio astronomy instrumentation—have all been leveraged into direct and indirect contributions to the SKA project. In 2018 CIRA personnel made direct contributions across the entire spectrum of SKA project activity. CIRA is helping to inform the design of the key science programs the completed SKA will undertake, the types of connectors that will be used on the antennas in the field, and everything in between. As pressure to deliver against the promise of SKA increases into the delivery phase of the project, this trend is set to continue.

CIRA is a key contributor to SKA construction and operations planning initiatives that are currently underway in earnest in anticipation of the project's imminent transition to a delivery focus. Chief among CIRA's contributions in the near term will be contributions to a number of key architecture and technology decisions that must be made as part of the process of translating the performance focussed 'design baseline' to a 'procurement baseline' matched to the project's budget and risk profiles. Having led the delivery of the MWA, CIRA is one a small number of organisations with experience that is directly relevant to framing, informing, weighing and taking these important trade-off decisions.

So, while CY2018 was a seminal year in SKA's long journey, there is plenty of work to be done yet. CIRA will continue to contribute its practical, experience based, insights and capabilities when and where they can have the maximum positive impact on the SKA program. An award of new funding, from the Federal Government, in late CY2018 will see an infusion of new (personnel) resources to enable CIRA to build on its past accomplishments in the project, and ensure that we can continue to have a meaningful impact on the SKA.

PV-Battery System Prototyping for the SKA-LOW

James Buchan



Maximum detected radiated emissions at every 45° orientation of the PV-battery prototype while circulating power with all power converters, control, and monitoring gear operating.

Testing radio emissions from the PV battery system. The prototype is positioned on the turn-table, 1m from the biconical antenna in the horizontal polarisation.

The SKA-LOW radio-telescope site will be located in the remote region of Western Australia near the Murchison Radio-astronomy Observatory (MRO) site and will require a significant amount of power to energise the radio receivers the all associated processing facilities. The SKA-LOW provides a unique load demand under harsh environmental conditions, which requires environmentally sustainable and renewable energy sources to be part of the power supply infrastructure.

Power considerations for the SKA_LOW radio telescopes face many technical challenges which necessitate the power system design to meet stringent electromagnetic compatibility (EMC) requirements. Compliance with the SKA-LOW EMC standards is a vital performance requirement to ensure that any power supply technology does not generate electromagnetic disturbances that will interfere with the radio telescope trying to detect faint radio signals in the distant Universe.

As such, photovoltaic (PV) systems with battery energy storage are being assessed as a viable power supply solution by prototyping a proof of concept PV-Battery system, which has been a collaborative effort with an industry partner, Balance Utility Solutions. In addition to assessing the EMC performance of the PV-Battery systems, design considerations to maintainability, reliability, energy availability and cost-effectiveness were also made. These design aspects are all major power supply requirements that are pivotal to the success of the SKA-LOW.

The prototype PV-Battery system requires 4.8kW of PV and 17.6 kWh of energy storage in order meet the load demand and satisfy the energy availability requirements of 128 radio receivers, which is half the capacity of a SKA-LOW Field Node. A maximum power point tracker is installed in the prototype system, which is capable of optimising the energy yield from the PV array and converting the output voltage of the array to match that of the battery bank for charging. Additionally, an inverter is installed to distribute 230V AC electricity to the Field Node.

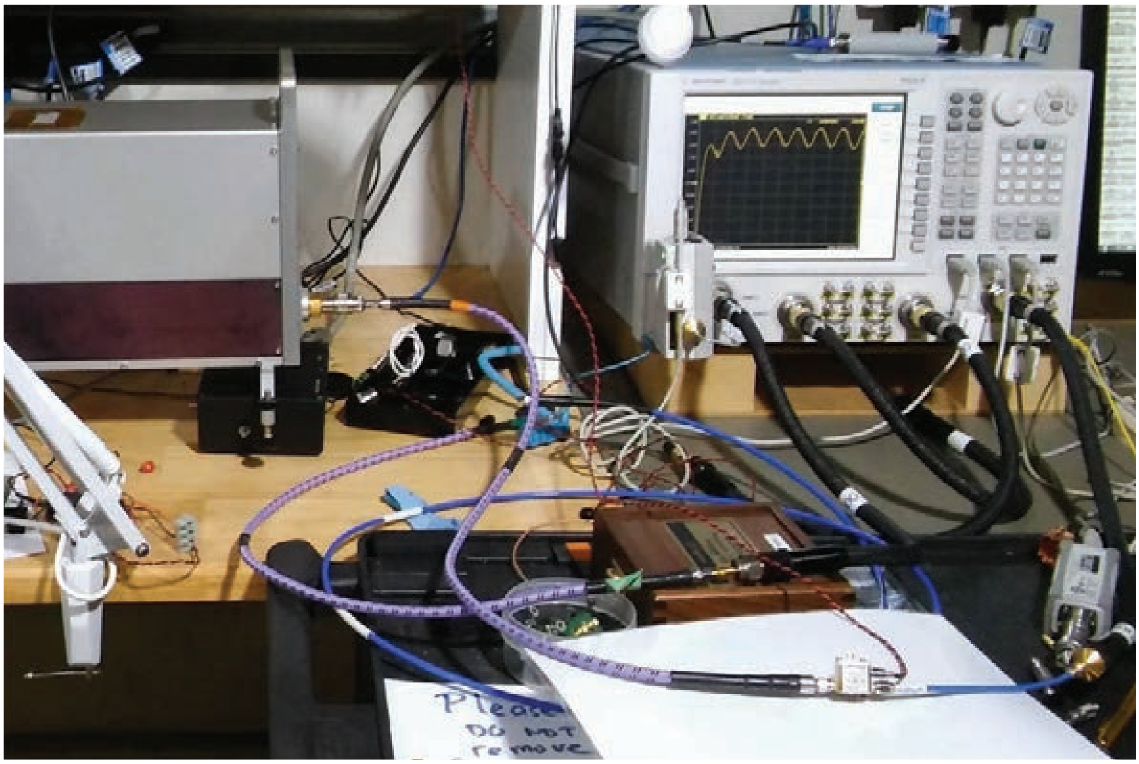
The PV-battery system prototype was developed to characterise the radiated emissions generated by all electrical and electronic components within the PV-Battery system. The EMC tests performed on the prototype assessed the level of emissions generated by the power converters, control, and monitoring equipment within the PV-Battery system. Understanding the emissions generated by the PV-battery system identifies the major culprits of electromagnetic interference generation and determines how much radiated emissions attenuation is required to comply with the unprecedented levels of sensitivity set by the SKA-LOW radiated emissions limit values.

To adequately perform EMC tests on the PV-Battery prototype, design considerations to the prototype PV-Battery system were also made such that the system could fit within an EMC chamber and rotate on the turntable while allowing the system to still charge and discharge under normal operating conditions. This circumvents the use of large PV panels to power the system, which is cumbersome when space is a limiting factor with the Curtin University EMC chamber. Instead, the prototypes are completely self-sufficient with the ability to circulate power courtesy of the battery bank combined with a power rectification stage.

EMC tests were performed in the Curtin University EMC Lab in a semi-anechoic chamber. The radiated emissions tests adopted theMIL-STD-461F testing procedures, which is the testing methodology advocated for the SKA-LOW EMC standards. The emission measurements were assessed against the limit values of MRO EMC requirements, which is 20dB less than of theMIL-STD-461F standards. This provides a preliminary assessment and characterisation of what is achievable considering a less stringent, but still rigorous EMC compliance procedure of the MRO.

Rapid and Accurate Extraction of Noise Parameters in the SKA-LOW Frequency Band

Adrian Sutinjo, Daniel Ung and Budi Juswardy



Taking measurements of an amplifier connected to an impedence tuner.

In the past, the noise generated by the low-noise amplifier (LNA) connected to each receiver in a low-frequency radio telescope has been assumed to be uncorrelated with one another. However, research in the past decade has shown that the noise emanating from the LNAs is in fact radiated through the antenna and is received by the neighbouring antennas. This effect creates a bias in the correlation terms produced by the radio telescope which is undesirable in certain sensitive observations.

Such bias can potentially be corrected if the bias can be quantified. This involves electromagnetic (EM) modelling as well as measurement of the LNA itself. Curtin Institute of Radio Astronomy (CIRA) has experience, expertise and the equipment and has been active in both EM modelling and low-noise measurements [1, 2]. In the context of low-noise measurement, we have developed methods of LNA characterization that is tailored for rapid measurement in the Low-Frequency Square Kilometre Array (SKA-LOW) frequency band of 50 MHz to 350 MHz which is a 7:1 bandwidth.

The first method involves the use of long coaxial cable [2] while the second employs an off-the shelf commercial impedance tuner. The coaxial cable method is inherently compatible with wide band measurement. However, this is not the case with the impedance tuner which in its standard configuration has to perform measurement at many tuner positions which is to be repeated over frequency.

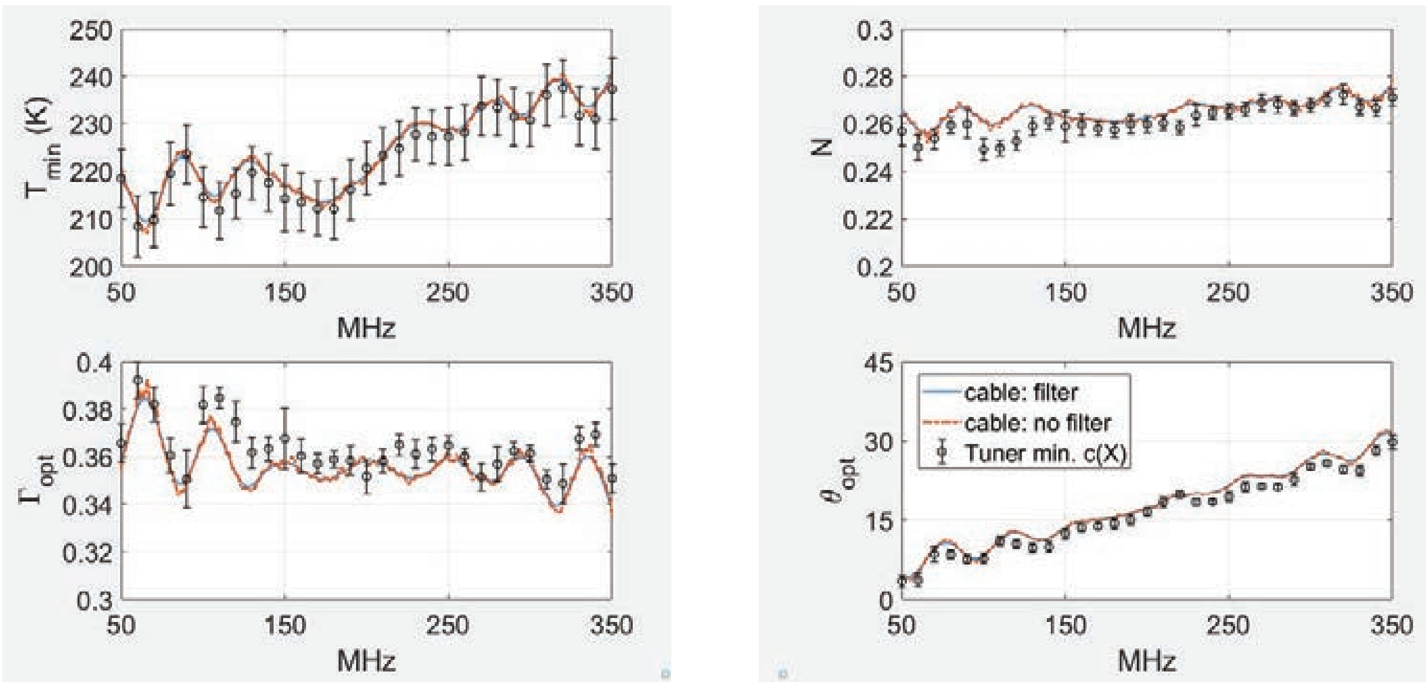
We have recently discovered that very significant time saving is achievable with the combination of insight into the noise parameter extraction process and strategic placement of the tuner probe. As a result, we can obtain high-speed and high-precision measurement over the entire SKA-Low bandwidth with just 7 tuner positions [3]. The comparison between the results obtained by the cable method and the tuner method for an off-the-shelf LNA are shown in the figure. The results generally converge to within approximately one error bar of the tuner method. Both the tuner and the cable methods are highly applicable to any wideband LNA measurements.

References

1. D. C. X. Ung, A. T. Sutinjo, D. Davidson, "Evaluating Receiver Noise Temperature of a Radio Telescope in the Presence of Mutual Coupling: Comparison of Current Methodologies," EuCAP 2019, April 2019 in Krakow, Poland

2. A. T. Sutinjo, D. C. X. Ung and B. Juswardy, "Cold-Source Noise Measurement of a Differential Input Single-Ended Output Low-Noise Amplifier Connected to a Low-Frequency Radio Astronomy Antenna," in IEEE Transactions on Antennas and Propagation, vol. 66, no. 10, pp. 5511-5520, Oct. 2018. doi: 10.1109/TAP.2018.2854285

3. A. T. Sutinjo and L. Belostotski, "Analytical Determinant of the Noise Parameter Extraction Matrix and Its Applications," to be presented in APS/URSI 2019 in July 2019 in Atlanta, USA

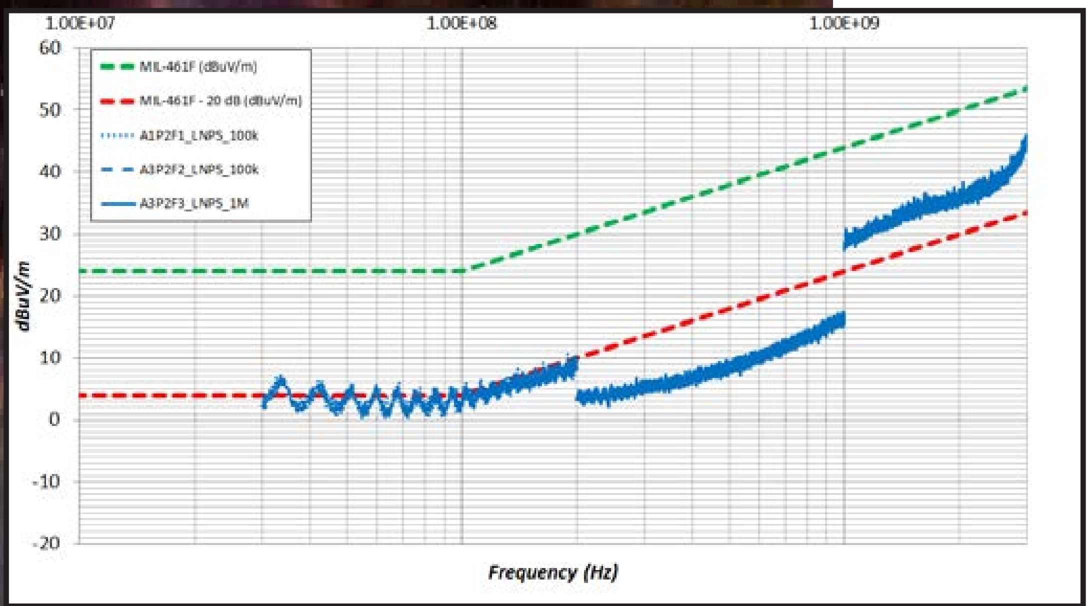


Comparison between measured noise parameters obtained using the tuner with 7 tuning positions and the long coaxial cable method.

Characterisation and enhancement of the EMC chamber facility

Budi Juswardy & David Kenney

CIRA Semi-anechoic EMC Chamber facility. Credit: David Kenney.



Measurement capabilities of CIRA EMC facility. The green and red lines show the target emission thresholds; the blue curves show the measurement noise floor, showing good sensitivity 20 dB below the MIL-STD-461F between 200 MHz - 1 GHz. Credit: Budi Juswardy.

The Curtin Institute of Radio Astronomy (CIRA) maintains and operates an electromagnetic compatibility (EMC) measurement facility, which is located on the main Bentley campus. This facility contains a semi-anechoic chamber, associated pick-up antennas, a turntable, control instrumentation and an electromagnetic interference (EMI) receiver (Rohde & Schwarz ESU26). This facility enables us to perform EMC characterisation of devices-under-test against civilian and military EMC compliance standards. In the context of our involvement with the Square Kilometer Array (SKA) project, we conduct measurements to ensure that instruments that we deploy in the field meet the EMC emission requirements of the Australian SKA site.

In the first quarter of 2018, we performed maintenance, characterisation and verification of the EMC facility. This facility is heavily utilised to determine the EMC compliance of various instruments to be deployed in the field at the Murchison Radio Observatory (MRO), so it was important to verify and have a record of the sensitivity performance of our setup.

We recorded the calibrated S-parameter response of all RF components, such as the response from all possible paths inside the switch box, which includes every coaxial cable and amplifier (after replacing one of the damaged amplifiers). We recorded different settings used in the EMI receiver, for reference and traceability of the sensitivity level of the instrument.

We also updated the EMI receiver's transducer correction data, to reflect the actual detected emission after factoring in the cabling and amplifiers used in the measurement set-up. Instead of manually entering the correction factor into the machine, a software script has been developed to seamlessly upload the updated transducer factors into the EMI receiver.

The outcome of these characterisation activities is that we have verified the sensitivity of the set-up used to measure EMI emission, and now have a reference point for the facility's equipment. To put this into the context of the SKA EMC requirements, in order to ensure radio quietness of the radio observatory, the Australian SKA site has adopted MIL-STD-461F (RE102), with an additional suppression level factor required depending on the placement and the location of the deployment of the instrument in the field.

As most CIRA instrumentation and experiments in the field are deployed between 1 km to 10 km from the Australian SKA Pathfinder (ASKAP), the MRO EMI emission management regime requires an additional suppression level of 20 dB below the radiated emission level specified by MIL-STD-461F. A common practice to meet this level is to measure the device-under-test (DUT) to MIL-STD-461F, and then encapsulate the DUT with additional EMI shielding for deployment in the field. However, it is often difficult to ensure the shielding effectiveness of the enclosure is not compromised, where there are modifications on the enclosure (e.g. after drilling and cutting the enclosure to mount connector for cablings).

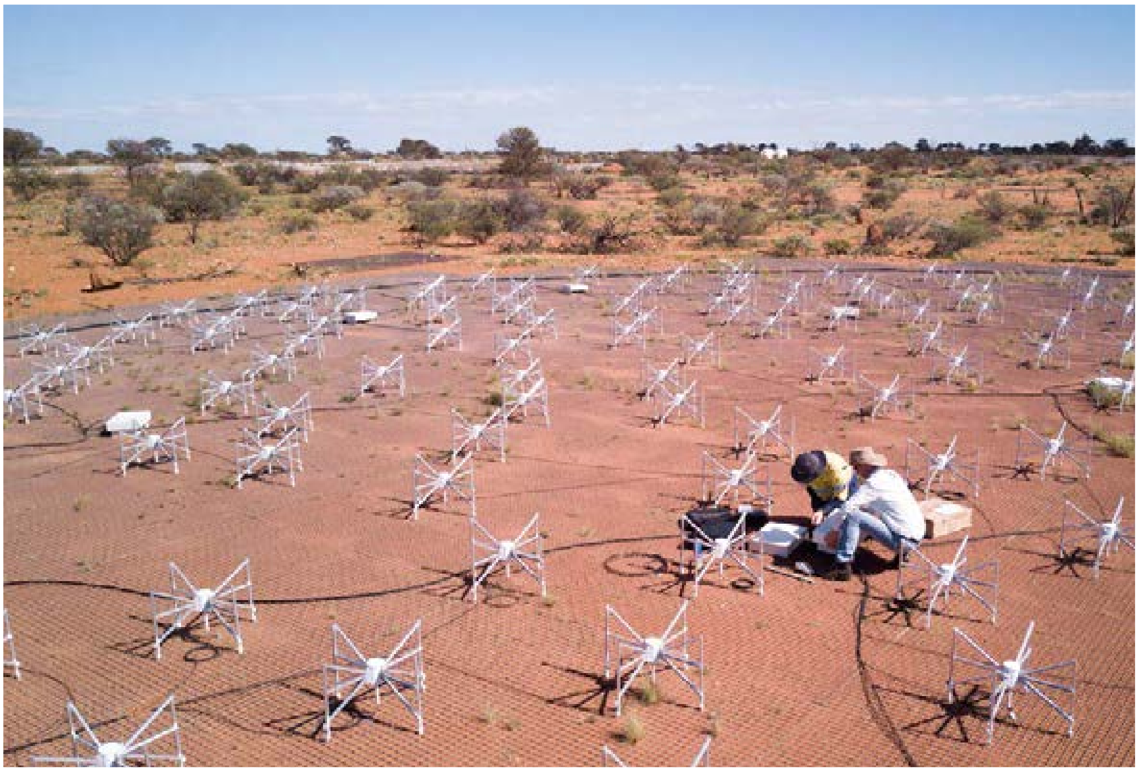
The approach we currently adopt is to measure the device under test directly down to the MRO's EMC target emissions level of MIL-STD-461F – 20 dB. However, our set-up only covers for the frequency range 30 MHz - 3 GHz, whereas the full frequency range of the MIL-STD-461F standard extends up to 18 GHz. Based on current instrumentation set-up and capabilities, we measure radiated emission over the following 3 frequency bands:

- 30 – 200 MHz: good sensitivity down to 10dB below MIL-STD-461F.
- 200 MHz – 1 GHz: good sensitivity down to 20 dB below MIL-STD-461F.
- 1 – 3 GHz: good sensitivity only at MIL-STD-461F level.

As we do not have sufficient sensitivity on two frequency bands, we often perform additional assessments for EMC compliance, such as post-processing of the obtained data. In practice, it is often challenging to strike a balance between providing sufficient sensitivity, having reasonable measurement time and capturing transient/ impulsive RFI-type emission over a wide frequency range. Therefore, we are also looking into assessing the impact of improving the sensitivity level by replacing the components used in the set-up. The hardware improvement and signal processing aspect of the EMC measurement is currently a work in progress, and an active area of research to enhance our EMC measurement capabilities to support SKA-related activities and beyond.

The Engineering Development Array detects cold ionised hydrogen towards the Galactic Centre at lowest ever radio frequency

Randall Wayth, Marcin Sokolowski and Jess Broderick



Randall Wayth and David Emrich working on the Engineering Development Array (EDA). Credit: ICRAR - Curtin.

Ionised hydrogen has been detected at the lowest radio frequency ever towards the centre of our Galaxy. The signal originates from a cloud that is both very cold (around -230 degrees Celsius) and also ionised, something that has never been detected before. This discovery may help to explain why stars don't form as quickly as they theoretically could.

The Engineering Development Array (EDA) is an SKA-Low test and verification system built and operated by CIRA. It consists of 256 MWA-style dipole antennas pseudo-randomly distributed over an area 35 metres in diameter. Signals from the dipole antennas are combined electronically such that the EDA acts like a single large antenna, or "station" in SKA terminology. The EDA was originally deployed in 2016 and used a two-stage analogue beamforming system to electronically point the station to the desired location on the sky. Radio signals from the EDA were captured by a flexible back-end data capture system, such that the data could be processed as a stand-alone system or could be re-formatted into a format suitable for integration with the MWA. In this experiment, the EDA was used as a stand-alone system, and the data capture system was configured to capture the data with very fine spectral resolution – just 1.25 kHz – which is required for detecting faint radio spectral lines from ionised and atomic gas in the interstellar medium of our Galaxy.

In July 2017 the EDA observed the Galactic Centre for approximately 3.3 hours, tracking the source as it transited overnight. The raw data were processed by summer student Emma Alexander, supervised by colleague Dr Jess Broderick, both then at ASTRON. The initial data processing successfully calibrated the bandpass of the EDA such that faint spectral line features in both emission and absorption were clearly visible. Because the data were processed with the custom EDA digital backend, the full spectral bandwidth between 0 and 327 MHz was available, and useful data were obtained starting from below 40 MHz to above 300 MHz.

Encouraged by the quality and frequency range of the data, analysis of the data was continued by both Dr Raymond Oonk, also at ASTRON, and Ms Alexander. They used a common "stacking" technique to combine data in spectral lines to boost the signal-to-noise in a small frequency range. The data revealed a full range of Carbon radio recombination lines (RRLs) between 40 and 310 MHz as well as ionised Hydrogen RRLs between 60 and 310 MHz.

Data from the Carbon RRLs were consistent with, and confirmed, previous observations towards the Galactic Centre where RRLs from cold (20-60 K) atomic gas have been observed. The data from ionised Hydrogen RRLs included a detection at 63 MHz, which is the lowest ever detection of an RRL from Hydrogen towards the Galactic Centre. Unlike observations at higher frequencies, the very low frequency observations from the EDA allow the temperature and density of the gas to be unambiguously determined. The data indicate that the signal originates in a nearby cloud of cold, yet ionised gas -- likely the nearby Riegel-Crutcher cloud.

The detection indicates that ionising radiation can penetrate deep into clouds of hydrogen without necessarily heating the cloud. The confirmation that this nearby cloud supports cold yet ionised Hydrogren may help explain why stars don't form as quickly as they theoretically could in the Milky Way.

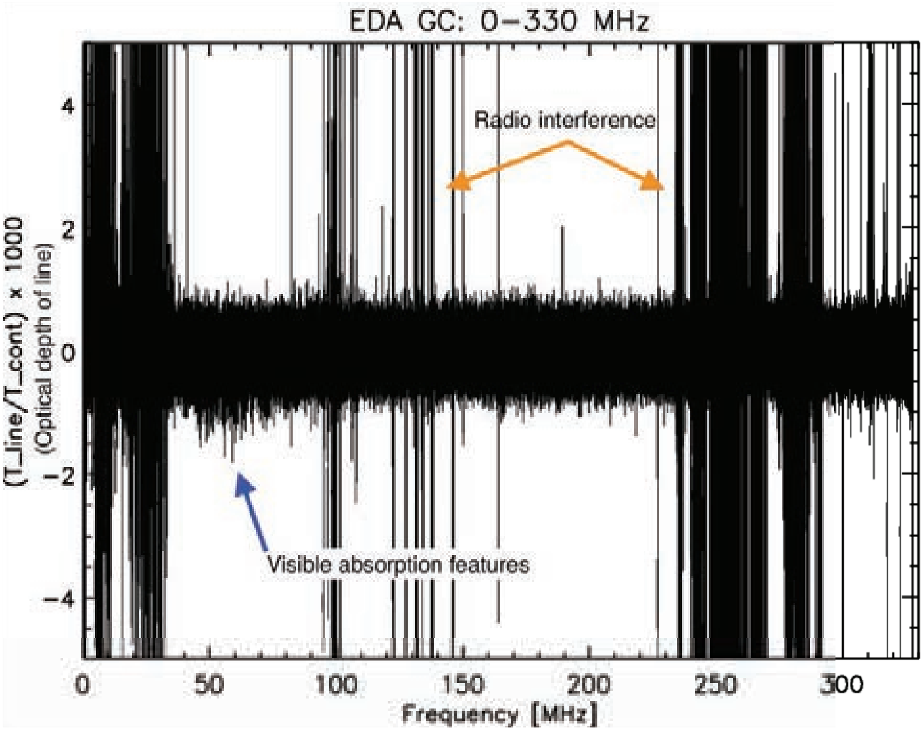


Image: The processed sky-subtracted spectral line data from the EDA. The plot shows mostly noise-like residuals over most of the spectrum. The large positive/negative lines are due to interference. Absorption lines due to atomic carbon are visible around 60-70 MHz.

SMART Box Design and Development

David Kenney

Image, above: CIRA and INAF design team members pictured together with the SMART Box prototype assembled in Medicina, Italy. Credit: INAF

Image, right: Modular Front-end Module plate containing 16 wavelength-division multiplexing RFoF transmitters.

An important part of designing and building SKA precursor systems, for that matter any system, is the opportunity to review and revise the solutions. Considering the power and signal distribution within a field station, rather than using a centralised approach a SMARTer solution was proposed.

An SKA1-Low sized field station consists of 256 dual-polarised antennas. DC power is distributed to and RF output signals are collected from each antenna polarisation. The power connection is made using a direct copper cable and the RF electrical signal is converted to an optical output for transport over optical cabling. Performing the RF-over-Fibre (RFoF) conversion of the output signals within each antenna provides a complex antenna design and a point of failure in a difficult to service location. Additionally it requires managing a delicate fibre optic connection direct to every antenna.

A centralised power and signal distribution scheme results in a dense cable and connection point at the distribution node. In order to avoid this, specifications and requirements for a Small Modular Aggregation and RFoF Trunk Box (SMART Box) were developed. Based on this information a prototype was produced combining designs from the Curtin Institute of Radio Astronomy (CIRA), the Italian National Institute of Astrophysics (INAF) and industry partner Balance Utility Solutions.

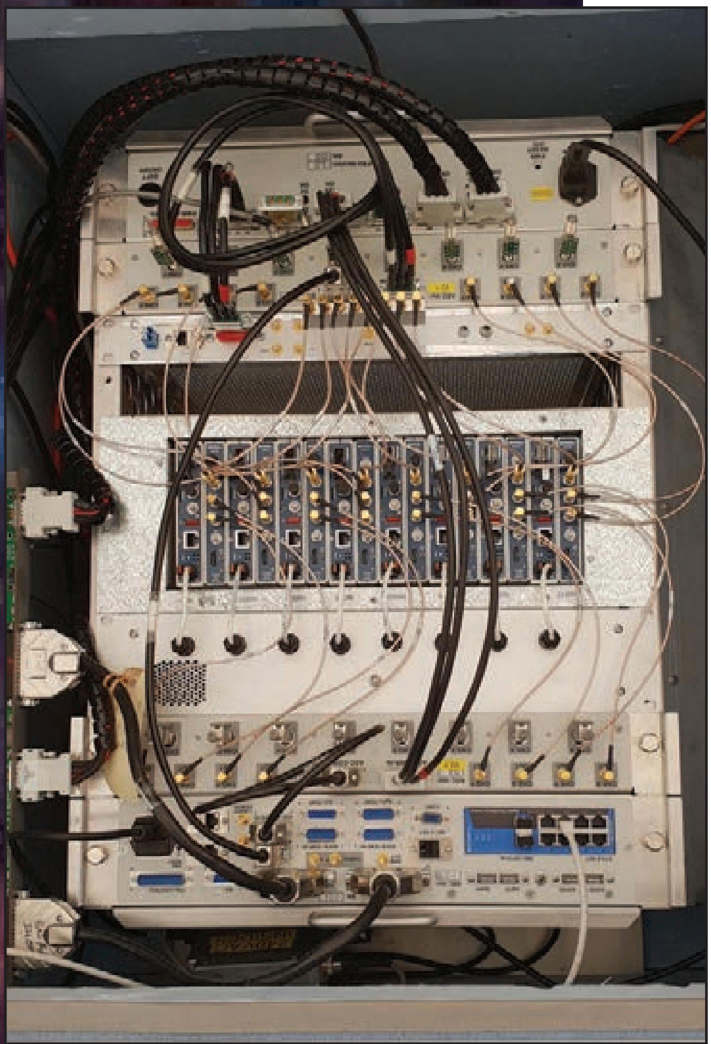
A SMART Box distributes power and signals to 16 antennas, commonly referred to as a tile. A full station is connected by using 16 SMART Boxes. Each SMART Box is provided with a 48V DC power source which is internally converted to 5V using a solution provide by Balance Utility Solutions. Distribution of the 5V is provided by a PCB central to the electronics. Radio-Over Fibre transmitters from INAF provide for coaxial connection for antenna dc and RF signals of which the latter is converted to an optical equivalent using wavelength-division multiplexing. This allows for the transport of both antenna polarisation signals over the same optical fibre using 1270nm and 1330nm optical wavelengths. A multi-core fibre cable is used for all of the signals from the tile and enters the enclosure via a brass waveguide. This waveguide heavily attenuates signals below its cut-off frequency, stopping signals below cut-off from entering or leaving the enclosure. As the optical cable is not electrically conductive it does not compromise the performance of the waveguide and hence the shielding effectiveness of the enclosure.

Prototype assembly and design performance testing, including temperature, tests was performed by a CIRA and INAF team at INAF's radio telescope facility in Medicina, Italy. The prototype was then tested for EMC compliance following functional testing at the CIRA Radio Astronomy Implementation Laboratory. In order to perform field trials at the Murchison Radio Astronomy Observatory (MRO) the prototype requires radiated emissions compliance. For deployment at the MRO the applicable radiated emissions specification is 20dB below the Navy Mobile and Army RE102 limits from military standard MIL-STD-461F. EMC tests were performed at the EMC laboratory at Curtin University.

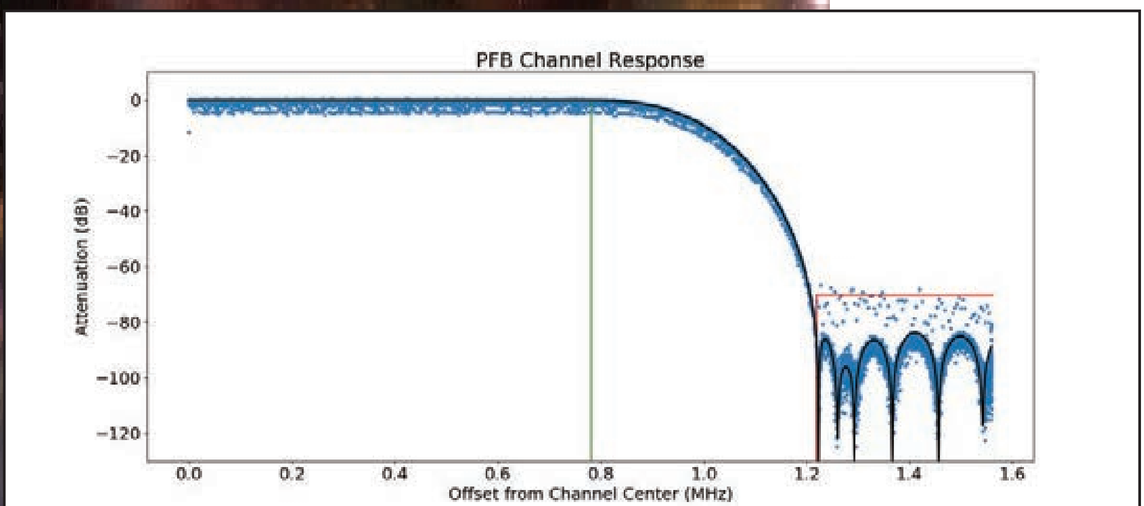
Ease of service and repair was an important requirement for the design. In the event of a failure within the SMART Box removing the 32 SMA coaxial connections as well as the power and optical cable is a complex and lengthy process. This issue is addressed in the design in a number of ways. The power converter is standalone with input and output cabling easily removed. The Front-end assembly, which incorporates the 16 RFoF modules can be quickly and easily removed and replaced. Internal coaxial connections to the RFoF modules are made using quick connect MCX plug and socket. Disconnection of the field fibre from the RFoF modules is achieved by removal of the field fibre LC connectors from the LC adapters located on the Front-end assembly. This solution allows minimal disturbance to the field cabling. Additionally, a single RFoF module can be easily replaced without removing the full assembly where this level of repair is required.

Development of a new Digital Receiver

Jake Jones



The prototype of the replacement MWA receiver. Eight NI FlexRIO's sit side by side where the ADFB module usually belongs.



The filter response function of the new Oversampling PFB with 1MHz wide channels and an oversampling factor of 1.28. (Black) Theoretical response. (Blue) Experimental results. (Green) Passband. (Red) Stopband.

The digital receiver is a crucial element of any radio telescope, however aging hardware and CIRA's increasingly ambitious science goals have resulted in the inevitability of hardware obsolescence. Hence in 2018 CIRA spent a significant effort on the development of a new digital receiver and demonstrated a working prototype of a drop-in replacement MWA receiver.

The digital receiver stage performs several key functions including:

- Analog to Digital Conversion
- Channelization
- Gain & Phase Correction
- Corner-Turning
- Telemetry

Typically, the required sampling rate results in a very high data throughput and as such requires significant computational resources. Field Programmable Gate Arrays (FPGA) are often used in order to handle this high level of throughput. In the case of the MWA receivers this has resulted in some limitations including a fixed output bandwidth of 30MHz, high levels of quantization and significant aliasing within channels. The current MWA receivers were custom designed and the FPGA's are fully utilized, leaving little to no room for future upgrades.

To minimise risk, CIRA has been seeking a Commercial off the shelf (COTS) digital receiver solution, one of which is the National Instruments FlexRIO 7935R. FPGA firmware development is notoriously difficult requiring specialised knowledge, however developing firmware for the FlexRIO is done using the NI LabView FPGA software which provides a graphical programming language dramatically reducing development time and providing abstractions such that the same firmware can be easily ported to other National Instruments devices. In addition to the extremely capable FPGA, the FlexRIO 7935R also hosts two 12 bit ADC inputs, a microcontroller device, 1GbE port and two 10GbE SFP ports for high speed serial data transfer. Overall the NI FlexRIO digitizer offers a low risk solution with the benefits of industry support, portability and rapid firmware development.

The most computationally intensive stage of the digital receiver is channelization in which a polyphase filterbank (PFB) is typically used to reduce aliasing within the course channels. The current MWA receivers implement an 8-tap critically sampled PFB which uses a minimal amount of computational resources but does not entirely eliminate aliasing around the channel edges, for this reason up to 30% of the channel is usually discarded. This problem is addressed in the new receiver by implementing an oversampling PFB instead. Although an oversampling PFB requires twice the resources of the critically sampled case, it entirely eliminates aliasing which has so far plagued MWA data.

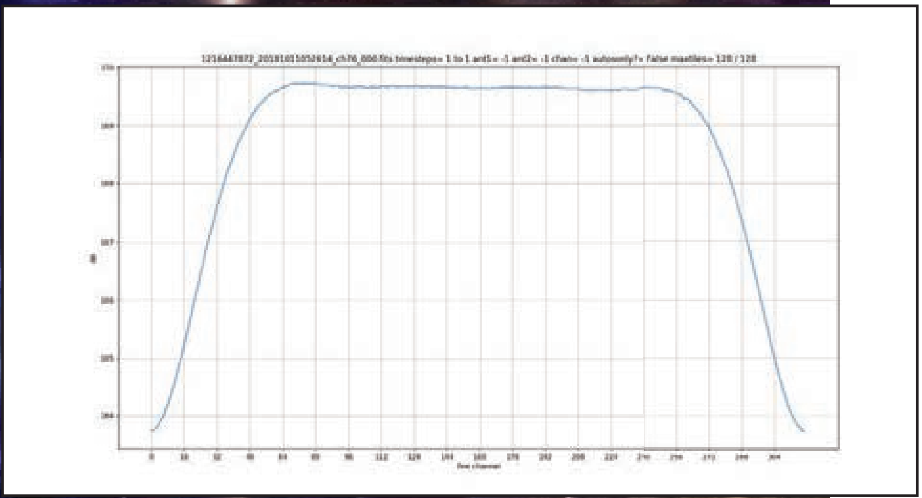
In addition to the oversampling PFB, several improvements have been implemented in the new receiver firmware over the course of its development. It is capable of transmitting up to 100MHz worth or bandwidth via UDP multicast and the data is quantized to no less than 8 bits per real and imaginary component. The receiver can apply channel dependent gain and phase corrections for calibration purposes or improving bit occupancy of low powered channels. It also has significantly improved telemetry, collecting live information such as input power, bit occupancy statistics and PPD's.

In December 2018 a prototype replacement of an MWA receiver was demonstrated. Since a single FlexRIO device has 2 ADC inputs, one device is assigned for each tile requiring 8 FlexRIO's to replace the digitiser in an MWA receiver enclosure. This required the development of supporting hardware including an 8 output power supply, a 1to8 clock & PPS distribution system and a 10GbE aggregation switch. Testing showed that systems performed nominally, and valid data was captured in the correlator building without any packet loss. The improved live telemetry of this system even helped in the diagnosis of some problems with the replacement ASC modules producing spurious harmonics.

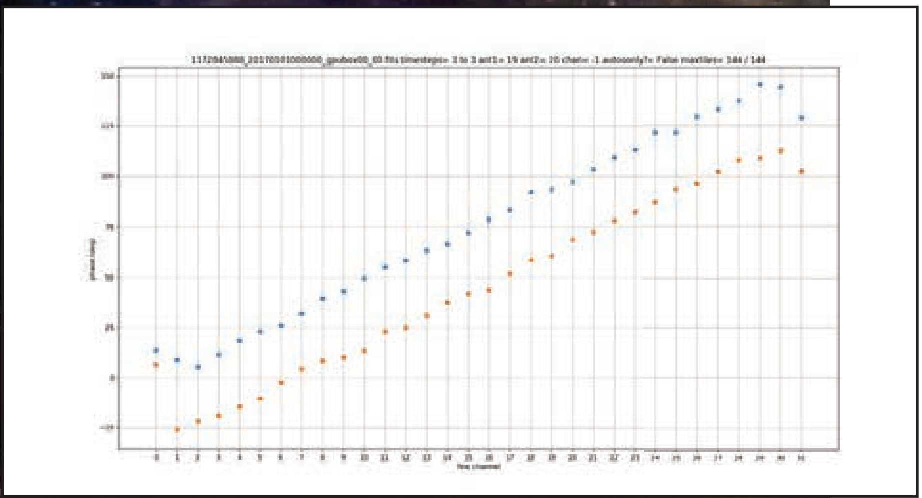
Overall the NI FlexRIO 7935R is a good replacement receiver candidate and has been demonstrated to work in the field however its cost is a limiting factor especially if it were deployed at scale. Moving forward we are working with National Instruments to develop a more refined and cost effective solution that builds on the work we have completed to date.

A New Correlator for the MWA

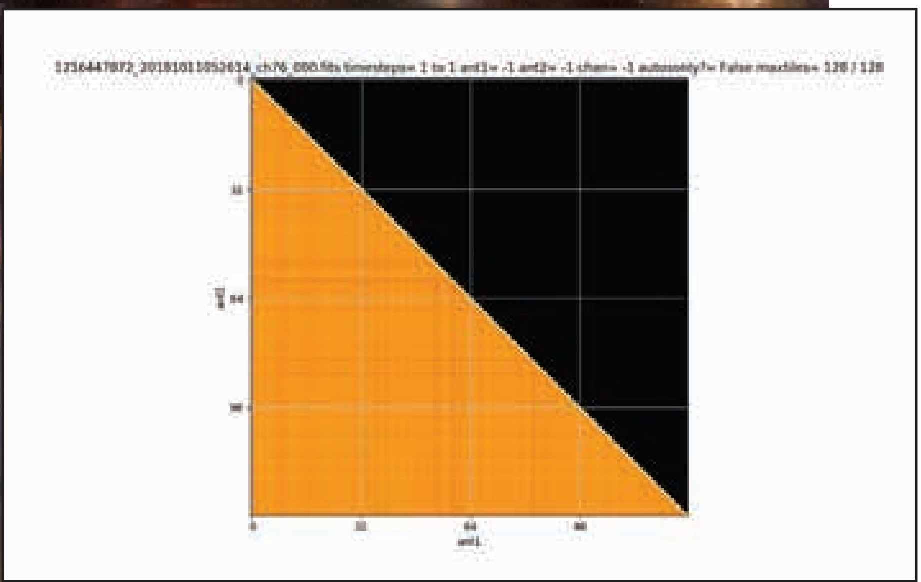
Ian Morrison, Brian Crosse and Greg Sleap



Cross-correlation power as a function of frequency (the x-axis). The shape of the plot correctly shows the band shape we expect to see from the data output by the 16 coarse channelisers in the field.



Sample cross-correlation phase plot showing a fringe off a bright, unresolved source.



Heat map of cross-correlation output with each axis representing an MWA tile and each intersection representing the corresponding cross-power.

2018 saw major progress on the development of a new digital correlator for the MWA to fully exploit the Phase II (and future planned) upgrades and provide new features, broader processing options and improved scalability.

Array telescopes like the Murchison Widefield Array (MWA) can produce magnificently detailed images of the sky, but forming these images is a complex process involving multiple stages of signal processing and data manipulation. At the heart of the process is the "correlator" – a computational beast that calculates the cross-correlations between every pair of array elements. When there are many array elements, the number of pairs ("baselines") can become overwhelmingly large. Following the Phase II upgrade, the MWA has 256 elements ("tiles"), although currently only 128 of these can be correlated at a time, meaning a total of 8,128 baselines. In the near future the goal is to correlate all 256 tiles, roughly quadrupling the number of baselines to 32,640. For each baseline, the correlator needs to perform tens of millions of real-time floating-point mathematical operations per second (FLOPS) for each coarse channel, and there are 24 coarse channels. That amounts to tens of teraFLOPS (where each teraFLOP is a million million FLOPS) – more than the world's fastest supercomputer in the year 2000 could have handled. But thankfully that was then and this is now. With the benefit of Moore's Law, the new 256-tile MWA correlator can be implemented with a cluster of 24 commercial-off-the-shelf compute servers, each accelerated by an embedded high-end Graphics Processing Unit (GPU).

The existing MWA 128-tile correlator has served the needs of the MWA community well for over 7 years. However, it suffers from limitations in its capabilities and flexibility, and the design cannot readily be scaled from 128 to 256 tiles. Work began on a next-generation correlator design that could handle 256 tiles and beyond, offer a broader range of time and frequency resolution options, support "fringe-stopping" delay corrections, and provide various other new features to better satisfy current and future science needs. At the same time the new design promises operational benefits including greater reliability, reduced power consumption and improved maintainability and extensibility.

By the beginning of 2018 the design details were largely complete for the new "MWAX correlator". Much of 2018 was dedicated to detailed software development and testing. While the new architectural design was always intended to be scalable to 256 tiles, testing proceeded initially with a version providing the enhanced MWAX functionality while still being limited to 128 tiles. Towards the end of 2018, the software was further streamlined and optimised, culminating in validation of real-time 256 tile correlation on representative GPU hardware. Benchmarking was conducted over several different latest-generation GPU platforms, leading to the preparation of a hardware requirement specification for the preferred platform, suitable for raising a request-for-quotation once the project is suitably funded.

The MWAX design didn't start from a blank sheet of paper. At its core is a highly-optimised cross-correlation library called xGPU – the same library employed in the existing correlator but with some important customisations by CIRA engineers to better manage the data ingest stage to reduce bus traffic and increase overall speed and scalability. We also borrowed extensively from the experience and codebase of the Swinburne-led UTMOST correlator, in particular the use of the PSRDADA library for efficient and flexible real-time data buffering – essential to obtaining stable performance and data throughput when using a software-based real-time signal processing solution.

One of the key innovations of the MWAX design was to change the data links between the coarse channelisers and the fine channelisers to multicast UDP Ethernet. Multicasting is a process whereby a data stream is sent to a network switch and then duplicated to one or more destinations with no extra load on the sender no matter how many destinations there are. In addition to enabling enhanced correlation capabilities, this new multicast design will transform the MWA's ability to perform multiple commensal tasks (such as real-time searches for Fast Radio Bursts (FRBs) or extraterrestrial technosignatures) at the same time as MWAX is performing correlations for the primary science use case.

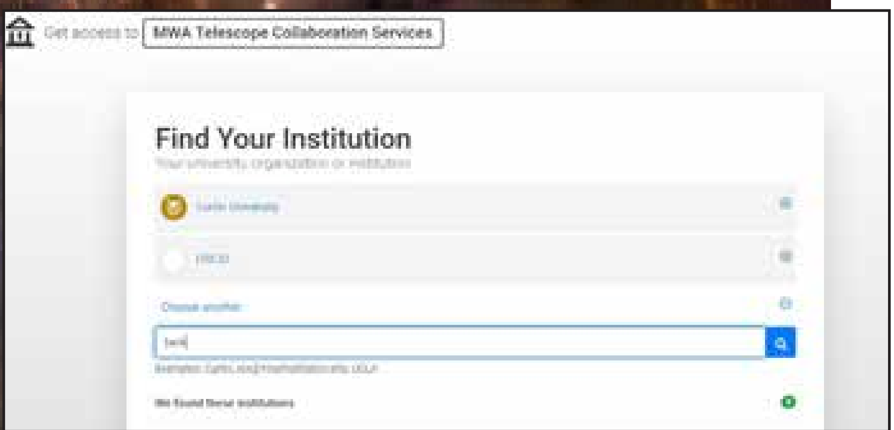
In 2019 the MWAX correlator will be further refined and rigorously validated so that it is fully ready to replace the existing correlator with minimal disruption to telescope operations. The additional features and greater flexibility will make the switch-over to the new correlator attractive even for 128 tiles, but the greatest benefits will come when new compute hardware and other infrastructure improvements allow all 256 tiles to be simultaneously correlated, providing a major step-change in the MWA's sensitivity and spatial resolution.

Managing the MWA Collaboration with a Federated Identity System

Greg Sleap, Mia Walker and Randall Wayth

The MWA has over 270 members and associates from twenty one member institutions.

The new MWA Wiki built on Atlassian Confluence wiki server.



The login chooser page for MWA member services allows users to select an authentication provider from a list of thousands of local and International institutions.

The Murchison Widefield Array (MWA) is developed and run by an international collaboration of 21 partners from Australia, New Zealand, Japan, China, Canada and the United States, led by Curtin University. Like many scientific collaborations, the set of participants changes over time, as individuals and institutions join and leave the collaboration. These patterns create challenges for providing access to MWA services upon joining (on-boarding) and removing that access upon leaving (off-boarding).

MWA Members require access to access and download MWA data, a wiki for documentation and collaboration, various mailing lists, source code repositories and other services. Each of these services is independent and requires members to have many different credentials (usually username/password). In addition, on-boarding and off-boarding are very manual processes with administrators having to perform many steps just for one member.

The MWA Principal Scientist is responsible for on and off-boarding new members and institutions, with much of the systems work being done by the MWA Operations team. During 2017, it was clear that with MWA Phase II approaching (and with It a slew of membership changes), there had to be a better way to reduce the burden on the Principal Scientist and MWA Operations team, as well as providing members with a more seamless and friendly user experience.

To help address these challenges, we looked to tools and techniques developed by and for the research and education community. Central to this is the concept of federated or external identity. With federated identity, a participant uses their home institution's credentials to authenticate to MWA services, instead of having separate usernames and passwords for each system.

Federated identity helps solve the authentication problem, or proving a user is who they claim to be. A Collaboration Management Platform (or CMP) can help solve the authorisation problem (determining what the user should have access to). The CMP is responsible for enrolling new participants, tracking their permissions, and removing access when the participant leaves - helping reduce the burden of on and off-boarding.

Finally, the various MWA services would need to be integrated into the federated collaboration infrastructure through a process called application integration. The details vary for each application, but in general each is reconfigured to rely upon the federated or external identities for authentication, and on the CMP for authorization.

During 2017 and 2018, the MWA Collaboration enlisted the help of the Spherical Cow Group (SCG)- a leader in providing identity management solutions to research organisations. Working with the MWA Operations team, SCG has deployed a CMP (specifically: COmanage) accessible via a federated identity system and helped integrate with key MWA services such as the MWA Confluence Wiki (https://wiki.mwatelescope.org) and the MWA All-Sky Virtual Observatory MWA ASVO (https://asvo.mwatelescope.org), a web-based portal allowing astronomers around the world to access MWA radio astronomy data. A mailman service, for managing e-mail distribution lists, is due to be integrated in 2019.

The on-boarding process was replaced with a single, simple web-based enrolment process. The new member chooses which login provider they would like to use. There are thousands of login providers to choose from. Via Curtin University's membership with the Australian Access Federation (AAF), we offer all of the major Australian institutions and universities, including CSIRO. The AAF is also a member of eduGAIN, a world-wide federation of identity providers, expanding our list of available login choices to thousands.

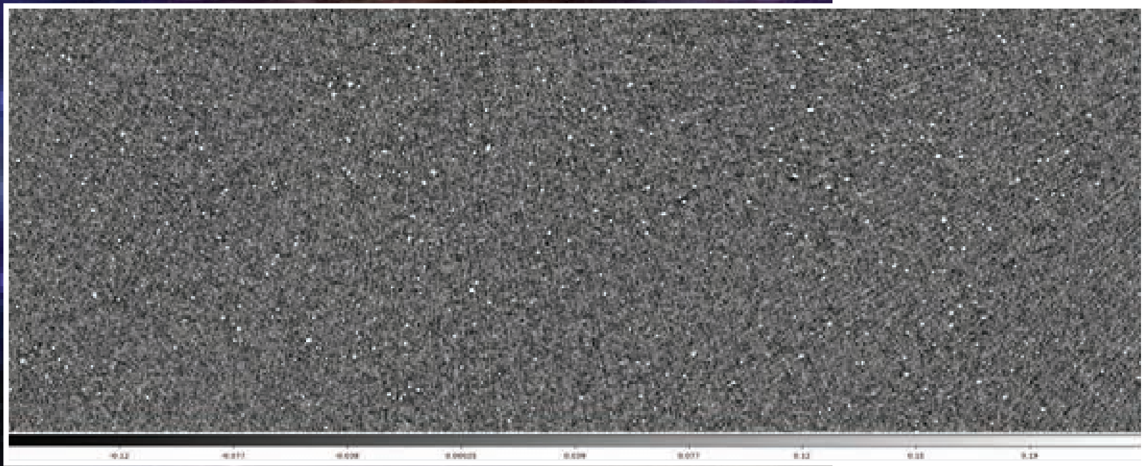
Unfortunately, not all countries and institutions have joined eduGAIN yet- including China, Japan and New Zealand - a significant fraction of our membership. For these members we implemented two "providers of last resort": UnitedID and ORCID. UnitedID is a free non-for-profit identity provider which requires users to sign up using any existing email account. ORCID provides a persistent unique identifier for researchers- linking them to their authored works. ORCID is especially useful for the MWA as many users already have ORCID accounts, ORCID's stay with members even if they move institutions and ORCID is much easier for Chinese members to use than UnitedID due to not relying on any Google-based services.

Once a login provider is selected, the user Is then taken to their chosen institution's login page where they log in as they would to access their institution's services. Some basic user information is returned to the MWA enrolment form where the new member can check or change information such as name, email address and job title. They then submit the web form, and once the Principal Scientist approves the membership request COmanage then provisions their member services, allowing them to log in to the wiki, the MWA ASVO and to be added to mailing lists (once the mailman service is ready in 2019). Off-boarding is also vastly simplified, allowing the Principal Scientist to revoke membership (and thus all access) with a single click within COmanage.

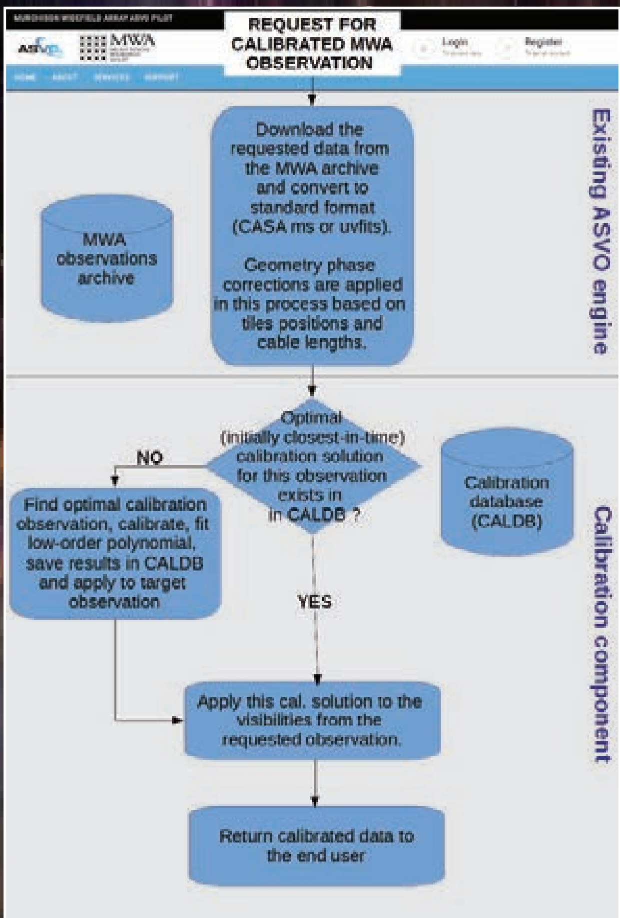
The new MWA federated membership system went live late 2018 and is enabling MWA members to access various services using a single login via a consistent interface. It has also reduced the burden placed on the Principal Scientist and MWA Operations team in managing memberships and logins to systems. With the new system being easily expandable, it will be possible to Integrate other applications in the future, including source control, group calendaring and more.

MWA Calibration Database for the All-Sky Virtual Observatory (ASVO)

Marcin Sokolowski, Chris Jordan, Greg Sleap, Andrew Williams and Randall Wayth



Example image obtained by calibrating observation collected at 2018-06-15 21:27:03 UTC and calibrating it with the closest in time calibration solution in the database.



General overview of the MWA ASVO system with the new calibration component.

In 2018 we enhanced the existing Murchison Widefield Array All-Sky Virtual Observatory (MWA ASVO; https://asvo.mwatelescope.org/dashboard) interface to the Murchison Widefield Array (MWA) data archive with a calibration component.

The original MWA ASVO interface provided external users with functionality to download any MWA visibility data, which becomes publicly available eighteen months after collection, subject to the MWA data access policies. The data were made available in the standard radio-astronomy data formats (CASA measurements set or UV fits files). However, the data were not calibrated and required several additional steps before sky images could be formed, which could be troublesome for users not familiar with the specificity of the MWA telescope. This new development allows every user without deep knowledge of "nitty-gritty" details of the MWA instrument and data to download calibrated data in a standard radio-astronomy format. It opens a new avenue for researchers worldwide to download calibrated data, create sky images using standard radio-astronomy software packages without a very deep knowledge of the MWA instrument and analyse these images for their purposes.

Development of this new functionality required several modifications in the existing MWA ASVO system. The data converting software (cotter) was made open source and extended with on-the-fly calibration enabling application of calibration solutions whilst the data is being converted into a standard radio-astronomy data format. We also developed a database of calibration solutions and an automatic pipeline (heracles) to populate this database with calibration solutions since the beginning of the MWA operations (early 2013). heracles reduces a specified list of calibration observations, calculates calibrations solutions, applies them and inserts into the database. In the process an image of the calibrator field is also created.

In order to populate the database as quickly as possible we tested several approaches. Initially, we were using a single server computer and a cloud system at the Pawsey supercomputer centre (Nimbus), but it turned out that we required more computing resources. For this reason, heracles was converted into a distributed system running on any free resources available (such as unused desktop computers in the CIRA visitors and student area or several other computers). This enabled us to download, calibrate, image and insert into calibration database solutions from nearly six years of the MWA operations. Currently the database contains calibration solutions from nearly 10,000 calibration observations, which provides on average five calibration solutions per day for the primary MWA frequency bands. The database grows daily as new calibrator observations are collected and the pipeline is also being used in near-real time to reduce new calibration solutions and insert them into the database.

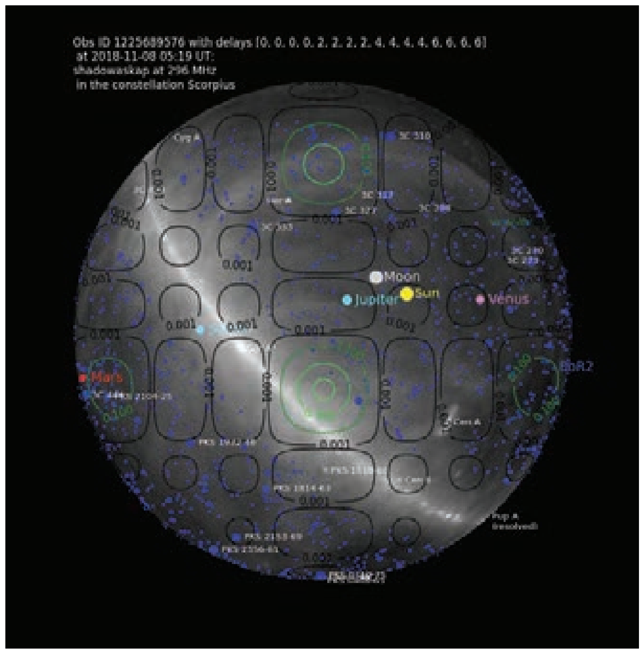
This near-real time reduction of calibration solutions enabled another valuable monitoring functionality for the MWA. As the calibrator observations from every morning and evening are reduced, calibrated and imaged, we plot their amplitudes and phases to monitor interferometric performance of the instrument. In particular, monitoring phases of calibration solutions allows us to immediately identify antennas (tiles) that are not performing well and require further attention or repair. It also helps with identification of problems with the MWA system clock and any potential perturbations or failures that it can undergo. Furthermore, the near-real time calibration solutions will be particularly important for the new fringe-stopping MWA correlator (see contribution by Ian Morrison), which requires up-to-date array of calibration solutions to perform correctly. Finally, this work can be extended to build a database of calibration solutions for the upcoming low-frequency component of the Square Kilometre Array telescope.

The development of the calibration components of the MWA ASVO interface is a very important contribution to the astronomical community in Australia and worldwide providing access to the MWA data archive to every researcher without deep knowledge of the instrument. Therefore, we expect that this endeavour will pay-off in a number of publications from researchers from outside the MWA collaboration using the MWA data.

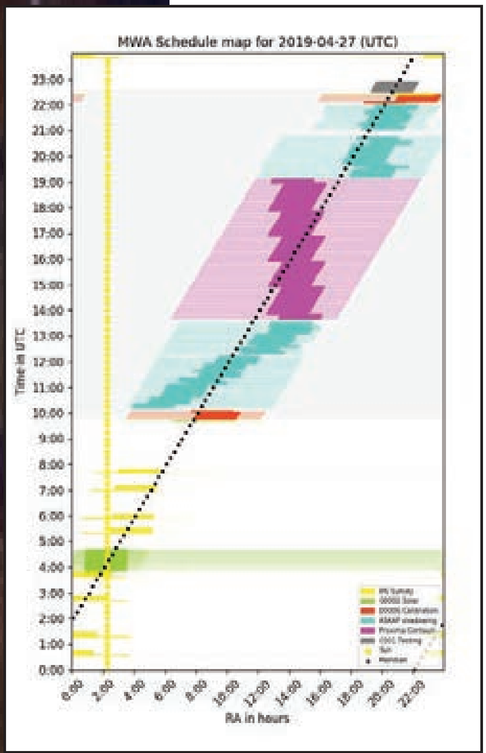
Screenshot from the MWA ASVO web page.

MWA Monitor and Control Improvements

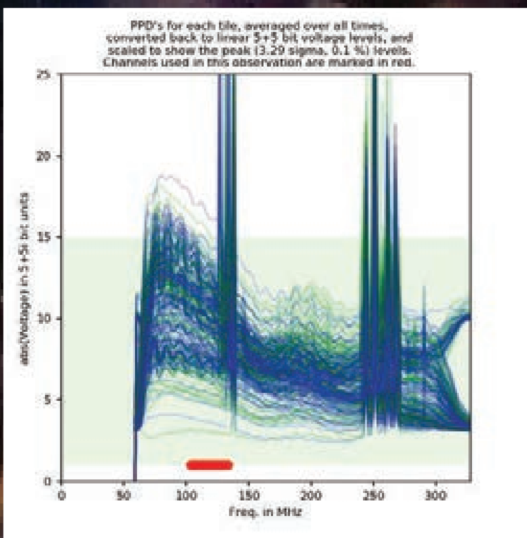
Andrew Williams



Left: A beam map of the sky, showing where the MWA is pointed during an observation.



Right: Timeline for scheduled observations.



Above: Signal power levels received by MWA antennas.

Right: A map of MWA antenna groups, showing faulty hardware in red.

Work on the MWA Monitor and Control (M&C) software in 2018 included some major new features, and a lot of work 'under the hood' to make the MWA software more robust, and more easily used by others.

The biggest new feature Is a new triggering system, allowing normal MWA observations to be interrupted for transient observations when a Virtual Observatory Event (VOEvent) is received. VOEvents are machine-readable text documents, passed in real time from telescopes detecting transient events (Gamma-Ray Bursts, etc.) to telescopes that can provide follow-up observations of those events.

The new triggering system is divided into two parts. The back end is a web service that has been installed on an on-site server, forming part of the M&C system. This back-end system accepts requests from clients via the Internet. An entirely separate front end (which can be run externally or on-site) parses incoming VOEvents, makes decisions about when to trigger a new observation (or re-point an existing triggered observation), and calls the web service to schedule the observations. Multiple front-ends responsible for monitoring and parsing different VOEvent streams and/or transient source types can be run in parallel. Separating the science (what VOEvents to trigger on, and why) from the scheduling function lets the operations team handle the back-end code that directly controls the telescope schedule, while allowing astronomers in the science project teams to write their own front-end parsing code to decide which events to follow, and what observation and follow-up strategies to adopt.

The new triggering system can interrupt existing MWA observations, and schedule new observations in normal correlator mode, in voltage capture mode, or a new 'voltage buffering' mode, where the last 150 seconds of raw voltage data, stored In a ring buffer in RAM, is dumped to disk, allowing data recorded minutes before the trigger was received to be captured. The new triggering system has been described in Hancock et al. (2019, submitted).

So far, new front end VOEvent handlers have been written for handling Gamma Ray Burst notifications from the Fermi and SWIFT space telescopes (with Paul Hancock and Gemma Anderson). Another two are being developed - one for gravitational wave events from LIGO (with Dougal Dobie from Sydney University and David Kaplan from the University of Wisconsin, Milwaukee), and another for neutrino detections from ANTARES (with Dougal Dobie and David Kaplan).

Another large project was a complete rewrite of the Python libraries and data structures representing MWA observations. When the M&C software was first written, the assumption was that the code would only be used on-site, by machines with direct access to the MWA schedule database. The library required a network connection to the database server, even if the user didn't intend to write or read observations to/from the database.

In 2018, this code was rewritten from scratch, and split into a library with structures representing MWA observations that could be used anywhere in the world, and another library building on that, allowing these structures to be loaded from and saved to the schedule database (only usable on-site).

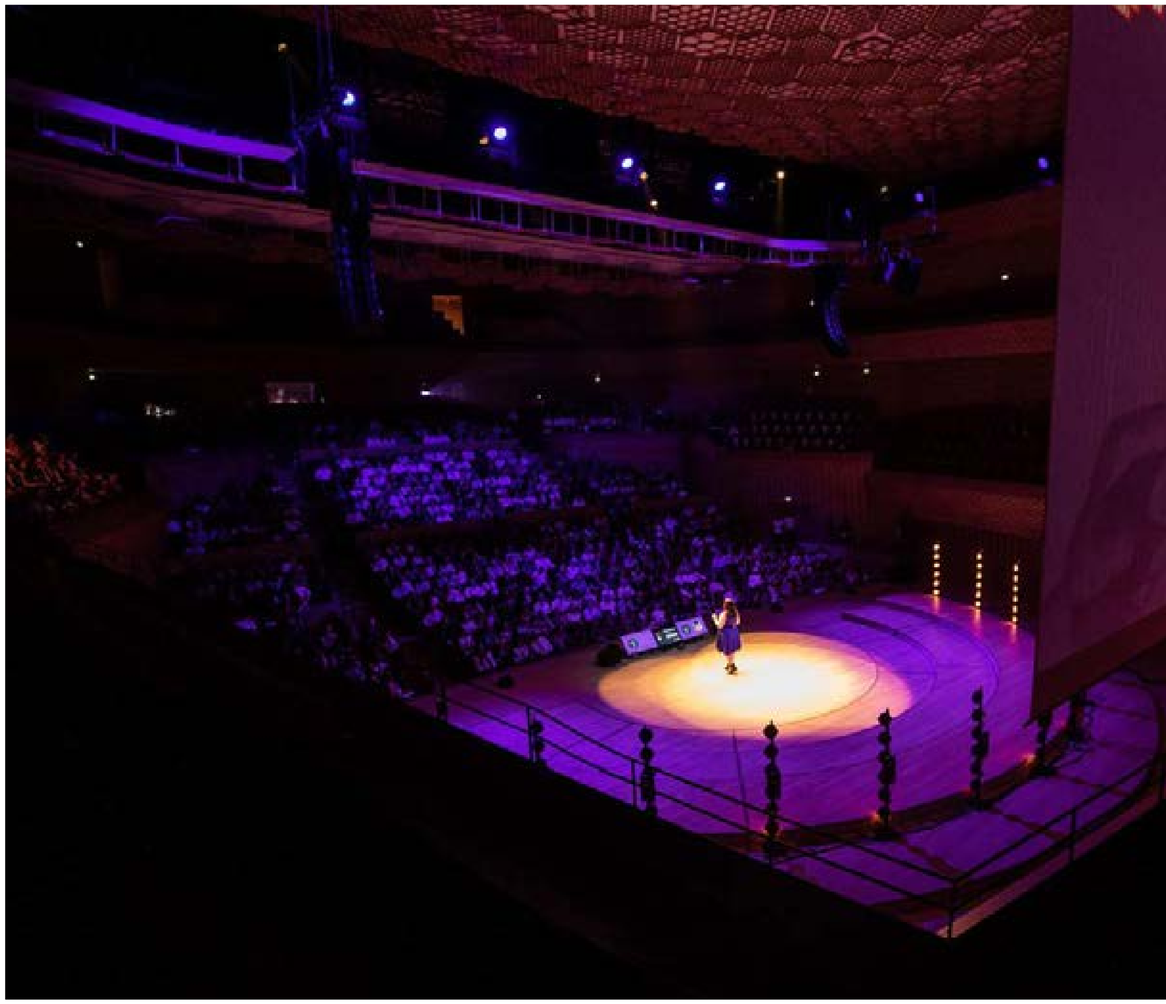
This split, along with other changes, made it much easier to work on software dealing with MWA observations, and led to a wide range of other M&C improvements directly visible to end-users. These improvements include some new dynamic web pages:

- An improved 'observation information' page, showing a beam map on the sky (pictured), any hardware errors that occurred during the observation, power levels at all tiles (pictured) allowing clipping and under-sampling problems to be diagnosed, etc.
- Other web pages showing telescope errors and faults, including a visual map of tile hardware faults (pictured).
- two dimensional (RA vs time) graphical maps showing observations in the MWA schedule (pictured).
- An improved web page for finding observations in the MWA using a wide range of constraints.

As well as the human-readable web pages, many new 'web services' were developed. Web services are dynamic machine-readable web pages, written so that code on one computer can request data from another computer. These web services allow any of the data on the observation info pages to be requested and read by remote software (eg data reduction pipelines). The metadata provided by these web services is in a range of possible formats, including plain text, HTML fragments that can be inserted into other web pages, JSON structures, PNG files, or the standard 'metafits' files used to describe MWA observations.

The new web services are being used by the MWA All Sky Virtual Observatory (ASVO) portal to request calibration solutions for data sets being downloaded, and by various science teams writing scripts to search for observations matching certain criteria, or that need detailed observation metadata.

HIGHLIGHTS



MWA Director Melanie Johnston-Hollitt presenting at L'ECHAPPEE VOLEE. Credit: Jacob Khrist.

CIRA astronomer Dr Natasha Hurley-Walker discussing the GLEAM survey for BBC show "The Sky at Night" at Curtin's HIVE.

TEACHING & OUTREACH

The Girls in Science Forum at Curtin University.

The 'Super Blue Blood Moon' event in Gingin. Credit: ICRAR.

Space sells!

Mia Walker

Above: An MWA tile at Astrofest Perth.

Right: Telescope preparation at Astrorocks Mt Magnet

Below: talks at John Curtin Gallery.

CIRA staff and students have an enthusiasm for science communication, with an incredible number of outreach and teaching activities recorded each year, and 2018 was no exception.

In January, SciTech hosted a Space Academy event in which CIRA researchers presented multiple talks on supermassive black holes, big data, and hunting for the first lights in the universe. The Gravity Discovery Centre in Gingin heralded the ‘Super Blue Blood Moon’ with telescope observations and talks by CIRA PhD students to over 4000 attendees.

More fun STEM outreach events included the Physics day at Adventure World, the Perth Science Festival which had hands-on and 3D activities for thousands of people, the networking events Science Café and the Innovator’s Tea Party for high school students and professionals, Scinapse Women in STEM Breakfast, Disrupted Festival, the Royal Australian Chemical Institute, AWGA, Swancon (a sci-fi convention), a TED-x Perth Observatory talk, and a live question-answer session with Dr Karl on ABC radio. ICRAR also hosted an ‘ask an astronomer’ twitter event called Stargazing Live which involved over a dozen CIRA scientists answering questions about space from the public.

The 10th anniversary of Perth’s annual astronomy festival, Astrofest, was a huge success. CIRA was well-represented with both scientists and engineers giving talks, showcasing technology and volunteering with telescopes at Curtin stadium. Students also helped out similarly at the Pingelly and Mount Magnet Astrofests.

The first public Open Days at the Murchison Radio-astronomy Observatory were heralded with tours by the MWA Director herself, Melanie Johnston-Hollitt, and members of the MWA Operations team. Johnston-Hollitt also spoke about the MWA and SKA to the Australian Institute of Physics Congress, in an interview with Business News, and on the Science Show podcast.

Other media attention included interviews and articles with ABC, RAC Magazine, BBC Sky, 6PR, Channel 7, GWN, 2SER, NPR (USA), The Senior newspaper, Mix94.5 FM, 96 FM, and the Telegraph (UK) on a range of topics including Stephen Hawking, water on mars, the launch of the Parker solar probe, and the IceCube neutrino result.

In addition to these events, there was also a continued focus on speaking at schools (Southern River College, Presbyterian Ladies’ College, Methodist Ladies’ College, Kelmscott Senior, John Willcock, Kensington Primary, Byford Secondary, Willetton Senior) to encourage and inspire the younger generation to consider possible careers in astronomy or space sciences. CIRA also welcomed back the Indigenous Australian Engineering School in July, with astronomy talks and activities for students from all over the country.

CIRA’s Executive Director Steven Tingay is also no stranger to research communication, being a panellist at the Universities Australia conference, a presenter to the EU, Dutch and Italian ambassadors, and a keynote speaker at the March for Science. Tingay has also made multiple media appearances regarding the SKA, black holes, space situational awareness, the Australian Space Agency, indigenous astronomy, and his paper on the interstellar object ‘Oumuamua.

CIRA also contributes strongly in the delivery of Curtin undergraduate units in the Physics and Engineering streams at all levels, in addition to the supervision of undergraduate, Honours, Masters, and PhD projects.

First year teaching covers the general units Physics and Introduction to Astronomy. Second year units taught by CIRA staff are: Physics of Stars and Galaxies, Statistical Mechanics, Thermodynamics, and Electromagnetism. Third/fourth year units include Relativistic Astrophysics and Cosmology, Engineering Electromagnetics and Transmission Lines, and Mobile Radio Communications.

As in previous years, CIRA ran a summer studentship program in 2018/19, aiming to engage with undergraduate students and expose them to the exciting research being done at CIRA. The students worked on a range of science and engineering projects, from Fast Radio Bursts to frameworks for cataloguing objects in space. The MWA is often central to these projects, with students also using the telescope to hunt for cosmic rays and find massive clusters in the early Universe. 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.

Refereed Publications
During 2018

CIRA staff and students are highlighted in bold.

Articles

Ahn, C. P., Seth, A. C., Cappellari, M., Krajnović, D., Strader, J., Voggel, K. T., Walsh, J. L., **Bahramian, A.**, Baumgardt, H., Brodie, J., Chilingarian, I., Chomiuk, L., den Brok, M., Frank, M., Hilker, M., McDermid, R. M., Mieske, S., Neumayer, N., **Nguyen, D. D.**, Pechetti, R., Romanowsky, A. J., & Spitler, L., The Black Hole in the Most Massive Ultracompact Dwarf Galaxy M59-UCD3, The Astrophysical Journal, 858, 102.

Aiello, S., Akrame, S.E., Ameli, F., Anassontzis, E. G., Andre, M., Androulakis, G., Anghinolfi, M., Anton, G., Ardid, M., Aublin, J., Avgitas, T., Baars, M., Bagatelas, C., Barbarino, G., Baret, B., Barrios-Marti, J., Belias, A., Berbee, E., van den Berg, A., Bertin, V., Biagi, S., Biagioni, A., Biernoth, C., Bormuth, R., Boumaaza, J., Bourret, S., Bouwhuis, M., Bozza, C., Branzas, H., Briukhanova, N., Bruijn, R., Brunner, J., Buis, E., Buompane, R., Busto, J., Calvo, D., Capone, A., Caramete, L., Celli, S., Chabab, M., Cherubini, S., Chiarella, V., Chiarusi, T., Circella, M., Cocimano, R., Coelho, J.A.B., Coleiro, A., Molla, M. C., Coniglione, R., Coyle, P., Creusot, A., Cuttone, G., D'Onofrio, A., Dallier, R., De Sio, C., Di Palma, I., Diaz, A.F., Distefano, C., Domi, A., Dona, R., Donzaud, C., Dornic, D., Dörr, M., Durocher, M., Eberl, T., van Eijk, D., El Bojaddaini, I., Elsaesser, D., Enzenhöfer, A., Ferrara, G., Fusco, L.A., Gal, T., Garufi, F., Gauchery, S., Geißelsöder, S., Gialanella, L., Giorgio, E., Giuliante, A., Gozzini, S.R., Gracia Ruiz, R., Graf, K., Grasso, D., Gregoire, T., Grella, G., Hallmann, S., van Haren, H., Heid, T., Heijboer, A., Hekalo, A., Hernandez-Rey, J.J., Hofestädt, J., Illuminati, G., **James, C. W.**, Jongen, M., Jongewaard, B., de Jong, M., de Jong, P., Kadler, M., Kalaczynski, P., Kalekin, O., Katz, U.F., Kahn Chowdhury, N.R., Kieft, G., Kießling, D., Koffeman, E.N., Kooijman, P., Kouchner, A., Kreter, M., Kulikovskiy, V., Lahmann, R., Le Breton, R., Leone, F., Leonora, E., Levi, G., Lincetto, M., Lonardo, A., Longhitano, F., Lotze, M., Loucatos, S., Maggi, G., Manczak, J., Mannheim, K., Margiotta, A., Marinelli, A., Markou, C., Martin, L., Martinez-Mora, J.A., Martini, A., Marzaioli, F., Mele, R., Melis, K.W., Migliozzi, P., Migneco, E., Mijakowski, P., Miranda, L. S., Mollo, C.M., Morganti, M., Moser, M., Moussa, A., Muller, R., Musumeci, M., Nauta, L., Navas, S., Nicolau, C.A., Nielsen, C., Organokov, M.,Orlando, A., Panagopoulos, V., Papalashvili, G., Papaleo, R., Pavalas, G.E., Pellegrini, G., Pellegrino, C., Perez Romero, J., Perrin-Terrin, M., Piattelli, P., Pikounis, K., Pisanti, O., Poire, C., Polydefki, G., Poma, G.E., Popa, V., Post, M., Pradier, T., Pühlhofer, G., Pulvirenti, S., Quinn, L., Raffaelli, F., Randazzo, N., Razzaque, S., Real, D., Resvanis, L., Reubelt, J., Riccobene, G., Richer, M., Rovelli, A., Salvadori, I., Samtleben, D.F.E., Losa, A. Sanchez, Sanguineti, M., Santangelo, A., Sapienza, P., Schermer, B., Sciacca, V., Seneca, J., Sgura, I., Shanidze, R., Sharma, A., Simeone, F., Sinopoulou, A., Spisso, B., Spurio, M., Stavropoulos, D., Steijger, J., Stellacci, S.M., Strandberg, B., Stransky, D., Stüven, T., Taiuti, M., Tatone, F., Tayalati, Y., Tenllado, E., Thakore, T., Timmer, P., Trovato, A., Tsagkli, S., Tzamariudaki, E., Tzanetatos, D., Valieri, C., Vallage, B., Van Elewyck, V., Versari, F., Viola, S., Vivolo, D., Volkert, M., de Waardt, L., Wilms, J., de Wolf, E., Zaborov, D., Zornoza, J.D., Zuniga, J., Characterisation of the Hamamatsu photomultipliers for the KM3NeT Neutrino Telescope, Journal of Instrumentation, Vol 13

Albert, A., André, M., Anghinolfi, M., Ardid, M., Aubert, J. -J., Aublin, J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., Belhorma, B., Bertin, V., Biagi, S., Bormuth, R., Boumaaza, J., Bourret, S., Bouwhuis, M. C., Brânzaş, H., Bruijn, R., Brunner, J., Busto, J., Capone, A., Caramete, L., Carr, J., Celli, S., Chabab, M., Cherkaoui El Moursli, R., Chiarusi, T., Circella, M., Coelho, J. A. B., Coleiro, A., Colomer, M., Coniglione, R., Costantini, H., Coyle, P., Creusot, A., Díaz, A. F., Deschamps, A., Distefano, C., Di Palma, I., Domi, A., Donzaud, C., Dornic, D., Drouhin, D., Eberl, T., El Bojaddaini, I., El Khayati, N., Elsässer, D., Enzenhöfer, A., Ettahiri, A., Fassi, F., Felis, I., Fermani, P., Ferrara, G., Fusco, L., Gay, P., Glotin, H., Grégoire, T., Ruiz, R. Gracia, Graf, K., Hallmann, S., van Haren, H., Heijboer, A. J., Hello, Y., Hernández-Rey, J. J., Hößl, J., Hofestädt, J., Illuminati, G., **James, C. W.**, de Jong, M., Jongen, M., Kadler, M., Kalekin, O., Katz, U., Khan-Chowdhury, N. R., Kouchner, A., Kreter, M., Kreykenbohm, I., Kulikovskiy, V., Lachaud, C., Lahmann, R., Lefèvre, D., Leonora, E., Levi, G., Lotze, M., Loucatos, S., Marcelin, M., Margiotta, A., Marinelli, A., Martínez-Mora, J. A., Mele, R., Melis, K., Migliozzi, P., Moussa, A., Navas, S., Nezri, E., Nuñez, A., Organokov, M., Păvălaş, G. E., Pellegrino, C., Piattelli, P., Popa, V., Pradier, T., Quinn, L., Racca, C., Randazzo, N., Riccobene, G., Sánchez-Losa, A., Saldaña, M., Salvadori, I., Samtleben, D. F. E., Sanguineti, M., Sapienza, P., Schüssler, F., Spurio, M., Stolarczyk, Th., Taiuti, M., Tayalati, Y., Trovato, A., Vallage, B., Van Elewyck, V., Versari,

F., Vivolo, D., Wilms, J., Zaborov, D., Zornoza, J. D., Zúñiga, J., ANTARES Collaboration, Aartsen, M. G., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., Samarai, I. Al, Altmann, D., Andeen, K., Anderson, T., Ansseau, I., Anton, G., Argüelles, C., Auffenberg, J., Axani, S., Backes, P., Bagherpour, H., Bai, X., Barbano, A., Barron, J. P., Barwick, S. W., Baum, V., Bay, R., Beatty, J. J., Becker Tjus, J., Becker, K. -H., BenZvi, S., Berley, D., Bernardini, E., Besson, D. Z., Binder, G., Bindig, D., Blaufuss, E., Blot, S., Bohm, C., Börner, M., Bos, F., Böser, S., Botner, O., Bourbeau, E., Bourbeau, J., Bradascio, F., Braun, J., Brenzke, M., Bretz, H. -P., Bron, S., Brostean-Kaiser, J., Burgman, A., Busse, R. S., Carver, T., CheUng, E., Chirkin, D., Christov, A., Clark, K., Classen, L., Collin, G. H., Conrad, J. M., Coppin, P., Correa, P., Cowen, D. F., Cross, R., Dave, P., Day, M., de André, J. P. A. M., De Clercq, C., DeLaunay, J. J., Dembinski, H., Deoskar, K., De Ridder, S., Desiati, P., de Vries, K. D., de Wasseige, G., de With, M., DeYoUng, T., Díaz-Vélez, J. C., di Lorenzo, V., Dujmovic, H., Dumm, J. P., Dunkman, M., Dvorak, E., Eberhardt, B., Ehrhardt, T., Eichmann, B., Eller, P., Evenson, P. A., Fahey, S., Fazely, A. R., Felde, J., Filimonov, K., Finley, C., Franckowiak, A., Friedman, E., Fritz, A., Gaisser, T. K., Gallagher, J., Ganster, E., Gerhardt, L., Ghorbani, K., Giang, W., Glauch, T., Glüsenkamp, T., Goldschmidt, A., Gonzalez, J. G., Grant, D., Griffith, Z., Haack, C., Hallgren, A., Halve, L., Halzen, F., Hanson, K., Hebecker, D., Heereman, D., Helbing, K., Hellauer, R., Hickford, S., Hignight, J., Hill, G. C., Hoffman, K. D., Hoffmann, R., Hoinka, T., Hokanson-Fasig, B., Hoshina, K., Huang, F., Huber, M., Hultqvist, K., Hünnefeld, M., Hussain, R., In, S., Iovine, N., Ishihara, A., Jacobi, E., Japaridze, G. S., Jeong, M., Jero, K., Jones, B. J. P., Kalaczynski, P., Kang, W., Kappes, A., Kappesser, D., Karg, T., Karle, A., Katz, U., Kauer, M., Keivani, A., Kelley, J. L., Kheirandish, A., Kim, J., Kintscher, T., Kiryluk, J., Kittler, T., Klein, S. R., Koirala, R., Kolanoski, H., Köpke, L., Kopper, C., Kopper, S., Koschinsky, J. P., Koskinen, D. J., Kowalski, M., Krings, K., Kroll, M., Krückl, G., Kunwar, S., Kurahashi, N., Kyriacou, A., Labare, M., Lanfranchi, J. L., Larson, M. J., Lauber, F., Leonard, K., Leuermann, M., Liu, Q. R., Lohfink, E., Lozano Mariscal, C. J., Lu, L., Lünemann, J., Luszczak, W., Madsen, J., Maggi, G., Mahn, K. B. M., Makino, Y., Mancina, S., Maruyama, R., Mase, K., Maunu, R., Meagher, K., Medici, M., Meier, M., Menne, T., Merino, G., Meures, T., Miarecki, S., Micallef, J., Momenté, G., Montaruli, T., Moore, R. W., Moulai, M., Nagai, R., Nahnhauer, R., Nakarmi, P., Naumann, U., Neer, G., Niederhausen, H., Nowicki, S. C., Nygren, D. R., Obertacke Pollmann, A., Olivas, A., O'Murchadha, A., O'Sullivan, E., Palczewski, T., Pandya, H., Pankova, D. V., Peiffer, P., Pepper, J. A., Pérez de los Heros, C., Pieloth, D., Pinat, E., Pizzuto, A., Plum, M., Price, P. B., Przybylski, G. T., Raab, C., Rameez, M., Rauch, L., Rawlins, K., Rea, I. C., Reimann, R., Relethford, B., Resconi, E., Rhode, W., Richman, M., Robertson, S., Rongen, M., Rott, C., Ruhe, T., Ryckbosch, D., Rysewyk, D., Safa, I., Sanchez Herrera, S. E., Sandrock, A., Sandroos, J., Santander, M., Sarkar, S., Sarkar, S., Satalecka, K., Schaufel, M., Schlunder, P., Schmidt, T., Schneider, A., Schöneberg, S., Schumacher, L., Sclafani, S., Seckel, D., Seunarine, S., Soedingrekso, J., Soldin, D., Song, M., Spiczak, G. M., Spiering, C., Stachurska, J., Stamatikos, M., Stanev, T., Stasik, A., Stein, R., Stettner, J., Steuer, A., Stezelberger, T., Stokstad, R. G., Stößl, A., Strotjohann, N. L., Stuttard, T., Sullivan, G. W., Sutherland, M., Taboada, I., Tenholt, F., Ter-Antonyan, S., Terliuk, A., Tilav, S., Toale, P. A., Tobin, M. N., Tönnis, C., Toscano, S., Tosi, D., Tselengidou, M., TUng, C. F., Turcati, A., Turley, C. F., Ty, B., Unger, E., Unland Elorrieta, M. A., Usner, M., Vandenbroucke, J., Van Driessche, W., van Eijk, D., van Eijndhoven, N., Vanheule, S., van Santen, J., Vraeghe, M., Walck, C., Wallace, A., Wallraff, M., Wandler, F. D., Wandkowsky, N., Watson, T. B., Waza, A., Weaver, C., Weiss, M. J., Wendt, C., Werthebach, J., Westerhoff, S., Whelan, B. J., Whitehorn, N., Wiebe, K., Wiebusch, C. H., Wille, L., Williams, D. R., Wills, L., Wolf, M., Wood, J., Wood, T. R., Woolsey, E., Woschnagg, K., Wrede, G., Xu, D. L., Xu, X. W., Xu, Y., Yanez, J. P., Yodh, G., Yoshida, S., Yuan, T., IceCube Collaboration, Gaggero, D., & Grasso, D., Joint Constraints on Galactic Diffuse Neutrino Emission from the ANTARES and IceCube Neutrino Telescopes, The Astrophysical Journal, 868, L20

Albert, A., André, M., Anghinolfi, M., Anton, G., Ardid, M., Aubert, J. -J., Aublin, J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., Belhorma, B., Bertin, V., Biagi, S., Bormuth, R., Boumaaza, J., Bourret, S., Bouwhuis, M. C., Brânzaş, H., Bruijn, R., Brunner, J., Busto, J., Capone, A., Caramete, L., Carr, J., Celli, S., Chabab, M., Cherkaoui El Moursli, R., Chiarusi, T., Circella, M., Coelho, J. A. B., Coleiro, A., Colomer, M., Coniglione, R., Costantini, H., Coyle, P., Creusot, A., Díaz, A. F., Deschamps, A., Distefano, C., Di Palma, I., Domi, A., Donzaud, C., Dornic, D., Drouhin, D., Eberl, T., El Bojaddaini, I., El Khayati, N., Elsässer, D., Enzenhöfer, A., Ettahiri, A., Fassi, F., Felis, I., Ferrara, G., Fusco, L. A., Gay, P., Glotin, H., Grégoire, T., Ruiz, R. Gracia, Graf, K., Hallmann, S., van Haren, H., Heijboer, A. J., Hello, Y., Hernández-Rey, J. J., Hößl, J., Hofestädt, J., Illuminati, G., **James, C. W.**, de Jong, M., Jongen, M., Kadler, M., Kalekin, O., Katz, U., Kouchner, A., Kreter, M., Kreykenbohm, I., Kulikovskiy, V., Lachaud, C., Lahmann, R., Lefèvre, D., Leonora, E., Levi, G., Lotze, M., Loucatos, S., Marcelin, M., Margiotta, A., Marinelli, A., Martínez-Mora, J. A., Mele, R., Melis, K., Migliozzi, P., Moussa, A., Navas, S., Nezri, E., Nuñez, A., Organokov, M., Păvălaş, G. E., Pellegrino, C., Piattelli, P., Popa, V., Pradier, T., Quinn, L., Racca, C., Randazzo, N., Riccobene, G., Sánchez-Losa, A., Saldaña, M., Salvadori, I., Samtleben, D. F. E., Sanguineti, M., Sapienza, P., Schüssler, F., Spurio, M., Stolarczyk, Th., Taiuti, M., Tayalati, Y., Trovato, A., Vallage, B., Van Elewyck, V., Versari, F., Vivolo, D., Wilms, J., Zaborov, D., Zornoza, J. D., Zúñiga, J., Long-term monitoring of the ANTARES optical module efficiencies using \$\$\^{40}$\backslash$mathrm{{K}}\$\$40Kdecays in sea water, The European Physical Journal C, Vol 78

Albert, A., André, M., Anghinolfi, M., Anton, G., Ardid, M., Aubert, J. -J., Aublin, J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., Belhorma, B., Bertin, V., Biagi, S., Bormuth, R., Bourret, S., Bouwhuis, M. C., Brânzaş, H., Bruijn, R., Brunner, J., Busto, J., Capone, A., Caramete, L., Carr, J., Celli, S., Cherkaoui El Moursli, R., Chiarusi, T., Circella, M., Coelho, J. A. B., Coleiro, A., Coniglione, R., Costantini, H., Coyle, P., Creusot, A., Díaz, A. F., Deschamps, A., De Bonis, G., Distefano, C., Di Palma, I., Domi, A., Donzaud, C., Dornic, D., Drouhin, D., Eberl, T., El Bojaddaini, I., El Khayati, N., Elsässer, D., Enzenhöfer, A., Ettahiri, A., Fassi, F., Felis, I., Fusco, L. A., Gay, P., Giordano, V., Glotin, H., Grégoire, T., Ruiz, R. Gracia, Graf, K., Hallmann, S., van Haren, H., Heijboer, A. J., Hello, Y., Hernández-Rey, J. J., Hößl, J., Hofestädt, J., Illuminati, G., **James, C. W.**, de Jong, M., Jongen, M., Kadler, M., Kalekin, O., Katz, U., Kießling, D., Kouchner, A., Kreter, M., Kreykenbohm, I., Kulikovskiy, V., Lachaud, C., Lahmann, R., Lefèvre, D., Leonora, E., Lotze, M., Loucatos, S., Marcelin, M., Margiotta, A., Marinelli, A., Martínez-Mora, J. A., Mele, R., Melis, K., Michael, T., Migliozzi, P., Moussa, A., Navas, S., Nezri, E., Organokov, M., Păvălaş, G. E., Pellegrino, C., Perrina, C., Piattelli, P., Popa, V., Pradier, T., Quinn, L., Racca, C., Riccobene, G., Sánchez-Losa, A., Saldaña, M., Salvadori, I., Samtleben, D. F. E., Sanguineti, M., Sapienza, P., Schüssler, F., Sieger, C., Spurio, M., Stolarczyk, Th., Taiuti, M., Tayalati, Y., Trovato, A., Turpin, D., Tönnis, C., Vallage, B., Van Elewyck, V., Versari, F., Vivolo, D., Vizzoca, A., Wilms, J., Zornoza, J. D., Zúñiga, J., & (The ANTARES Collaboration, All-flavor Search for a Diffuse Flux of Cosmic Neutrinos with Nine Years of ANTARES Data, The Astrophysical Journal, 853, L7

Anderson, G. E., Staley, T. D., van der Horst, A. J., Fender, R. P., Rowlinson, A., Mooley, K. P., Broderick, J. W., Wijers, R. A. M. J., Rumsey, C., and Titterington, D. J., The Arcminute Microkelvin Imager catalogue of gamma-ray burst afterglows at 15.7 GHz, Monthly Notices of the Royal Astronomical Society, 473, 1512

Baglio, Maria Cristina, Russell, David M., Casella, Piergiorgio, Noori, Hind Al, Yazeedi, Aisha Al, Belloni, Tomaso, Buckley, David A. H., Cadolle Bel, Marion, Ceccobello, Chiara, Corbel, Stephane, Coti Zelati, Francesco, Díaz Trigo, Maria, Fender, Rob P., Gallo, Elena, Gandhi, Poshak, Homan, Jeroen, Koljonen, Karri I. I., Lewis, Fraser, Maccarone, Thomas J., Malzac, Julien, Markoff, Sera, **Miller-Jones, James C. A.**, O'Brien, Kieran, Russell, Thomas D., Saikia, Payaswini, Shahbaz, Tariq, Sivakoff, Greg R., Soria, Roberto, Testa, Vincenzo, Tetarenko, Alexandra J., van den Ancker, Mario E., and Vincentelli, Federico M., A Wildly Flickering Jet in the Black Hole X-Ray Binary MAXI J1535-571, The Astrophysical Journal, 867, 114

Bahramian, A., Strader, J., Chomiuk, Laura, Heinke, Craig O., **Miller-Jones, James C. A.**, Degenaar, N., Tetarenko, A. J., **Tudor, V.**, Tremou, E., Shishkovsky, L., Wijnands, R., Maccarone, T. J., Sivakoff, G. R., and Ransom, S., The MAVERIC Survey: A Transitional Millisecond Pulsar Candidate in Terzan 5, The Astrophysical Journal, 864, 28

Beuchert, T., Rodríguez-Ardila, A., Moss, V. A., Schulz, R., Kadler, M., Wilms, J., Angioni, R., Callingham, J. R., Gräfe, C., Krauß, F., Kreikenbohm, A., Langejahn, M., Leiter, K., Maccagni, F. M., Müller, C., Ojha, R., Ros, E., and **Tingay, S. J.**, Extended X-ray emission in PKS 1718-649, Astronomy and Astrophysics, 612, L4

Bennett, D. P.; Udalski, A.; Han, C.; Bond, I. A.; Beaulieu, J. -P.; Skowron, J.; Gaudi, B. S.; Koshimoto, N.; Abe, F.; Asakura, Y.; Barry, R. K.; Bhattacharya, A.; Donachie, M.; Evans, P.; Fukui, A.; Hirao, Y.; Itow, Y.; Li, M. C. A.; Ling, C. H.; Masuda, K. Matsubara, Y.; Muraki, Y.; Nagakane, M.; Ohnishi, K.; Oyokawa, H.; Ranc, C.; Rattenbury, N. J.; Rosenthal, M. M.; Saito, To.; Sharan, A.; Sullivan, D. J.; Sumi, T.; Suzuki, D.; Tristram, P. J.; Yonehara, A.; MOA Collaboration; Szymański, M. K.; Poleski, R.; Soszyński, I.; Ulaczyk, K.; Wyrzykowski, Ł.; OGLE Collaboration; DePoy, D.; Gould, A.; Pogge, R. W.; Yee, J. C.; ⊠FUN Collaboration; Albrow, M. D.; Bachelet, E.; Batista, V.; Bowens-Rubin, R.; Brillant, S.; Caldwell, J. A. R.; Cole, A.; Coutures, C.; Dieters, S.; Dominis Prester, D.; Donatowicz, J.; Fouqué, P.; Horne, K.; Hundertmark, M.; Kains, N.; Kane, S. R.; Marquette, J. -B.; Menzies, J.; Pollard, K. R.; Ranc, C.; Sahu, K. C.; Wambsganss, J.; **Williams, A.**; Zub, M.; PLANET Collaboration, The First Planetary Microlensing Event with Two Microlensed Source Stars, The Astronomical Journal, Volume 155, Issue 3, article id. 141

Bhandari, S., Keane, E. F., Barr, E. D., Jameson, A., Petroff, E., Johnston, S., Bailes, M., **Bhat, N. D. R.**, Burgay, M., Burke-Spolaor, S., Caleb, M., Eatough, R. P., Flynn, C., Green, J. A., Jankowski, F., Kramer, M., Krishnan, V. Venkatraman, Morello, V., Possenti, A., Stappers, B., Tiburzi, C., van Straten, W., Andreoni, I., Butterley, T., Chandra, P., Cooke, J., Corongiu, A., Coward, D. M., Dhillon, V. S., Dodson, R., Hardy, L. K., Howell, E. J., Jaroenjittichai, P., Klotz, A., Littlefair, S. P., Marsh, T. R., Mickaliger, M., Muxlow, T., Perrodin, D., Pritchard, T., Sawangwit, U., Terai, T., Tominaga, N., Torne, P., Totani, T., Trois, A., Turpin, D., Niino, Y., Wilson, R. W., Albert, A., André, M., Anghinolfi, M., Anton, G., Ardid, M., Aubert, J. -J., Avgitas, T., Baret, B., Barrios-Martí, J., Basa, S., Belhorma, B., Bertin, V., Biagi, S., Bormuth, R., Bourret, S., Bouwhuis, M. C., Brânzaş, H., Bruijn, R., Brunner, J., Busto, J., Capone, A., Caramete, L., Carr, J., Celli, S., Moursli, R. Cherkaoui El, Chiarusi, T., Circella, M., Coelho, J. A. B., Coleiro, A., Coniglione, R., Costantini, H., Coyle, P., Creusot, A., Díaz, A. F., Deschamps, A., De Bonis, G., Distefano, C., Palma, I. Di, Domi, A., Donzaud, C., Dornic, D., Drouhin, D., Eberl, T., Bojaddaini, I. El, Khayati, N. El, Elsässer, D., Enzenhöfer, A., Ettahiri, A., Fassi, F., Felis, I., Fusco, L. A., Gay, P., Giordano, V., Glotin, H., Gregoire, T., Gracia-Ruiz, R., Graf, K., Hallmann, S., van Haren, H., Heijboer, A. J., Hello, Y., Hernández-Rey, J. J., Hößl, J., Hofestädt, J., Hugon, C., Illuminati, G., **James, C. W.**, de Jong, M., Jongen, M., Kadler, M., Kalekin, O., Katz, U., Kießling, D., Kouchner, A., Kreter, M., Kreykenbohm, I., Kulikovskiy, V., Lachaud, C., Lahmann, R., Lefèvre, D., Leonora, E., Loucatos, S., Marcelin, M., Margiotta, A., Marinelli, A., Martínez-Mora, J. A., Mele, R., Melis, K., Michael, T., Migliozzi, P., Moussa, A., Navas, S., Nezri, E., Organokov, M., Păvălaş, G. E., Pellegrino, C., Perrina, C., Piattelli, P., Popa, V., Pradier, T., Quinn, L., Racca, C., Riccobene, G., Sánchez-Losa, A., Saldaña, M., Salvadori, I., Samtleben, D. F. E., Sanguineti, M., Sapienza, P., Schüssler, F., Sieger, C., Spurio, M., Stolarczyk, Th, Taiuti, M., Tayalati, Y., Trovato, A., Turpin, D., Tönnis, C., Vallage, B., Van Elewyck, V., Versari, F., Vivolo, D., Vizzocca, A., Wilms, J., Zornoza, J. D., and Zúñiga, J., The SUrvey for Pulsars and Extragalactic Radio Bursts - II. New FRB discoveries and their follow-up, Monthly Notices of the Royal Astronomical Society, 475, 1427

Bhat, N. D. R., **Tremblay, S. E.**, Kirsten, F., **Meyers, B. W.**, **Sokolowski, M.**, van Straten, W., **McSweeney, S. J.**, Ord, S. M., Shannon, R. M., Beardsley, A., **Crosse, B.**, **Emrich, D.**, Franzen, T. M. O., **Horsley, L.**, **Johnston-Hollitt, M.**, Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Steele, K.**, **Tingay, S. J.**, **Trott, C. M.**, **Walker, M.**, **Wayth, R. B.**, **Williams, A.**, and Wu, C., Observations of Low-frequency Radio Emission from Millisecond Pulsars and Multipath Propagation in the Interstellar Medium, The Astrophysical Journal Supplement Series, 238, 1

Bogdanov, S., Deller, A. T., **Miller-Jones, J. C. A.**, Archibald, A. M., Hessels, J. W. T., Jaodand, A., Patruno, A., Bassa, C., and D'Angelo, C., Simultaneous Chandra and VLA Observations of the Transitional Millisecond Pulsar PSR J1023+0038: Anti-correlated X-Ray and Radio Variability, The Astrophysical Journal, 856, 54

Broderick, J. W., Fender, R. P., **Miller-Jones, J. C. A.**, Trushkin, S. A., Stewart, A. J., **Anderson, G. E.**, Staley, T. D., Blundell, K. M., Pietka, M., Markoff, S., Rowlinson, A., Swinbank, J. D., van der Horst, A. J., Bell, M. E., Breton, R. P., Carbone, D., Corbel, S., Eislöffel, J., Falcke, H., Grießmeier,

J. -M., Hessels, J. W. T., Kondratiev, V. I., Law, C. J., Molenaar, G. J., Serylak, M., Stappers, B. W., van Leeuwen, J., Wijers, R. A. M. J., Wijnands, R., Wise, M. W., and Zarka, P., LOFAR 150-MHz observations of SS 433 and W 50, Monthly Notices of the Royal Astronomical Society, 475, 5360

Caballero, R. N., Guo, Y. J., Lee, K. J., Lazarus, P., Champion, D. J., Desvignes, G., Kramer, M., Plant, K., Arzoumanian, Z., Bailes, M., Bassa, C. G., **Bhat, N. D. R**., Brazier, A., Burgay, M., Burke-Spolaor, S., Chamberlin, S. J., Chatterjee, S., Cognard, I., Cordes, J. M., Dai, S., Demorest, P., Dolch, T., Ferdman, R. D., Fonseca, E., Gair, J. R., Garver-Daniels, N., Gentile, P., Gonzalez, M. E., Graikou, E., Guillemot, L., Hobbs, G., Janssen, G. H., Karuppusamy, R., Keith, M. J., Kerr, M., Lam, M. T., Lasky, P. D., Lazio, T. J. W., Levin, L., Liu, K., Lommen, A. N., Lorimer, D. R., Lynch, R. S., Madison, D. R., Manchester, R. N., McKee, J. W., McLaughlin, M. A., McWilliams, S. T., Mingarelli, C. M. F., Nice, D. J., Osłowski, S., Palliyaguru, N. T., Pennucci, T. T., Perera, B. B. P., Perrodin, D., Possenti, A., Ransom, S. M., Reardon, D. J., Sanidas, S. A., Sesana, A., Shaifullah, G., Shannon, R. M., Siemens, X., Simon, J., Spiewak, R., Stairs, I., Stappers, B., Stinebring, D. R., Stovall, K., Swiggum, J. K., Taylor, S. R., Theureau, G., Tiburzi, C., Toomey, L., van Haasteren, R., van Straten, W., Verbiest, J. P. W., Wang, J. B., Zhu, X. J., and Zhu, W. W., Studying the Solar system with the International Pulsar Timing Array, Monthly Notices of the Royal Astronomical Society, 481, 5501

Bozzo, E., **Bahramian, A.**, Ferrigno, C., Sanna, A., Strader, J., Lewis, F., Russell, D. M., di Salvo, T., Burderi, L., Riggio, A., Papitto, A., Gandhi, P., & Romano, P., IGR J17329-2731: The birth of a symbiotic X-ray binary, Astronomy and Astrophysics, 613, A22.

Cairns, I. H., Lobzin, V. V., Donea, A., **Tingay, S. J.**, McCauley, P. I., Oberoi, D., Duffin, R. T., Reiner, M. J., **Hurley-Walker, N.**, Kudryavtseva, N. A., Melrose, D. B., Harding, J. C., Bernardi, G., Bowman, J. D., Cappallo, R. J., Corey, B. E., Deshpande, A., **Emrich, D.**, Goeke, R., Hazelton, B. J., **Johnston-Hollitt, M.**, Kaplan, D. L., Kasper, J. C., Kratzenberg, E., Lonsdale, C. J., Lynch, M. J., McWhirter, S. R., Mitchell, D. A., Morales, M. F., Morgan, E., Ord, S. M., Prabu, T., Roshi, A., Shankar, N. Udaya, Srivani, K. S., Subrahmanyan, R., **Wayth, R. B.**, Waterson, M., Webster, R. L., Whitney, A. R., **Williams, A.**, and Williams, C. L., Low Altitude Solar Magnetic Reconnection, Type III Solar Radio Bursts, and X-ray Emissions, Scientific Reports, 8, 1676

Caleb, M., Keane, E. F., van Straten, W., Kramer, M., **Macquart, J. P.**, Bailes, M., Barr, E. D., **Bhat, N. D. R**., Bhandari, S., Burgay, M., Farah, W., Jameson, A., Jankowski, F., Johnston, S., Petroff, E., Possenti, A., Stappers, B. W., Tiburzi, C., and Venkatraman Krishnan, V., The SUrvey for Pulsars and Extragalactic Radio Bursts - III. Polarization properties of FRBs 160102 and 151230, Monthly Notices of the Royal Astronomical Society, 478, 2046

Cameron, A. D., Champion, D. J., Kramer, M., Bailes, M., Barr, E. D., Bassa, C. G., Bhandari, S., **Bhat, N. D. R**., Burgay, M., Burke-Spolaor, S., Eatough, R. P., Flynn, C. M. L., Freire, P. C. C., Jameson, A., Johnston, S., Karuppusamy, R., Keith, M. J., Levin, L., Lorimer, D. R., Lyne, A. G., McLaughlin, M. A., Ng, C., Petroff, E., Possenti, A., Ridolfi, A., Stappers, B. W., van Straten, W., Tauris, T. M., Tiburzi, C., and Wex, N., The High Time Resolution Universe Pulsar Survey - XIII. PSR J1757-1854, the most accelerated binary pulsar, Monthly Notices of the Royal Astronomical Society, 475, L57

Camilo, F., Scholz, P., Serylak, M., Buchner, S., Merryfield, M., Kaspi, V. M., Archibald, R. F., Bailes, M., Jameson, A., van Straten, W., Sarkissian, J., Reynolds, J. E., Johnston, S., Hobbs, G., Abbott, T. D., Adam, R. M., Adams, G. B., Alberts, T., Andreas, R., Asad, K. M. B., Baker, D. E., Baloyi, T., Bauermeister, E. F., Baxana, T., Bennett, T. G. H., Bernardi, G., Booisen, D., Booth, R. S., Botha, D. H., Boyana, L., Brederode, L. R. S., Burger, J. P., Cheetham, T., Conradie, J., Conradie, J. P., **Davidson, D. B.**, De Bruin, G., de Swardt, B., de Villiers, C., de Villiers, D. I. L., de Villiers, M. S., de Villiers, W., De Waal, C., Dikgale, M. A., du Toit, G., du Toit, L. J., Esterhuyse, S. W. P., Fanaroff, B., Fataar, S., Foley, A. R., Foster, G., Fourie, D., Gamatham, R., Gatsi, T., Geschke, R., Goedhart, S., Grobler, T. L., Gumede, S. C., Hlakola, M. J., Hokwana, A., Hoorn, D. H., Horn, D., Horrell, J., Hugo, B., Isaacson, A., Jacobs, O., Jansen van Rensburg, J. P., Jonas, J. L., Jordaan, B., Joubert, A., Joubert, F., Józsa, G. I. G., Julie, R., Julius, C. C., Kapp, F., Karastergiou, A., Karels, F., Kariseb, M., Karuppusamy, R., Kasper, V., Knox-Davies, E. C., Koch, D., Kotzé, P. P. A., Krebs, A., Kriek, N., Kriel, H., Kusel, T., Lamoor, S., Lehmensiek, R., Liebenberg, D., Liebenberg, I., Lord, R. T., Lunsky, B., Mabombo, N., Macdonald, T., Macfarlane, P., Madisa, K., MafhUngo, L., Magnus, L. G., Magozore, C., Mahgoub, O., Main, J. P. L., Makhathini, S., Malan, J. A., Malgas, P., Manley, J. R., Manzini, M., Marais, L., Marais, N., Marais, S. J., Maree, M., Martens, A., Matshawule, S. D., Matthysen, N., Mauch, T., McNally, L. D., Merry, B., Millenaar, R. P., Mjikelo, C., Mkhabela, N., Mnyandu, N., Moeng, I. T., Mokone, O. J., Monama, T. E., Montshiwa, K., Moss, V., Mphego, M., New, W., Ngcebetsha, B., Ngoasheng, K., Niehaus, H., Ntuli, P., Nzama, A., Obies, F., Obrocka, M., Ockards, M. T., Olyn, C., Oozeer, N., Otto, A. J., Padayachee, Y., Passmoor, S., Patel, A. A., Paula, S., Peens-Hough, A., Pholoholo, B., Prozesky, P., Rakoma, S., Ramaila, A. J. T., Rammala, I., Ramudzuli, Z. R., Rasivhaga, M., Ratcliffe, S., Reader, H. C., Renil, R., Richter, L., Robyntjies, A., Rosekrans, D., Rust, A., Salie, S., Sambu, N., Schollar, C. T. G., Schwardt, L., Seranyane, S., Sethosa, G., Sharpe, C., Siebrits, R., Sirothia, S. K., Slabber, M. J., Smirnov, O., Smith, S., Sofeya, L., Songqumase, N., Spann, R., Stappers, B., Steyn, D., Steyn, T. J., Strong, R., Struthers, A., Stuart, C., Sunnylall, P., Swart, P. S., Taljaard, B., Tasse, C., Taylor, G., Theron, I. P., Thondikulam, V., Thorat, K., Tiplady, A., Toruvanda, O., van Aardt, J., van Balla, T., van den Heever, L., van der Byl, A., van der Merwe, C., van der Merwe, P., van Niekerk, P. C., van Rooyen, R., van Staden, J. P., van Tonder, V., van Wyk, R., Wait, I., Walker, A. L., Wallace, B., Welz, M., Williams, L. P., Xaia, B., YoUng, N., & Zitha, S., Revival of the Magnetar PSR J1622-4950: Observations with MeerKAT, Parkes, XMM-Newton, Swift, Chandra, and NuSTAR, The Astrophysical Journal, 856, 180

Steeb J.-W., **Davidson D.B.**, Wijnholds S.J., "Mitigation of Non-Narrowband Radio-Frequency Interference", Radio Science Bulletin, No 365, pp.~10--19.

Chhetri, R., Morgan, J., Ekers, R.D., Macquart, J.-P., Sadler, E. M., Giroletti, M., Callingham, J. R., and **Tingay, S.J.**, Interplanetary scintillation studies with the Murchison Widefield Array - II. Properties of sub-arcsecond compact sources at low radio frequencies, Monthly Notices of the Royal Astronomical Society, 474, 4937

Chhetri, R., Ekers, R. D., Morgan, J., Macquart, J.-P., and Franzen, T. M. O., Interplanetary scintillation studies with the Murchison Widefield Array III: comparison of source counts and densities for radio sources and their sub-arcsecond components at 162 MHz, Monthly Notices of the Royal Astronomical Society, 479, 2318

Collier, J. D., **Tingay, S. J.**, Callingham, J. R., Norris, R. P., Filipović, M. D., Galvin, T. J., Huynh, M. T., Intema, H. T., Marvil, J., O'Brien, A. N., Roper, Q., Sirothia, S., Tothill, N. F. H., Bell, M. E., For, B. -Q., Gaensler, B. M., **Hancock, P. J.**, Hindson, L., **Hurley-Walker, N., Johnston-Hollitt, M.**, Kapińska, A. D., Lenc, E., **Morgan, J.**, Procopio, P., Staveley-Smith, L., **Wayth, R. B.**, Wu, C., Zheng, Q., Heywood, I., and Popping, A., High-resolution observations of low-luminosity gigahertz-peaked spectrum and compact steep-spectrum sources, Monthly Notices of the Royal Astronomical Society, 477, 578

Da Costa, G. S., Soria, R., Farrell, S. A., Bayliss, D., Bessell, M. S., Vogt, F. P. A., Zhou, G., Points, S. D., Beers, T. C., López-Sánchez, Á. R., Bannister, K. W., Bell, M., **Hancock, P. J.**, Burlon, D., Gaensler, B. M., Sadler, E. M., **Tingay, S.J.**, Keller, S. C., Schmidt, B. P., and Tisserand, P., SMSS J130522.47-293113.0: a high-latitude stellar X-ray source with pc-scale outflow relics?, Monthly Notices of the Royal Astronomical Society, 477, 766

Dage, K. C., Zepf, S. E., **Bahramian, A.**, Kundu, A., Maccarone, T. J., & Peacock, M. B., X-Ray Variability from the Ultraluminous Black Hole Candidate X-Ray Binary in the Globular Cluster RZ 2109, The Astrophysical Journal, 862, 108.

Dinçer, Tolga, Bailyn, Charles D., **Miller-Jones, James C. A.**, Buxton, Michelle, and MacDonald, Rachel K. D., Multiwavength Observations of the Black Hole X-Ray Binary A0620-00 in Quiescence, The Astrophysical Journal, 852, 4

Drouart, G. and Falkendal, T., MR-MOOSE: an advanced SED-fitting tool for heterogeneous multi-wavelength data sets, Monthly Notices of the Royal Astronomical Society, 477, 4981

Díaz Trigo, M., Altamirano, D., Dinçer, T., **Miller-Jones, J. C. A.**, Russell, D. M., Sanna, A., Bailyn, C., Lewis, F., Migliari, S., and Rahoui, F., The evolving jet spectrum of the neutron star X-ray binary Aql X-1 in transitional states during its 2016 outburst, Astronomy and Astrophysics, 616, A23

Edwards, P. G., Ojha, R., Dodson, R., Lovell, J. E. J., Reynolds, J. E., Tzioumis, A. K., Quick, J., Nicolson, G., and **Tingay, S. J.**, VLBI Observations of Southern Gamma-Ray Sources. III, Publications of the Astronomical Society of Australia, 35, e009

Fan, L., Knudsen, K. K., Fogasy, J., and **Drouart, G.**, ALMA Detections of CO Emission in the Most Luminous, Heavily Dust-obscured Quasars at z > 3, The Astrophysical Journal, 856, L5

Farah, W., Flynn, C., Bailes, M., Jameson, A., Bannister, K. W., Barr, E. D., Bateman, T., Bhandari, S., Caleb, M., Campbell-Wilson, D., Chang, S. -W., Deller, A., Green, A. J., Hunstead, R., Jankowski, F., Keane, E., **Macquart, J. -P.**, Möller, A., Onken, C. A., Osłowski, S., Parthasarathy, A., Plant, K., Ravi, V., Shannon, R. M., Tucker, B. E., Venkatraman Krishnan, V., and Wolf, C., FRB microstructure revealed by the real-time detection of FRB170827, Monthly Notices of the Royal Astronomical Society, 478, 1209

For, B. -Q., Staveley-Smith, L., **Hurley-Walker, N.**, Franzen, T., Kapińska, A. D., Filipović, M. D., Collier, J. D., Wu, C., Grieve, K., Callingham, J. R., Bell, M. E., Bernardi, G., Bowman, J. D., Briggs, F., Cappallo, R. J., Deshpande, A. A., Dwarakanath, K. S., Gaensler, B. M., Greenhill, L. J., **Hancock, P.**, Hazelton, B. J., Hindson, L., **Johnston-Hollitt, M.**, Kaplan, D. L., Lenc, E., Lonsdale, C. J., **McKinley, B.**, McWhirter, S. R., Mitchell, D. A., Morales, M. F., Morgan, E., **Morgan, J.**, Oberoi, D., Offringa, A., Ord, S. M., Prabu, T., Procopio, P., Shankar, N. Udaya, Srivani, K. S., Subrahmanyan, R., **Tingay, S. J., Wayth, R. B.**, Webster, R. L., **Williams, A.**, Williams, C. L., and Zheng, Q., A multifrequency radio continuum study of the Magellanic Clouds - I. Overall structure and star formation rates, Monthly Notices of the Royal Astronomical Society, 480, 2743

Frail, D. A., Ray, P. S., Mooley, K. P., **Hancock, P.,** Burnett, T. H., Jagannathan, P., Ferrara, E. C., Intema, H. T., de Gasperin, F., Demorest, P. B., Stovall, K., and McKinnon, M. M., An image-based search for pulsars among Fermi unassociated LAT sources, Monthly Notices of the Royal Astronomical Society, 475, 942

Galvin, T. J., **Seymour, N.**, Marvil, J., Filipović, M. D., Tothill, N. F. H., McDermid, R. M., **Hurley-Walker, N., Hancock, P. J.**, Callingham, J. R., Cook, R. H., Norris, R. P., Bell, M. E., Dwarakanath, K. S., For, B., Gaensler, B. M., Hindson, L., **Johnston-Hollitt, M.,** Kapińska, A. D., Lenc, E., **McKinley, B., Morgan, J.**, Offringa, A. R., Procopio, P., Staveley-Smith, L., **Wayth, R. B.**, Wu, C., and Zheng, Q., The spectral energy distribution of powerful starburst galaxies - I. Modelling the radio continuum, Monthly Notices of the Royal Astronomical Society, 474, 779

Giovannini, G., Savolainen, T., Orienti, M., Nakamura, M., Nagai, H., Kino, M., Giroletti, M., Hada, K., Bruni, G., Kovalev, Y. Y., Anderson, J. M., D'Ammando, F., Hodgson, J., Honma, M., Krichbaum, T. P., Lee, S. -S., Lico, R., Lisakov, M. M., Lobanov, A. P., Petrov, L., Sohn, B. W., Sokolovsky, K. V., Voitsik, P. A., Zensus, J. A., and **Tingay, S., J** wide and collimated radio jet in 3C84 on the scale of a few hundred gravitational radii, Nature Astronomy, 2, 472

Greiner, J., Bolmer, J., Wieringa, M., van der Horst, A. J., Petry, D., Schulze, S., Knust, F., de Bruyn, G., Krühler, T., Wiseman, P., Klose, S., Delvaux, C., Graham, J. F., Kann, D. A., Moin, A., Nicuesa-Guelbenzu, A., Schady, P., Schmidl, S., Schweyer, T., Tanga, M., **Tingay, S. J.**, van Eerten, H., and Varela, K., Large-amplitude late-time radio variability in GRB 151027B, Astronomy and Astrophysics, 614, A29

Hancock, P. J., Trott, C. M., and **Hurley-Walker, N.**, Source Finding in the Era of the SKA (Precursors): Aegean 2.0, Publications of the Astronomical Society of Australia, 35, e011

Harvey, V. M., Franzen, T., **Morgan, J.**, and **Seymour, N**., A novel approach for characterizing broad-band radio spectral energy distributions, Monthly Notices of the Royal Astronomical Society, 476, 2717

Hurley-Walker, N. and Hancock, P. J., De-distorting ionospheric effects in the image plane, Astronomy and Computing, 25, 94

Hutter, A., **Trott, C. M.**, and Dayal, P., Survey parameters for detecting 21-cm-Ly - emitter cross-correlations with the Square Kilometre Array, Monthly Notices of the Royal Astronomical Society, 479, L129

IceCube Collaboration, Aartsen, M. G., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., Al Samarai, I., Altmann, D., Andeen, K., Anderson, T., Ansseau, I., Anton, G., Argüelles, C., Auffenberg, J., Axani, S., Bagherpour, H., Bai, X., Barron, J. P., Barwick, S. W., Baum, V., Bay, R., Beatty, J. J., Becker Tjus, J., Becker, K. -H., BenZvi, S., Berley, D., Bernardini, E., Besson, D. Z., Binder, G., Bindig, D., Blaufuss, E., Blot, S., Bohm, C., Börner, M., Bos, F., Böser, S., Botner, O., Bourbeau, E., Bourbeau, J., Bradascio, F., Braun, J., Brenzke, M., Bretz, H. -P., Bron, S., Brostean-Kaiser, J., Burgman, A., Busse, R. S., Carver, T., Cheung, E., Chirkin, D., Christov, A., Clark, K., Classen, L., Coenders, S., Collin, G. H., Conrad, J. M., Coppin, P., Correa, P., Cowen, D. F., Cross, R., Dave, P., Day, M., de André, J. P. A. M., De Clercq, C., DeLaunay, J. J., Dembinski, H., De Ridder, S., Desiati, P., de Vries, K. D., de Wasseige, G., de With, M., DeYoung, T., Díaz-Vélez, J. C., di Lorenzo, V., Dujmovic, H., Dumm, J. P., Dunkman, M., Dvorak, E., Eberhardt, B., Ehrhardt, T., Eichmann, B., Eller, P., Evenson, P. A., Fahey, S., Fazely, A. R., Felde, J., Filimonov, K., Finley, C., Flis, S., Franckowiak, A., Friedman, E., Fritz, A., Gaisser, T. K., Gallagher, J., Gerhardt, L., Ghorbani, K., Glauch, T., Glüsenkamp, T., Goldschmidt, A., Gonzalez, J. G., Grant, D., Griffith, Z., Haack, C., Hallgren, A., Halzen, F., Hanson, K., Hebecker, D., Heereman, D., Helbing, K., Hellauer, R., Hickford, S., Hignight, J., Hill, G. C., Hoffman, K. D., Hoffmann, R., Hoinka, T., Hokanson-Fasig, B., Hoshina, K., Huang, F., Huber, M., Hultqvist, K., Hünnefeld, M., Hussain, R., In, S., Iovine, N., Ishihara, A., Jacobi, E., Japaridze, G. S., Jeong, M., Jero, K., Jones, B. J. P., Kalaczynski, P., Kang, W., Kappes, A., Kappesser, D., Karg, T., Karle, A., Katz, U., Kauer, M., Keivani, A., Kelley, J. L., Kheirandish, A., Kim, J., Kim, M., Kintscher, T., Kiryluk, J., Kittler, T., Klein, S. R., Koirala, R., Kolanoski, H., Köpke, L., Kopper, C., Kopper, S., Koschinsky, J. P., Koskinen, D. J., Kowalski, M., Krings, K., Kroll, M., Krückl, G., Kunwar, S., Kurahashi, N., Kuwabara, T., Kyriacou, A., Labare, M., Lanfranchi, J. L., Larson, M. J., Lauber, F., Leonard, K., Lesiak-Bzdak, M., Leuermann, M., Liu, Q. R., Lozano Mariscal, C. J., Lu, L., Lünemann, J., Luszczak, W., Madsen, J., Maggi, G., Mahn, K. B. M., Mancina, S., Maruyama, R., Mase, K., Maunu, R., Meagher, K., Medici, M., Meier, M., Menne, T., Merino, G., Meures, T., Miarecki, S., Micallef, J., Momenté, G., Montaruli, T., Moore, R. W., S, Morse, R., Moulai, M., Nahnhauer, R., Nakarmi, P., Naumann, U., Neer, G., Niederhausen, H., Nowicki, S. C., Nygren, D. R., Obertacke Pollmann, A., Olivas, A., O'Murchadha, A., O'Sullivan, E., Palczewski, T., Pandya, H., Pankova, D. V., Peiffer, P., Pepper, J. A., Pérez de los Heros, C., Pieloth, D., Pinat, E., Plum, M., Price, P. B., Przybylski, G. T., Raab, C., Rädel, L., Rameez, M., Rauch, L., Rawlins, K., Rea, I. C., Reimann, R., Relethford, B., Relich, M., Resconi, E., Rhode, W., Richman, M., Robertson, S., Rongen, M., Rott, C., Ruhe, T., Ryckbosch, D., Rysewyk, D., Safa, I., Sälzer, T., Sanchez Herrera, S. E., Sandrock, A., Sandroos, J., Santander, M., Sarkar, S., Sarkar, S., Satalecka, K., Schlunder, P., Schmidt, T., Schneider, A., Schoenen, S., Schöneberg, S., Schumacher, L., Sclafani, S., Seckel, D., Seunarine, S., Soedingrekso, J., Soldin, D., Song, M., Spiczak, G. M., Spiering, C., Stachurska, J., Stamatikos, M., Stanev, T., Stasik, A., Stein, R., Stettner, J., Steuer, A., Stezelberger, T., Stokstad, R. G., Stößl, A., Strotjohann, N. L., Stuttard, T., Sullivan, G. W., Sutherland, M., Taboada, I., Tatar, J., Tenholt, F., Ter-Antonyan, S., Terliuk, A., Tilav, S., Toale, P. A., Tobin, M. N., Toennis, C., Toscano, S., Tosi, D., Tselengidou, M., TUng, C. F., Turcati, A., Turley, C. F., Ty, B., Unger, E., Usner, M., Vandenbroucke, J., Van Driessche, W., van Eijk, D., van Eijndhoven, N., Vanheule, S., van Santen, J., Vogel, E., Vraeghe, M., Walck, C., Wallace, A., Wallraff, M., Wandler, F. D., Wandkowsky, N., Waza, A., Weaver, C., Weiss, M. J., Wendt, C., Werthebach, J., Westerhoff, S., Whelan, B. J., Whitehorn, N., Wiebe, K., Wiebusch, C. H., Wille, L., Williams, D. R., Wills, L., Wolf, M., Wood, J., Wood, T. R., Woschnagg, K., Xu, D. L., Xu, X. W., Xu, Y., Yanez, J. P., Yodh, G., Yoshida, S., Yuan, T., Fermi-LAT Collaboration, Abdollahi, S., Ajello, M., Angioni, R., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Bissaldi, E., Blandford, R. D., Bonino, R., Bottacini, E., Bregeon, J., Bruel, P., Buehler, R., Burnett, T. H., Burns, E., Buson, S., Cameron, R. A., Caputo, R., Caraveo, P. A., Cavazzuti, E., Charles, E., Chen, S., CheUng, C. C., Chiang, J., Chiaro, G., Ciprini, S., Cohen-Tanugi, J., Conrad, J., Costantin, D., Cutini, S., D'Ammando, F., de Palma, F., Digel, S. W., Di Lalla, N., Di Mauro, M., Di Venere, L., Domínguez, A., Favuzzi, C., Franckowiak, A., Fukazawa, Y., Funk, S., Fusco, P., Gargano, F., Gasparrini, D., Giglietto, N., Giomi, M., Giommi, P., Giordano, F., Giroletti, M., Glanzman, T., Green, D., Grenier, I. A., Grondin, M. -H., Guiriec, S., Harding, A. K., Hayashida, M., Hays, E., Hewitt, J. W., Horan, D., Jóhannesson, G., Kadler, M., Kensei, S., Kocevski, D., Krauss, F., Kreter, M., Kuss, M., La Mura, G., Larsson, S., Latronico, L., Lemoine-Goumard, M., Li, J., Longo, F., Loparco, F., Lovellette, M. N., Lubrano, P., Magill, J. D., Maldera, S., Malyshev, D., Manfreda, A., Mazziotta, M. N., McEnery, J. E., Meyer, M., Michelson, P. F., Mizuno, T., Monzani, M. E., Morselli, A., Moskalenko, I. V., Negro, M., Nuss, E., Ojha, R., Omodei, N., Orienti, M., Orlando, E., Palatiello, M., Paliya, V. S., Perkins, J. S., Persic, M., Pesce-Rollins, M., Piron, F., Porter, T. A., Principe, G., Rainò, S., Rando, R., Rani, B., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Renault-Tinacci, N., Ritz, S., Rochester, L. S., Saz Parkinson, P. M., Sgrò, C., Siskind, E. J., Spandre, G., Spinelli, P., Suson, D. J., Tajima, H., Takahashi, M., Tanaka, Y., Thayer, J. B., Thompson, D. J., Tibaldo, L., Torres, D. F., Torresi, E., Tosti, G., Troja, E., Valverde, J., Vianello, G., Vogel, M., Wood, K., Wood, M., Zaharijas, G., MAGIC Collaboration, Ahnen, M. L., Ansoldi, S., Antonelli, L. A., Arcaro, C., Baack, D., Babić, A., Banerjee, B., Bangale, P., Barres de Almeida, U., Barrio, J. A., Becerra González, J., Bednarek, W., Bernardini, E., Berti, A., Bhattacharyya, W., Biland, A., Blanch, O., Bonnoli, G., Carosi, A., Carosi, R., Ceribella, G., Chatterjee, A., Colak, S. M., Colin, P., Colombo, E., Contreras, J. L., Cortina, J., Covino, S., Cumani, P., Da Vela, P., Dazzi, F., De Angelis, A., De Lotto, B., Delfino, M., Delgado, J., Di Pierro, F., Domínguez, A., Dominis Prester, D., Dorner, D., Doro, M., Einecke, S., Elsaesser, D., Fallah Ramazani, V., Fernández-Barral, A., Fidalgo, D., Foffano, L., Pfrang, K., Fonseca, M. V., Font, L., Franceschini, A., Fruck, C., Galindo, D., Gallozzi, S., García López, R. J., Garczarczyk, M., Gaug, M., Giammaria, P., Godinović, N., Gora, D., Guberman, D., Hadasch, D., Hahn, A., Hassan, T., Hayashida, M., Herrera, J., Hose, J., Hrupec, D., Inoue, S., Ishio, K., Konno, Y., Kubo, H., Kushida, J., Lelas, D., Lindfors, E., Lombardi, S., Longo, F., López, M., Maggio, C., Majumdar, P., Makariev, M., Maneva, G., Manganaro, M., Mannheim, K., Maraschi, L., Mariotti, M., Martínez, M., Masuda, S., Mazin, D., Minev, M., M, J. M., Mirzoyan, R., Moralejo, A., Moreno, V., Moretti, E., Nagayoshi, T., Neustroev, V., Niedzwiecki, A., Nievas Rosillo, M., Nigro, C., Nilsson, K., Ninci, D., Nishijima, K., Noda, K., Nogués, L., Paiano, S., Palacio, J., Paneque, D., Paoletti, R., Paredes, J. M., Pedaletti, G., Peresano, M., Persic, M., Prada Moroni, P. G., Prandini, E., Puljak, I., Rodriguez Garcia, J., Reichardt, I., Rhode, W., Ribó, M., Rico, J., Righi, C., Rugliancich, A., Saito, T., Satalecka, K., Schweizer, T., Sitarek, J., Šnidaric´, I., Sobczynska, D., Stamerra, A., Strzys, M., Surić, T., Takahashi, M., Tavecchio, F., Temnikov, P., Terzić, T., Teshima, M., Torres-Albà, N., Treves, A., Tsujimoto, S., Vanzo, G., Vazquez Acosta, M., Vovk, I., Ward, J. E., Will, M., S, Zaric´, D., AGILE Team, Lucarelli, F., Tavani, M., Piano, G., Donnarumma, I., Pittori, C., Verrecchia, F., Barbiellini, G., Bulgarelli, A., Caraveo, P., Cattaneo, P. W., Colafrancesco, S., Costa, E., Di Cocco, G., Ferrari, A., Gianotti, F., Giuliani, A., Lipari, P., Mereghetti, S., Morselli, A., Pacciani, L., Paoletti, F., Parmiggiani, N., Pellizzoni, A., Picozza, P., Pilia, M., Rappoldi, A., Trois, A., Vercellone, S., Vittorini, V., ASAS-SN Team, Stanek, A. Franckowiak K. Z., Kochanek, C. S., Beacom, J. F., Thompson, T. A., Holoien, T. W. -S., Dong, S., Prieto, J. L., Shappee, B. J., Holmbo, S., HAWC Collaboration, Abeysekara, A. U., Albert, A., Alfaro, R., Alvarez, C., Arceo, R., Arteaga-Velázquez, J. C., Avila Rojas, D., Ayala Solares, H. A., Becerril, A., Belmont-Moreno, E., Bernal, A., Caballero-Mora, K. S., Capistrán, T., Carramiñana, A., Casanova, S., Castillo, M., Cotti, U., Cotzomi, J., Coutiño de León, S., De León, C., De la Fuente, E., Diaz Hernandez, R., Dichiara, S., Dingus, B. L., DuVernois, M. A., Díaz-Vélez, J. C., Ellsworth, R. W., Engel, K., Fiorino, D. W., Fleischhack, H., Fraija, N., García-González, J. A., Garfias, F., González Muñoz, A., González, M. M., Goodman, J. A., Hampel-Arias, Z., Harding, J. P., Hernandez, S., Hona, B., Hueyotl-Zahuantitla, F., Hui, C. M., Hüntemeyer, P., Iriarte, A., Jardin-Blicq, A., Joshi, V., Kaufmann, S., Kunde, G. J., Lara, A., Lauer, R. J., Lee, W. H., Lennarz, D., León Vargas, H., Linnemann, J. T., Longinotti, A. L., Luis-Raya, G., Luna-García, R., Malone, K., Marinelli, S. S., Martinez, O., Martinez-Castellanos, I., Martínez-Castro, J., Martínez-Huerta, H., Matthews, J. A., Miranda-Romagnoli, P., Moreno, E., Mostafá, M., Nayerhoda, A., Nellen, L., Newbold, M., Nisa, M. U., Noriega-Papaqui, R., Pelayo, R., Pretz, J., Pérez-Pérez, E. G., Ren, Z., Rho, C. D., Rivière, C., Rosa-González, D., Rosenberg, M., Ruiz-Velasco, E., Ruiz-Velasco, E., Salesa Greus, F., Sandoval, A., Schneider, M., Schoorlemmer, H., Sinnis, G., Smith, A. J., Springer, R. W., Surajbali, P., Tibolla, O., Tollefson, K., Torres, I., Villaseñor, L., Weisgarber, T., Werner, F., Yapici, T., Gaurang, Y., Zepeda, A., Zhou, H., Álvarez, J. D., H. E. S. S. Collaboration, Abdalla, H., Angüner, E. O., Armand, C., Backes, M., Becherini, Y., Berge, D., Böttcher, M., Boisson, C., Bolmont, J., Bonnefoy, S., Bordas, P., Brun, F., Büchele, M., Bulik, T., Caroff, S., Carosi, A., Casanova, S., Cerruti, M., Chakraborty, N., Chandra, S., Chen, A., Colafrancesco, S., Davids, I. D., Deil, C., Devin, J., Djannati-Ataï, A., Egberts, K., Emery, G., Eschbach, S., Fiasson, A., Fontaine, G., Funk, S., Füßling, M., Gallant, Y. A., Gaté, F., Giavitto, G., Glawion, D., Glicenstein, J. F., Gottschall, D., Grondin, M. -H., Haupt, M., Henri, G., Hinton, J. A., Hoischen, C., Holch, T. L., Huber, D., Jamrozy, M., Jankowsky, D., Jankowsky, F., Jouvin, L., JUng-Richardt, I., Kerszberg, D., Khélifi, B., King, J., Klepser, S., Kluz´niak, W., Komin, Nu., Kraus, M., Lefaucheur, J., Lemière, A., Lemoine-Goumard, M., Lenain, J. -P., Leser, E., Lohse, T., López-Coto, R., Lorentz, M., Lypova, I., Marandon, V., Guillem Martí-Devesa, G., Maurin, G., Mitchell, A. M. W., Moderski, R., Mohamed, M., Mohrmann, L., Moulin, E., Murach, T., de Naurois, M., Niederwanger, F., Niemiec, J., Oakes, L., O'Brien, P., Ohm, S., Ostrowski, M., Oya, I., Panter, M., Parsons, R. D., Perennes, C., Piel, Q., Pita, S., Poireau, V., Priyana Noel, A., Prokoph, H., Pühlhofer, G., Quirrenbach, A., Raab, S., Rauth, R., Renaud, M., Rieger, F., Rinchiuso, L., Romoli, C., Rowell, G., Rudak, B., Sasaki, D. A., Sanchez, M., Schlickeiser, R., Schüssler, F., Schulz, A., Schwanke, U., Seglar-Arroyo, M., Shafi, N., Simoni, R., Sol, H., Stegmann, C., Steppa, C., Tavernier, T., Taylor, A. M., Tiziani, D., Trichard, C., Tsirou, M., van Eldik, C., van Rensburg, C., van Soelen, B., Veh, J., Vincent, P., Voisin, F., Wagner, S. J., Wagner, R. M., Wierzcholska, A., Zanin, R., Zdziarski, A. A., Zech, A., Ziegler, A., Zorn, J., Żywucka, N., INTEGRAL Team, Savchenko, V., Ferrigno, C., Bazzano, A., Diehl, R., Kuulkers, E., Laurent, P., Mereghetti, S., Natalucci, L., Panessa, F., Rodi, J., Ubertini, P., Kanata, Kiso and Subaru Observing Teams, Morokuma, T., Ohta, K., Tanaka, Y. T., Mori, H., Yamanaka, M., Kawabata, K. S., Utsumi, Y., Nakaoka, T., Kawabata, M., Nagashima, H., Yoshida, M., Matsuoka, Y., Itoh, R., Kapteyn Team, Keel, W., Liverpool Telescope Team, Copperwheat, C., Steele, I., Swift/NuSTAR Team, Cenko, S. B., Cowen, D. F., DeLaunay, J. J., Evans, P. A., Fox, D. B., Keivani, A., Kennea, J. A., Marshall, F. E., Osborne, J. P., Santander, M., Tohuvavohu, A., Turley, C. F., VERITAS Collaboration, Abeysekara, A. U., Archer, A., Benbow, W., Bird, R., Brill, A., Brose, R., Buchovecky, M., Buckley, J. H., Bugaev, V., Christiansen, J. L., Connolly, M. P., Cui, W., Daniel, M. K., Errando, M., Falcone, A., Feng, Q., Finley, J. P., Fortson, L., Furniss, A., Gueta, O., Hütten, M., Hervet, O., Hughes, G., Humensky, T. B., Johnson, C. A., Kaaret, P., Kar, P., Kelley-Hoskins, N., Kertzman, M., Kieda, D., Krause, M., Krennrich, F., Kumar, S., Lang, M. J., Lin, T. T. Y., Maier, G., McArthur, S., Moriarty, P., Mukherjee, R., Nieto, D., O'Brien, S., Ong, R. A., Otte, A. N., Park, N., Petrashyk, A., Pohl, M., Popkow, A., Pueschel, S. E., Quinn, J., Ragan, K., Reynolds, P. T., Richards, G. T., Roache, E., Rulten, C., Sadeh, I., Santander, M., Scott, S. S., Sembroski, G. H., Shahinyan, K., Sushch, I., Trépanier, S., Tyler, J., Vassiliev, V. V., Wakely, S. P., Weinstein, A., Wells, R. M., Wilcox, P., Wilhelm, A., Williams, D. A., Zitzer, B., VLA/B Team, Tetarenko, A. J., Kimball, A. E., **Miller-Jones, J. C. A.**, and Sivakoff, G. R., Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A, Science, 361, eaat1378

Joseph R. C., Trott, C. M., and **Wayth, R.B.**, The Bias and Uncertainty of Redundant and Sky-based Calibration Under Realistic Sky and Telescope Conditions, The Astronomical Journal, 156, 285

Keane, E. F., Barr, E. D., Jameson, A., Morello, V., Caleb, M., Bhandari, S., Petroff, E., Possenti, A., Burgay, M., Tiburzi, C., Bailes, M., **Bhat, N. D. R.**, Burke-Spolaor, S., Eatough, R. P., Flynn, C., Jankowski, F., Johnston, S., Kramer, M., Levin, L., Ng, C., van Straten, W., and Krishnan, V. Venkatraman, The SUrvey for Pulsars and Extragalactic Radio Bursts - I. Survey description and overview, Monthly Notices of the Royal Astronomical Society, 473, 116

Koay, J. Y., **Macquart, J.-P.**, Jauncey, D. L., Pursimo, T., Giroletti, M., Bignall, H. E., Lovell, J. E. J., Rickett, B. J., Kedziora-Chudczer, L., Ojha, R., and Reynolds, C., The MASIV Survey - IV. Relationship between intra-day scintillation and intrinsic variability of radio AGNs, Monthly Notices of the Royal Astronomical Society, 474, 4396

Li, W., Pober, J. C., Hazelton, B. J., Barry, N., Morales, M. F., Sullivan, I., Parsons, A. R., Ali, Z. S., Dillon, J. S., Beardsley, A. P., Bowman, J. D., Briggs, F., Byrne, R., Carroll, P., **Crosse, B., Emrich, D.**, Ewall-Wice, A., Feng, L., Franzen, T. M. O., Hewitt, J. N., **Horsley, L.**, Jacobs, D. C., **Johnston-Hollitt, M., Jordan, C., Joseph, R. C.**, Kaplan, D. L., **Kenney, D.,** Kim, H., Kittiwisit, P., Lanman, A., **Line, J., McKinley, B.**, Mitchell, D. A., **Murray, S**., Neben, A., Offringa, A. R., Pallot, D., Paul, S., Pindor, B., Procopio, P., Rahimi, M., Riding, J., Sethi, S. K., Udaya Shankar, N., **Steele, K.**, Subrahmanian, R., Tegmark, M., Thyagarajan, N., **Tingay, S. J., Trott, C., Walker, M., Wayth, R. B.**, Webster, R. L., **Williams, A.**, Wu, C., and Wyithe, S., Comparing Redundant and Sky-model-based Interferometric Calibration: A First Look with Phase II of the MWA, The Astrophysical Journal, 863, 170

Line, J. L. B., McKinley, B., Rasti, J., Bhardwaj, M., **Wayth, R. B.**, Webster, R. L., **Ung, D., Emrich, D., Horsley, L.**, Beardsley, A., **Crosse, B.**, Franzen, T. M. O., Gaensler, B. M., **Johnston-Hollitt, M.**, Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Steele, K., Tingay, S. J., Trott, C. M., Walker, M., Williams, A.**, and Wu, C., In situ measurement of MWA primary beam variation using ORBCOMM, Publications of the Astronomical Society of Australia, 35, 45

Liu, Jiren, **Soria, R**., Qiao, Erlin, and Liu, Jifeng, Discovery of a pulsating Fe K - Line in GX 301-2, Monthly Notices of the Royal Astronomical Society, 480, 4746

Macquart, J. -P. and Ekers, R. D., Fast radio burst event rate counts - I. Interpreting the observations, Monthly Notices of the Royal Astronomical Society, 474, 1900

Macquart, J. -P. and Ekers, R.D., FRB event rate counts - II. Fluence, redshift, and dispersion measure distributions, Monthly Notices of the Royal Astronomical Society, 480, 4211

Mahony, E. K., **Ekers, R. D., Macquart, J.-P.**, Sadler, E. M., Bannister, K. W., Bhandari, S., Flynn, C., Koribalski, B. S., Prochaska, J. X., Ryder, S. D., S., Ryan M., Tejos, N., Whiting, M.T., and Wong, O. I., A Search for the Host Galaxy of FRB 171020, The Astrophysical Journal, 867, L10

Marlar, Andrea, Shemmer, Ohad, Anderson, S. F., Brandt, W. N., Diamond-Stanic, A. M., Fan, X., Luo, B., **Plotkin, R. M.**, Richards, Gordon T., Schneider, D. P., and Wu, Jianfeng, Steep Hard-X-Ray Spectra Indicate Extremely High Accretion Rates in Weak Emission-Line Quasars, The Astrophysical Journal, 865, 92

McCauley, P. I., Cairns, I.H., and **Morgan,** J., Densities Probed by Coronal Type III Radio Burst Imaging, Solar Physics, 293, 132

McKinley, B., Tingay, S. J., Carretti, E., Ellis, S., Bland-Hawthorn, J., Morganti, R., **Line, J.,** McDonald, M., Veilleux, S., Wahl Olsen, R., Sidonio, M., **Ekers, R.**, Offringa, A. R., Procopio, P., Pindor, B., **Wayth, R. B., Hurley-Walker,** N., Bernardi, G., Gaensler, B. M., Haverkorn, M., Kesteven, M., Poppi, S., and Staveley-Smith, L., The jet/wind outflow in Centaurus A: a local laboratory for AGN feedback, Monthly Notices of the Royal Astronomical Society, 474, 4056

McKinley, B., Bernardi, G., **Trott, C. M., Line, J. L. B., Wayth, R. B.**, Offringa, A. R., Pindor, B., **Jordan, C. H., Sokolowski, M., Tingay, S. J.**, Lenc, E., **Hurley-Walker, N.**, Bowman, J. D., Briggs, F., and Webster, R. L., Measuring the global 21-cm signal with the MWA-I: improved measurements of the Galactic synchrotron background using lunar occultation, Monthly Notices of the Royal Astronomical Society, 481, 5034

Meyers, B. W., Tremblay, S. E., Bhat, N. D. R., Flynn, C., Gupta, V., Shannon, R. M., **Murray, S. G., Sobey, C**., Ord, S. M., Osłowski, S., **Crosse, B.**, **Williams, A.**, Jankowski, F., Farah, W., Venkatraman Krishnan, V., Bateman, T., Bailes, M., Beardsley, A., **Emrich, D.**, Franzen, T. M. O., Gaensler, B. M., **Horsley, L., Johnston-Hollitt, M.**, Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Steele, K., Tingay, S. J., Trott, C. M., Walker, M., Wayth, R. B.**, and Wu, C., Hunting for Radio Emission from the Intermittent Pulsar J1107-5907 at Low Frequencies, The Astrophysical Journal, 869, 134

Michilli, D., Seymour, A., Hessels, J. W. T., Spitler, L. G., Gajjar, V., Archibald, A. M., Bower, G. C., Chatterjee, S., Cordes, J. M., Gourdji, K., Heald, G. H., Kaspi, V. M., Law, C. J., **Sobey, C**., Adams, E. A. K., Bassa, C.

G., Bogdanov, S., Brinkman, C., Demorest, P., Fernandez, F., **Hellbourg, G**., Lazio, T. J. W., Lynch, R. S., Maddox, N., Marcote, B., McLaughlin, M. A., Paragi, Z., Ransom, S. M., Scholz, P., Siemion, A. P. V., Tendulkar, S. P., van Rooy, P., Wharton, R. S., and Whitlow, D., An extreme magneto-ionic environment associated with the fast radio burst source FRB 121102, Nature, 553, 182

Miller-Jones, J. C. A., Deller, A. T., Shannon, R. M., Dodson, R., Moldón, J., Ribó, M., Dubus, G., Johnston, S., Paredes, J. M., Ransom, S. M., and Tomsick, J. A., The geometric distance and binary orbit of PSR B1259-63, Monthly Notices of the Royal Astronomical Society, 479, 4849

Morgan, J. S., Macquart, J. -P., Ekers, R., Chhetri, R., Tokumaru, M., Manoharan, P. K., **Tremblay, S.**, Bisi, M. M., and Jackson, B. V., Interplanetary Scintillation with the Murchison Widefield Array I: a sub-arcsecond survey over 900 deg² at 79 and 158 MHz, Monthly Notices of the Royal Astronomical Society, 473, 2965

Murray, S. G., Robotham, A. S. G., and Power, C., An Empirical Mass Function Distribution, The Astrophysical Journal, 855, 5

Murray, S. G. and Trott, C. M., The Effect of Baseline Layouts on the Epoch of Reionization Foreground Wedge: A Semianalytical Approach, The Astrophysical Journal, 869, 25

Müller, C., Kadler, M., Ojha, R., Schulz, R., Trüstedt, J., Edwards, P. G., Ros, E., Carpenter, B., Angioni, R., Blanchard, J., Böck, M., Burd, P. R., Dörr, M., Dutka, M. S., Eberl, T., Gulyaev, S., Hase, H., Horiuchi, S., Katz, U., Krauß, F., Lovell, J. E. J., Natusch, T., Nesci, R., Phillips, C., Plötz, C., Pursimo, T., Quick, J. F. H., Stevens, J., Thompson, D. J., **Tingay, S. J.**, Tzioumis, A. K., Weston, S., Wilms, J., and Zensus, J. A., TANAMI: Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry. II. Additional sources, Astronomy and Astrophysics, 610, A1

Ni, Q., Brandt, W. N., Luo, B., Hall, P. B., Shen, Yue, Anderson, S. F., **Plotkin, R. M.**, Richards, Gordon T., Schneider, D. P., Shemmer, O., and Wu, Jianfeng, Connecting the X-ray properties of weak-line and typical quasars: testing for a geometrically thick accretion disk, Monthly Notices of the Royal Astronomical Society, 480, 5184

Noirot, G., Stern, D., Mei, S. Wylezalek, D., Cooke, E. A., De Breuck, C., Galametz, A., Hatch, N. A., Vernet, J., Brodwin, M., Eisenhardt, P., Gonzalez, A.H., Jarvis, M., Rettura, A., **Seymour, N**., and Stanford, S. A., HST Grism Confirmation of 16 Structures at 1.4<z<2.8 from the Clusters Around Radio-Loud AGN (CARLA) Survey, The Astrophysical Journal, 859, 38

Obreschkow, D., **Murray, S. G.**, Robotham, A. S. G., and Westmeier, T., Eddington's demon: inferring galaxy mass functions and other distributions from uncertain data, Monthly Notices of the Royal Astronomical Society, 474, 5500

Polzin, E. J., Breton, R. P., Clarke, A. O., Kondratiev, V. I., Stappers, B. W., Hessels, J. W. T., Bassa, C. G., Broderick, J. W., Grießmeier, J. -M., **Sobey, C.**, ter Veen, S., van Leeuwen, J., and Weltevrede, P., The low-frequency radio eclipses of the black widow pulsar J1810+1744, Monthly Notices of the Royal Astronomical Society, 476, 1968

Phiri T.J., **Davidson D.B**., Wiid P.G., ``A Deterministic Propagation Model for Multipath

Analysis at SKA Precursor Telescopes - A Case Study on MeerKAT", IEEE Transactions on Antennas and Propagation. Vol. 66, No. 12, pp. 6500-6509

Rampadarath, H., Soria, R., **Urquhart, R.,** Argo, M. K., Brightman, M., Lacey, C. K., Schlegel, E. M., Beswick, R. J., Baldi, R. D., Muxlow, T. W. B., McHardy, I. M., Williams, D. R. A., and Dumas, G., Jets, arcs, and shocks: NGC 5195 at radio wavelengths, Monthly Notices of the Royal Astronomical Society, 476, 2876

Riseley, C. J., Lenc, E., Van Eck, C. L., Heald, G., Gaensler, B. M., Anderson, C. S., **Hancock, P. J., Hurley-Walker, N.**, Sridhar, S. S., and **White, S. V**., The POlarised GLEAM Survey (POGS) I: First results from a low-frequency radio Linear polarisation survey of the southern sky, Publications of the Astronomical Society of Australia, 35, 43

Russell, D. M., Qasim, A. A., Bernardini, F., **Plotkin, R. M.**, Lewis, F., Koljonen, K.I. I., and Yang, Y., Optical Precursors to Black Hole X-Ray Binary Outbursts: An Evolving Synchrotron Jet Spectrum in Swift J1357.2-0933, The Astrophysical Journal, 852, 90

Rivera Sandoval, L. E., Wijnands, R., Degenaar, N., Cavecchi, Y., Heinke, C. O., Cackett, E. M., Homan, J., Altamirano, D., **Bahramian, A.**, Sivakoff, G. R., Miller, J. M., & Parikh, A. S., Extreme quiescent variability of the transient neutron star low-mass X-ray binary EXO 1745-248 in Terzan 5, Monthly Notices of the Royal Astronomical Society, 479, 2777.

Russell, T. D., Degenaar, N., Wijnands, R., van den Eijnden, J., Gusinskaia, N. V., Hessels, J. W. T., and **Miller-Jones, J. C. A.**, The Radio-bright Accreting Millisecond X-Ray Pulsar IGR J17591-2342, The Astrophysical Journal, 869, L16

Shannon, R. M., **Macquart, J. -P.**, Bannister, K. W., **Ekers, R. D., James, C.W.**, Osłowski, S., Qiu, H., Sammons, M., Hotan, A. W., Voronkov, M. A., Beresford, R. J., Brothers, M., Brown, A. J., Bunton, J. D., Chippendale, A. P., Haskins, C., Leach, M., Marquarding, M., McConnell, D., Pilawa, M. A., Sadler, E. M., Troup, E. R., Tuthill, J., Whiting, M. T., Allison, J. R., Anderson, C. S., Bell, M. E., Collier, J. D., Gürkan, G., Heald, G., and Riseley, C. J., The dispersion-brightness relation for fast radio bursts from a wide-field survey, Nature, 562, 386

Sanna, A., **Bahramian, A**., Bozzo, E., Heinke, C., Altamirano, D., Wijnands, R., Degenaar, N., Maccarone, T., Riggio, A., Di Salvo, T., Iaria, R., Burgay, M., Possenti, A., Ferrigno, C., Papitto, A., Sivakoff, G. R., D'Amico, N., & Burderi, L., Discovery of 105 Hz coherent pulsations in the ultracompact binary IGR J16597-3704, Astronomy and Astrophysics, 610, L2

Shin, J., **Plotkin, R. M.**, Woo, J., Gallo, E., and Mulchaey, J. S., A Catalog of X-Ray Point Sources in the Abell 133 Region, The Astrophysical Journal Supplement Series, 238, 23

Shishkovsky, Laura, Strader, Jay, Chomiuk, Laura, **Bahramian, A.**, Tremou, Evangelia, Li, Kwan-Lok, Salinas, Ricardo, **Tudor, V., Miller-Jones, James C. A.,** Maccarone, Thomas J., Heinke, Craig O., and Sivakoff, Gregory R., The MAVERIC Survey: A Red Straggler Binary with an Invisible Companion in the Galactic Globular Cluster M10, The Astrophysical Journal, 855, 55

Smith, Beverly J., Campbell, Kristen, Struck, Curtis, Soria, Roberto, Swartz, Douglas, Magno, Macon, Dunn, Brianne, and Giroux, Mark L., Diffuse X-Ray-emitting Gas in Major Mergers, The Astronomical Journal, 155, 81

Sokolowski, M., Bhat, N. D. R., Macquart, J. -P., Shannon, R. M., Bannister, K. W., **Ekers, R. D.**, Scott, D. R., Beardsley, A. P., **Crosse, B.**, **Emrich, D.**, Franzen, T. M. O., Gaensler, B. M., **Horsley, L., Johnston-Hollitt, M.**, Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Sleap, G., Steele, K., Tingay, S. J., Trott, C. M., Walker, M., Wayth, R. B., Williams, A.**, and Wu, C., No Low-frequency Emission from Extremely Bright Fast Radio Bursts, The Astrophysical Journal, 867, L12

Spiewak, R., Bailes, M., Barr, E. D., **Bhat, N. D. R.**, Burgay, M., Cameron, A. D., Champion, D. J., Flynn, C. M. L., Jameson, A., Johnston, S., Keith, M. J., Kramer, M., Kulkarni, S. R., Levin, L., Lyne, A. G., Morello, V., Ng, C., Possenti, A., Ravi, V., Stappers, B. W., van Straten, W., and Tiburzi, C., PSR J2322-2650 - a low-luminosity millisecond pulsar with a planetary-mass companion, Monthly Notices of the Royal Astronomical Society, 475, 469

Steeb J.-W., **Davidson D.B**., Wijnholds S.J., "Computationally Efficient Radio Frequency Source Localization for Radio Interferometric Arrays'' Radio Science, Vol 53, pp. 1-15

Steiner, A. W., Heinke, C. O., Bogdanov, S., Li, C. K., Ho, W. C. G., **Bahramian, A.**, & Han, S., Constraining the mass and radius of neutron stars in globular clusters, Monthly Notices of the Royal Astronomical Society, 476, 421.

Su, H., Macquart, J. P., Hurley-Walker, N., McClure-Griffiths, N. M., Jackson, C. A., **Tingay, S. J**., Tian, W. W., Gaensler, B. M., **McKinley, B**., Kapińska, A. D., Hindson, L., **Hancock, P., Wayth, R. B.**, Staveley-Smith, L., **Morgan, J., Johnston-Hollitt, M.**, Lenc, E., Bell, M. E., Callingham, J. R., Dwarkanath, K. S., For, B. -Q., Offringa, A. R., Procopio, P., Wu, C., and Zheng, Q., Galactic synchrotron distribution derived from 152 H II region absorption features in the full GLEAM survey, Monthly Notices of the Royal Astronomical Society, 479, 4041

Swihart, S.J., Strader, J., Shishkovsky, L., Chomiuk, L., **Bahramian, A.**, Heinke, Craig O., **Miller-Jones, James C. A**., Edwards, P. G., and Cheung, C. C., A Multiwavelength View of the Neutron Star Binary 1FGL J1417.7-4402: A Progenitor to Canonical Millisecond Pulsars, The Astrophysical Journal, 866, 83

Sutinjo, A.T., Ung, D.C.X., and Juswardy, B., Cold-source noise measurement of a differential input single-ended output low-Noise amplifier connected to a low-frequency radio astronomy antenna, IEEE Transactions on Antennas and Propagation, 66 (10), art. no. 8408814, pp. 5511-5520

Tan, C. M., Bassa, C. G., Cooper, S., Dijkema, T. J., Esposito, P., Hessels, J. W. T., Kondratiev, V. I., Kramer, M., Michilli, D., Sanidas, S., Shimwell, T. W., Stappers, B. W., van Leeuwen, J., Cognard, I., Grießmeier, J. -M., Karastergiou, A., Keane, E. F., **Sobey, C**., and Weltevrede, P., LOFAR Discovery of a 23.5 s Radio Pulsar, The Astrophysical Journal, 866, 54

Tetarenko, A. J., **Bahramian, A.**, Wijnands, R., Heinke, C. O., Maccarone, T. J., **Miller-Jones, J. C. A.**, Strader, J., Chomiuk, L., Degenaar, N., Sivakoff, G. R., Altamirano, D., Deller, A. T., Kennea, J. A., Li, K. L., **Plotkin, R. M.**, Russell, T. D., and Shaw, A. W., A Radio Frequency Study of the Accreting Millisecond X-ray Pulsar, IGR J16597-3704, in the Globular Cluster NGC 6256, The Astrophysical Journal, 854, 125

Tetarenko, A. J., Freeman, P., Rosolowsky, E. W., **Miller-Jones, J. C. A**., and Sivakoff, G. R., Mapping jet-ISM interactions in X-ray binaries with ALMA: a GRS 1915+105 case study, Monthly Notices of the Royal Astronomical Society, 475, 448

Tingay, S. J., Tremblay, C. D., and Croft, S., A Search for Extraterrestrial Intelligence (SETI) toward the Galactic Anticenter with the Murchison Widefield Array, The Astrophysical Journal, 856, 31

Tingay, S. J., Kaplan, D. L., Lenc, E., Croft, S., **McKinley, B.**, Beardsley, A., **Crosse, B., Emrich, D**., Franzen, T. M. O., Gaensler, B. M., **Horsley**, L., **Johnston-Hollitt, M., Kenney, D.**, Morales, M. F., Pallot, D., **Steele, K., Trott, C. M., Walker, M., Wayth, R. B., Williams, A.,** and Wu, C., A Serendipitous MWA Search for Narrowband Signals from 'Oumuamua, The Astrophysical Journal, 857, 11

Townsley, L. K., Broos, P. S., Garmire, G. P., **Anderson, G. E.**, Feigelson, Eric D., Naylor, Tim, and Povich, Matthew S., The Massive Star-forming Regions Omnibus X-ray Catalog, Second Installment, The Astrophysical Journal Supplement Series, 235, 43

Tremblay, C. D., Jones, P. A., Cunningham, M., **Hurley-Walker, N., Jordan, C. H., and Tingay, S. J.**, A Molecular Line Survey around Orion at Low Frequencies with the MWA, The Astrophysical Journal, 860, 145

Tremblay, C. D., Jordan, C. H., Cunningham, M., Jones, P. A., and **Hurley-Walker, N.**, Low-Frequency Carbon Recombination Lines in the Orion Molecular Cloud Complex, Publications of the Astronomical Society of Australia, 35, e018

Tremou, E., Strader, J. Chomiuk, L., Shishkovsky, L., Maccarone, T. J., **Miller-Jones, J. C. A., Tudor, V.,** Heinke, C. O., Sivakoff, G. R., Seth, A. C., and Noyola, E., The MAVERIC Survey: Still No Evidence for Accreting Intermediate-mass Black Holes in Globular Clusters, The Astrophysical Journal, 862, 16

Trott, C. M., Jordan, C. H., Murray, S. G., Pindor, B., Mitchell, D. A., **Wayth, R. B., Line, J., McKinley, B.**, Beardsley, A., Bowman, J., Briggs, F., Hazelton, B. J., Hewitt, J., Jacobs, D., Morales, M. F., Pober, J. C., Sethi, S., Shankar, U., Subrahmanyan, R., Tegmark, M., **Tingay, S. J.**, Webster, R. L., and Wyithe, J. S. B., Assessment of Ionospheric Activity Tolerances for Epoch of Reionization Science with the Murchison Widefield Array, The Astrophysical Journal, 867, 15

Tucker, M. A., Shappee, B. J., Holoien, T. W. -S., Auchettl, K., Strader, J., Stanek, K. Z., Kochanek, C. S., **Bahramian, A.**, ASAS-SN, Dong, Subo, Prieto, J. L., Shields, J., Thompson, Todd A., Beacom, John F., Chomiuk, L., ATLAS, Denneau, L., Flewelling, H., Heinze, A. N., Smith, K. W., Stalder, B., Tonry, J. L., Weiland, H., Rest, A., Huber, M. E., Rowan, D. M., and Dage, K., ASASSN-18ey: The Rise of a New Black Hole X-Ray Binary, The Astrophysical Journal, 867, L9

Tudor, V., Miller-Jones, J. C. A., Knigge, C., Maccarone, T. J., Tauris, T. M., **Bahramian, A.**, Chomiuk, L., Heinke, C. O., Sivakoff, G. R., Strader, J., **Plotkin, R. M.,** Soria, R., Albrow, M. D., **Anderson, G. E**., van den Berg, M., Bernardini, F., Bogdanov, S., Britt, C. T., Russell, D. M., and Zurek, D. R., HST spectrum and timing of the ultracompact X-ray binary candidate 47 Tuc X9, Monthly Notices of the Royal Astronomical Society, 476, 1889

Urquhart, R., Soria, R., Johnston-Hollitt M., Pakull, M. W., Motch, C., Schwope, A., **Miller-Jones, J. C. A.**, and **Anderson, G. E.**, Multiband counterparts of two eclipsing ultraluminous X-ray sources in M 51, Monthly Notices of the Royal Astronomical Society, 475, 3561

Vacca, V., Murgia, M., Govoni, F., Loi, F., Vazza, F., Finoguenov, A., Carretti, E., Feretti, L., Giovannini, G., Concu, R., Melis, A., Gheller, C., Paladino, R., Poppi, S., Valente, G., Bernardi, G., Boschin, W., Brienza, M., Clarke, T. E., Colafrancesco, S., Enßlin, T. A., Ferrari, C., de Gasperin, F., Gastaldello, F., Girardi, M., Gregorini, L., **Johnston-Hollitt, M**., Junklewitz, H., Orrù, E., Parma, P., Perley, R., and Taylor, G. B., Observations of a nearby filament of galaxy clusters with the Sardinia Radio Telescope, Monthly Notices of the Royal Astronomical Society, 479, 776

van den Eijnden, J., Degenaar, N., Russell, T. D., **Miller-Jones, J. C. A.**, Wijnands, R., Miller, J. M., King, A. L., and Rupen, M. P., Radio emission from the X-ray pulsar Her X-1: a jet launched by a strong magnetic field neutron star?, Monthly Notices of the Royal Astronomical Society, 473, L141

van den Eijnden, J., Degenaar, N., Russell, T. D., **Miller-Jones, J. C. A.**, Wijnands, R., Miller, J. M., King, A. L., and Rupen, M. P., Discovery of radio emission from the symbiotic X-ray binary system GX 1+4, Monthly Notices of the Royal Astronomical Society, 474, L91

van den Eijnden, J., Degenaar, N., Russell, T. D., Wijnands, R., **Miller-Jones, J. C. A.**, Sivakoff, G. R., and Hernández Santisteban, J. V., An evolving jet from a strongly magnetized accreting X-ray pulsar, Nature, 562, 233

Wang, S., Soria, Roberto, **Urquhart, R.** and Liu, Jifeng, Discovery of two eclipsing X-ray binaries in M 51, Monthly Notices of the Royal Astronomical Society, 477, 3623

K.F. Warnick, R. Maaskant, M.V. Ivashina, D.B. **Davidson, B.D.** Jeffs, ``Phased Arrays for Radio Astronomy, Remote Sensing, and Satellite Communications'', Cambridge University Press, Cambridge, England. 2018. ISBN: 9781108423922.

Wayth, R. B., Tingay, S. J., Trott, C. M., Emrich, D., Johnston-Hollitt, M., McKinley, B., Gaensler, B. M., Beardsley, A. P., **Booler, T., Crosse, B.**, Franzen, T. M. O., **Horsley, L.**, Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Sleap, G., Steele, K., Walker, M., Williams, A.**, Wu, C., Cairns, Iver. H., Filipovic, M. D., Johnston, S., Murphy, T., Quinn, P., Staveley-Smith, L., Webster, R., and Wyithe, J. S. B., The Phase II Murchison Widefield Array: Design overview, Publications of the Astronomical Society of Australia, 35, 33

Weston, S. D., **Seymour, N**., Gulyaev, S., Norris, R. P., Banfield, J., Vaccari, M., Hopkins, A. M., and Franzen, T. M. O., Automated cross-identifying radio to infrared surveys using the LRPY algorithm: a case study, Monthly Notices of the Royal Astronomical Society, 473, 4523

Yan, Q., Xu, Ye, Walsh, A. J., **Macquart, J. P.**, MacLeod, G. C., Zhang, Bo, **Hancock, P. J.,** Chen, Xi, and Tang, Zheng-Hong, Improved selection criteria for H II regions, based on IRAS sources, Monthly Notices of the Royal Astronomical Society, 476, 3981

Yang, M., Bonanos, A. Z., Jiang, B., Gao, J. **Xue, M**., Wang, Shu, Lam, Man I., Spetsieri, Zoi T., Ren, Yi, and Gavras, Panagiotis, Red supergiant stars in the Large Magellanic Cloud. II. Infrared properties and mid-infrared variability, Astronomy and Astrophysics, 616, A175

Zhang, X., **Hancock, P.**, Devillepoix, H. A. R., **Wayth, R. B.**, Beardsley, A., **Crosse, B.**, **Emrich, D.**, Franzen, T. M. O., Gaensler, B. M., **Horsley**, **L.**, **Johnston-Hollitt, M.,** Kaplan, D. L., **Kenney, D.**, Morales, M. F., Pallot, D., **Steele, K., Tingay, S. J., Trott, C. M., Walker, M., Williams, A.**, Wu, C., Ji, Jianghui, and Ma, Yuehua, Limits on radio emission from meteors using the MWA, Monthly Notices of the Royal Astronomical Society, 477, 5167

Zheng, Q., **Johnston-Hollitt, M., Duchesne, S. W.,** and Li, W. T., Detection of a double relic in the Torpedo cluster: SPT-CL J0245-5302, Monthly Notices of the Royal Astronomical Society, 479, 730

Zucca, P., Morosan, D. E., Rouillard, A. P., Fallows, R., Gallagher, P. T., Magdalenic, J., Klein, K. -L., Mann, G., Vocks, C., Carley, E. P., Bisi, M. M., Kontar, E. P., Rothkaehl, H., Dabrowski, B., Krankowski, A., Anderson, J., Asgekar, A., Bell, M. E., Bentum, M. J., Best, P., Blaauw, R., Breitling, F., Broderick, J. W., Brouw, W. N., Brüggen, M., Butcher, H. R., Ciardi, B., de Geus, E., Deller, A., Duscha, S., Eislöffel, J., Garrett, M. A., Grießmeier, J. M., Gunst, A. W., Heald, G., Hoeft, M., Hörandel, J., Iacobelli, M., Juette, E., Karastergiou, A., van Leeuwen, J., McKay-Bukowski, D., Mulder, H., Munk, H., Nelles, A., Orru, E., Paas, H., Pandey, V. N., Pekal, R., Pizzo, R., Polatidis, A. G., Reich, W., Rowlinson, A., Schwarz, D. J., Shulevski, A., Sluman, J., Smirnov, O., **Sobey, C**., Soida, M., Thoudam, S., Toribio, M. C., Vermeulen, R., van Weeren, R. J., Wucknitz, O., and Zarka, P., Shock location and CME 3D reconstruction of a solar type II radio burst with LOFAR, Astronomy and Astrophysics, 615, A89

International peer-reviewed conference proceedings

Baelemans R., Sutinjo A., Smolders B., **Davidson D. B**., Johannsen U., **Wayth R.**, ``Analysis of surface waves modes in planar connected arrays'', paper presented at the 19th International Conference on Electromagnetics in Advanced Applications ICEAA'19, Las Americas Hotel, Cartagena de Indias, Columbia, pp.446 -- 449

Davidson, D.B., Sutinjo, A., Wayth, R., Ung, D., De Villiers, D.I., Gilmore, J., De Vaate, J.G.B., **Baelemans, R.,** and Smolders, A.B., Recent Progress on the Design of Aperture Arrays for Radio Astronomy, IEEE Radio and Antenna Days of the Indian Ocean, RADIO 2018, art. no. 8572328

De Vaate, J.G.B., **Davidson, D.B.** and Wijnholds, S.J., Regular Sparse Arrays: The Impact of Grating Lobes on Radio Astronomical Observations, 2018 2nd URSI Atlantic Radio Science Meeting, AT-RASC 2018, art. no. 8471347

Nguyen, B., Sutinjo, A., and Wayth, R., Analysis of radio frequency interference mitigation using two reference antennas and closure relations in interferometric arrays, Proceedings of the 2018 20th International Conference on Electromagnetics in Advanced Applications, ICEAA 2018, art. no. 8520456, pp. 493-496

Phiri T.J., Kuja S.O., Wiid P.G., **Davidson D.B**., ``Towards full-scale environmental modelling: a UTD hack for finite dielectric ground planes in FEKO'', paper presented at the 19th International Conference on Electromagnetics in Advanced Applications ICEAA'19, Las Americas Hotel, Cartagena de Indias, Columbia , pp.~348--351.

Steeb J.-W., **Davidson D. B**. , Wijnholds S.J., `` Mitigation of Non-Narrowband Radio Frequency Interference'', paper presented at the 2nd URSI AT-RASC, Gran Canaria

Books

D.B. Davidson, A. Sutinjo, R. Wayth, D. Ung, J.G. bij de Vaate, D.I.L. de Villiers, J. Gilmore, **R. Baelemans**, A.B. Smolders, ``Recent Progress on the Design of Aperture Arrays for Radio Astronomy'', IEEE Radio 2018 conference, Mauritius, pp.1-2.

Staff Profiles

Directors

1. Prof Steven Tingay
   Executive Director

2. Mr Tom Booler
   Director, Operations

3 Prof David Davidson
   Director, Engineering

4. Prof Melanie Johnston-Hollitt
   Director, MWA

5. A/Prof James Miller-Jones
   Director, Science

Staff

6. Dr Gemma Anderson
   Discovery Early Career Researcher

7. Dr Arash Bahramian
   Research Associate

8. Dr Ramesh Bhat
   Senior Research Fellow

9. Mr Timothy Bumbak
   MWA Electronics Technician

10. Dr Rajan Chhetri
    Research Associate

11. Ms Evelyn Clune
    Adminstrative Officer

12. Mr Brian Crosse
    Instrument Engineer, Signal Chain

1

2

3

4

5

6

7

8

9

10

11

12

Image Credits: ICRAR

Staff Profiles

13. Dr Guillaume Drouart
    Research Associate

14. Ms Angela Dunleavy
    Administrative Coordinator

15. Mr David Emrich
    Instrument Engineer, Site Operations

16. Dr Paul Hancock
    Early Career Research Fellow

17. Dr Gregory Hellbourg
    Senior Research Fellow

18. Mr Luke Horsley
    Engineering Support Technician

19. Dr Natasha Hurley-Walker
    Early Career Research Fellow

20. Dr Clancy James
    Research Fellow

21. Ms Emily Johnson
    Administrative Officer

22. Mr Jake Jones
    Engineering Graduate Intern

23. Dr Christopher Jordan
    Research Associate

24. Dr Budi Juswardy
    Research Engineer

13

14

15

16

17

18

19

20

21

22

23

24

Image Credits: ICRAR

Staff Profiles

25. Dr Adela Kawka
    Senior Research Fellow

26. Mr David Kenney
    Senior Technical Officer

27. Dr Jack Line
    Research Associate

28. Dr Christene Lynch
    Research Associate

29. Dr Jean-Pierre Macquart
    Senior Research Fellow

30. Dr Ben McKinley
    Research Fellow

31. Mr Andrew McPhail
    Fieldwork Coordinator

32. Dr John Morgan
    Research Fellow

33. Mr Joel Morris
    MWA Site Hand

34. Dr Ian Morrison
    Research Fellow

35. Dr Steven Murray
    Research Associate

36. Dr Nipanjana Patra
    Research Fellow

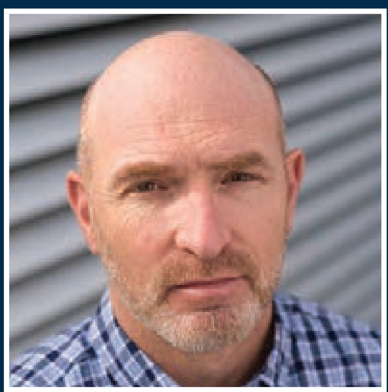
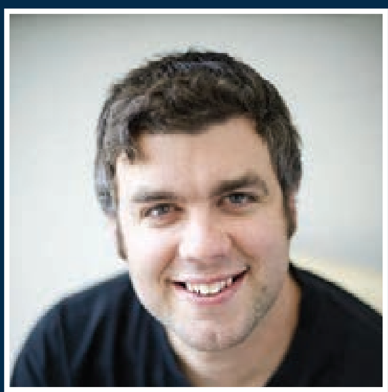

25

26

27

28

29

30

31

32

33

34

35

36

Image Credits: ICRAR

Staff Profiles

37. Dr Richard Plotkin
    Senior Research Fellow

38. Ms Tina Salisbury
    Operations Coordinator

39. Dr Nick Seymour
    Senior Lecturer

40. Ms Teresa Slaven-Blair
    ASTRO 3D Outreach Support Officer

41. Mr Greg Sleap
    MWA Data Manager

42. Dr Charlotte Sobey
    Research Associate

43. Dr Marcin Sokolowski
    Research Fellow

44. Ms Kimberly Steele
    Engineering Graduate Intern

45. Dr Adrian Sutinjo
    Senior Lecturer

46. Mr Jonathan Tickner
    Senior Technical Officer

47. Dr Steven Tremblay
    Research Fellow

48. A/Prof Cathryn Trott
    Associate Professor

37

38

39

40

41

42

43

44

45

46

47

48

Image Credits: ICRAR

Staff Profiles

49. Mr Daniel Ung
    Support Engineer, Aperture Array

50. Ms Mia Walker
    Project Officer

51. A/Prof Randall Wayth
    Associate Professor

52. Mr Malcolm Whinfield
    MWA Electronics Technician

53. Dr Sarah White
    Research Associate

54. Dr Andrew Williams
    Instrument Engineer, Monitor & Control

49

50

51

52

53

54

Image Credits: ICRAR

Student Profiles

1. Mr Wayne Arcus
   PhD

2. Ms Pikky Atri
   PhD

3. Mr Rene Baelemans
   PhD

4. Mr James Buchan
   PhD

5. Mr Elliott Charlton
   Honours

6. Mr Jaiverdhan Chauhan
   PhD

7. Mr Jaiden Cook
   Honours

8. Mr Stefan Duchesne
   PhD

9. Mr Brendan Hennessy
   PhD

10. Mr Torrance Hodgson
    PhD

11. Mr Rabah Abdul-Jabbar Jasem
    PhD

12. Mr Ronniy Joseph
    PhD


1


2


3


4


5


6


7


8


9


10


11

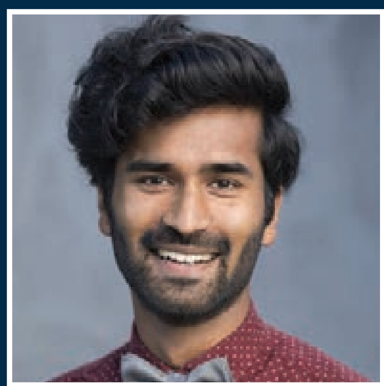

12

Image Credits: ICRAR

Student Profiles

13. Ms Dilpreet Kaur
    PhD

14. Mr Do Won Kim
    PhD

15. Mr Michael Kriele
    PhD

16. Mr Sammy McSweeney
    PhD

17. Mr Bradley Meyers
    PhD

18. Ms Seema Morab
    PhD

19. Ms Ainulnabilah Nasuruin
    PhD

20. Mr Bach Nguyen
    PhD

21. Mr Steve Raj Prabu
    Masters

22. Ms Haihua Qiao
    PhD

23. Mr Benjamin Quici
    Honours

24. Mr Matthew Ryan
    Honours


13

14

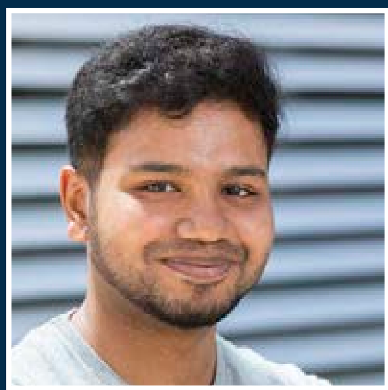
15

16

17

18

19

20

21

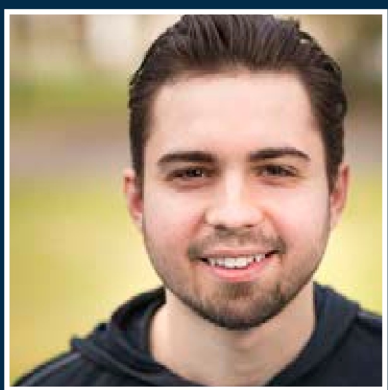
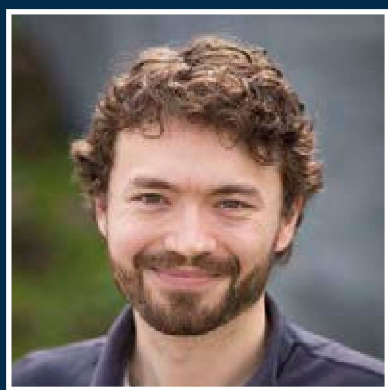
22

23

24

Image Credits: ICRAR

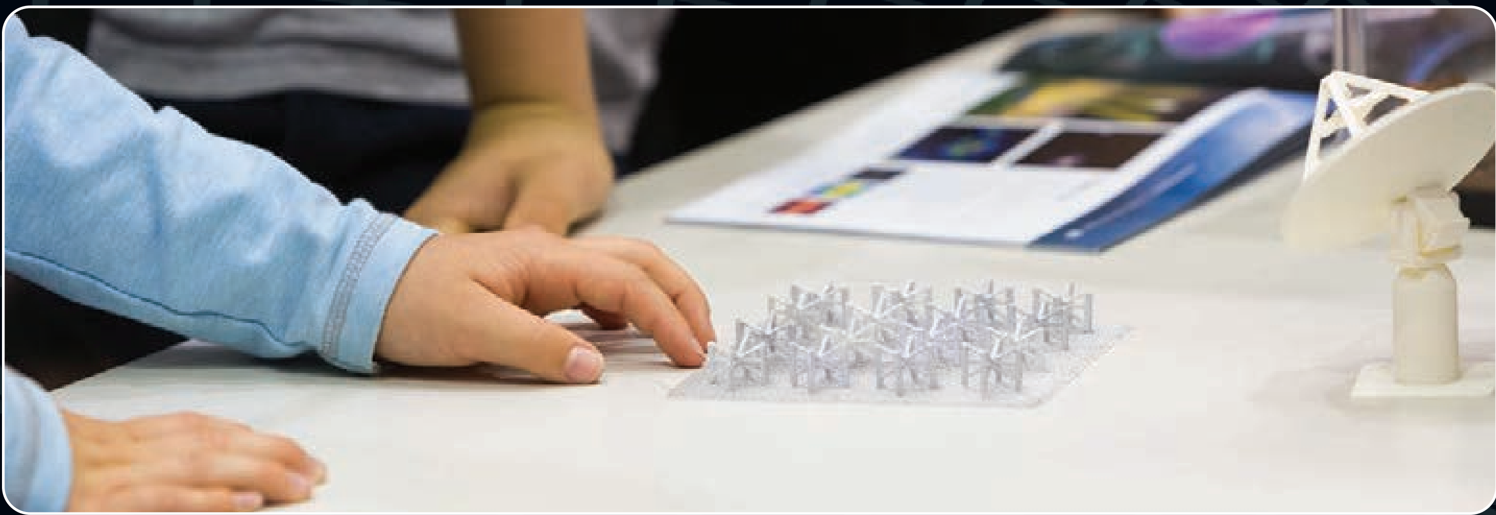
Student Profiles

25. Ms Erica Thygesen
    Honours
26. Mr Hongquan Su
    PhD
27. Mr Nicholas Swainston
    PhD
28. Ms Chenoa Tremblay
    PhD
29. Mr Vlad Tudor
    PhD
30. Mr Daniel Ung
    Masters
31. Mr Ryan Urquhart
    PhD
32. Mr Alexander Williamson
    PhD
33. Ms Mengyao Xue
    PhD
34. Mr Qingzeng Yan
    PhD
35. Ms Xiang Zhang
    PhD

Curtin University

CIRA

CURTIN INSTITUTE OF RADIO ASTRONOMY



2018

ANNUAL REPORT

Contact Us:
Curtin Institute of Radio Astronomy
Curtin University.
Postal Address:
GPO Box U1987 Perth WA 6845
Tel: +61 8 9266 9899
Fax: +61 8 9266 9246
Email: cira@curtin.edu.au
Street Address:
Building 610 - 1 Turner Avenue,
Technology Park, Bentley WA 6102

Curtin University