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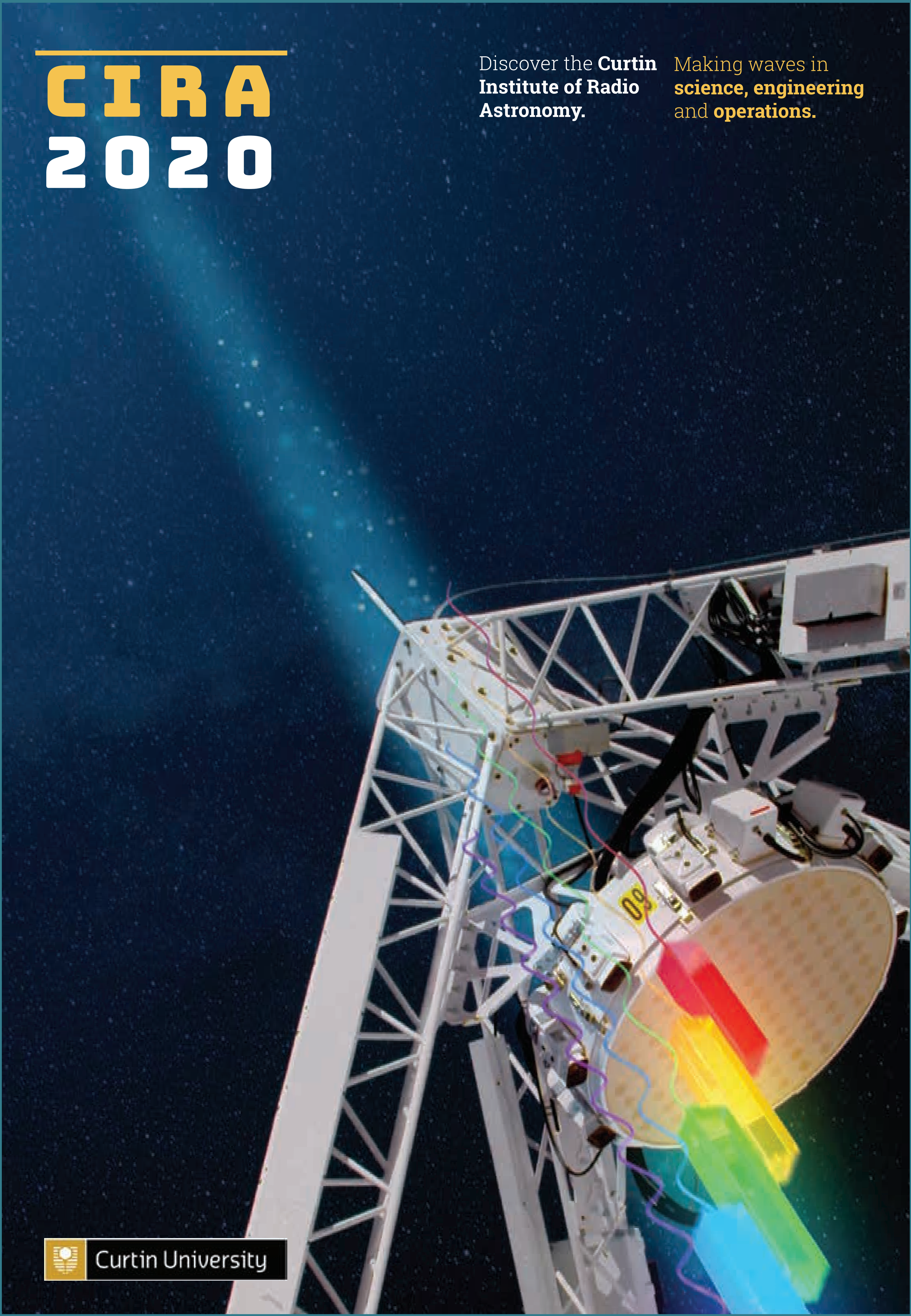

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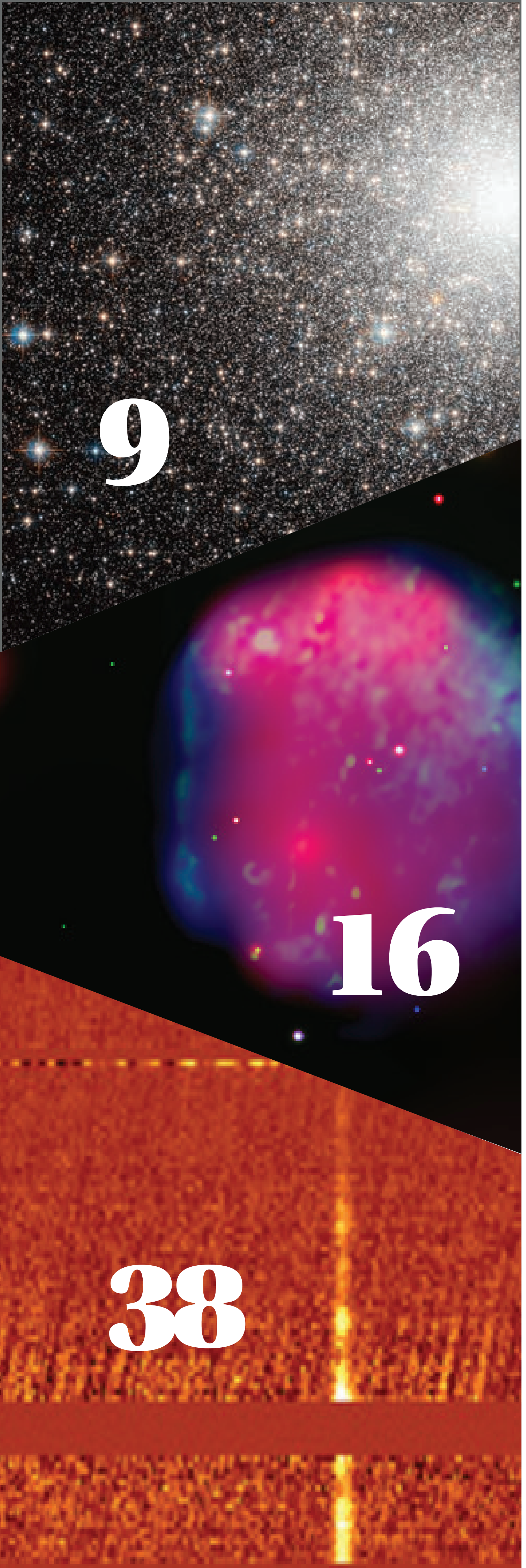

SUMMARY

This annual report covers the calendar year 2020.

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Cover Images
Front: CSIRO’s ASKAP measures the delay between the wavelengths of the FRB, allowing astronomers to calculate the density of the missing matter.
Credit: ICRAR and CSIRO/Alex Cherney

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DIRECTOR'S REPORT

A challenging year, **faced together**

Professor Steven Tingay
CIRA Executive Director

The year 2020 was certainly of a type few, if any, of us have previously experienced. The COVID-19 pandemic affected every part of the world and so many facets of our existence, and continues to do so. While in Australia, and particularly in Western Australia, we have been well managed and fortunate not to have experienced what some other parts of the world have experienced, there is no doubt that the disruption in 2020 was significant.

The University sector in Australia has been challenged across the board. Dealing with the pandemic response during 2020, in terms of the health and safety of staff and students, required hard work. And in the on-going aftermath of 2020, hard decisions have been made in the sector across Australia. At Curtin University, we have generally come through 2020 in relatively good shape, although those hard decisions have been made here as well. 2021 and 2022 are likely to remain challenging.

At CIRA, we experienced all of the things the rest of the broader community and the University community experienced. The first half of 2020 contained many extended moments of stress and anxiety for many people, including at CIRA. With a high percentage of our staff and students with families overseas, anxiety and stress were often amplified by distance and separation.

I have been very proud of the way CIRA carried itself through 2020, despite some challenging moments. I think most people played their part to see us through in the best way possible. Never perfect, because nothing is ever perfect, but almost everyone pulled together in a very constructive manner. I extend that to the broader University senior management. Everyone did their best and the empirical fact is that the results are impressive. Everyone remained safe, those who needed support got it, and our teaching and research activities continued to function.

Beyond my general appreciation to the group, there are many people I would like to thank. I would like to thank my colleagues on the CIRA Executive team, for the constructive contributions they made throughout the year, in particular Tom Booler. I'd like to thank Christene Lynch, who was Chair of DevCom during this period, who ended up with a fair bit on her plate. I'd like to thank everyone who has been involved in undergraduate teaching, for their move to online teaching in 2020 at unprecedented speed, and for rolling with the punches since then. Maintaining effective teaching is obviously a core priority for a university, and it was great to see the commitment from our staff in this regard.

Of course, along the way we lost our valued colleague and friend, Jean-Pierre Macquart, in tragic and unexpected circumstances. This hit us all hard and it will be an honour to continue to remember JP, including through the establishment of a new PhD scholarship in his name. Our thoughts are, and will be, with JP's wife Sherine and their children.

The last part of 2020 saw CIRA in a scattered state, even after COVID-19 lockdowns finished, due to the refurbishment of our building. So, it seemed that the upheavals never really came to an end in 2020. I'm sure everyone needed that break over the summer.

But, while 2021 still brings COVID-19 concerns, CIRA is extremely well placed to continue to prosper. The building refurbishment is complete and we are settling in. SKA construction is due to commence in 2021, and the Australian Government has committed an additional $387M to the project. We are currently writing contracts with the SKAO for Curtin's participation in the SKA construction program, over the coming decade. CONTINUED-

Above: Prof Steven Tingay at the filming of 'Star Tracks.' Image credit: ICRAR

CIRA's programs are all going along very strongly, Curtin is in good shape overall, and ICRAR continues to enjoy strong support from The University of Western Australia, Curtin University, and the State Government.

The MWA is being upgraded and will continue to be an important asset for global radio astronomy in preparation for the SKA, over most of the rest of this decade. Via our Translation and Impact program, we are finding new avenues for the unique skills mix at CIRA, including in space applications and, increasingly, in Defence research.

The remainder of this decade looks exciting for us, despite recent challenges. It will be an opportunity rich environment for our staff and students, for CIRA, and for our university. I'm certainly looking forward to 2021 and beyond, for these reasons and more.

MURCHISON WIDEFIELD ARRAY

The end of an era **with the MWA telescope**

Professor Melanie Johnston-Hollitt
MWA Director

2020 was a big year for everyone for different reasons. For the MWA it was a year that tested the flexibility and ingenuity of the team as we dealt with working from home whilst maintaining the core services of the observatory. It was also a year in which the design, planning, and funding for the new MWA correlator, MWAX, was completed. Both of these things were heroic efforts conducted by a small, tight-knit team, who continue to provide a level of service and professionalism which is seriously impressive and have put the MWA on an excellent path forward.

The response to COVID saw the team perform a business continuity assessment for MWA services, produce a transition to remote work plan, and enact that plan, all within a week. As a result, the MWA suffered no interruptions to service during COVID. Despite the difficulties of working in a pandemic, there were a number of highlights for the project in 2020 including improved ASVO services, site operations, monitoring and control, and numerous repairs and refits. However, the standout achievement was the completion of the design and planning for the new MWAX correlator. MWAX is a joint project across CIRA involving members of the MWA and Engineering teams. The MWAX team comprised of Ian Morrison, Brian Crosse, Greg Sleap, Mia Walker, Andrew Williams and I, assisted by Andy McPhail and Dave Emrich completed a comprehensive set of design, planning, procurement, and scheduling documents which were assessed by external experts from Astronomy Australia Limited (AAL) and an internally run Critical Design Review (CDR) panel. Both the AAL Project Oversight Committee and the CDR Panel commended the team for MWAX, and the CDR was successfully completed in December. Furthermore, the NCRIS funding application I submitted in May 2019 for $1 million to cover the costs of MWAX was announced in December, removing the last hurdle for project. MWAX is due to be installed in 2021 and to commence operations later in the year, which will mark the commencement of Phase III of the MWA. In addition, the AAL Board indicated Australian NCRIS Operating funding would continue at the present level of 1.495 million pa for the next two years until mid 2023.

In terms of MWA personnel, 2020 saw some changes to both Operations and Management the teams with new hires and changes of personnel. Firstly, we again expanded the Operations Team with new additions; Harrison Barlow as the new ASVO Web Developer, and Phillip Giersch as the MWA Technician. Both Harry and Phil came on board in March about a week before the COVID-19 shutdown that commenced in Western Australia. Harry effectively commenced his role remotely as the team transitioned to working from home for several months. Meanwhile Phil commenced his role on vital MWA maintenance in the lab of a building which was almost deserted, except for a skeleton staff who needed continued access. Despite this they integrated into the team flawlessly and both contributed significantly to operations. Finally, Derwent McElhinney was hired to join the Ops Team in support of the Australian SKA Regional Centre Design Study. Derwent will join the MWA team at the beginning of 2021.

On the Management side 2020 saw some temporary shuffling of the team with Mia Walker stepping into the role of MWA Program Manager replacing Tom Booler whilst he was seconded to the SKAO in early 2020, and from mid-year Brian Crosse as Acting Principal Engineer whilst Randall Wayth was on long service leave. Tom and Randall will both return to their management roles in 2021 but I am indebted to Mia and Brian for picking up these roles in 2020 and the dedication and professionalism they showed in the process. Finally, Luke Pratley (Toronto) transitioned from the role of deputy to Principal Scientist replacing Adam Beardsley (ASU).

CONTINUED-

Above, from left to right: Professor Chris Moran, Mrs Sherine Macquart, Professor Melanie Johnston-Hollitt and Curtin University Provost, Professor John Cordery. Photo taken at the 2020 Research and Engagement Awards, at which Johnston-Hollitt spoke about the late Associate Professor Jean-Pierre (JP) Macquart. Credit: Curtin

CIRA staff and students continue to dominate publications using MWA data, leading 60% of the refereed journal articles and contributing to 84% of the total MWA publications. In particular, the Galactic and Extragalactic group at CIRA were the most active publishers of MWA data in 2020 and generated the most press coverage for MWA publications.

This marks the end of my 3-year term as MWA Director and the end of 9 years associated with the high-level management of the MWA. I depart the MWA Team along with Rike McLernon, to move to the Curtin Institute of Computation where we continue our respective roles as director and administrator, albeit in a slightly larger context. I leave the MWA on the brink of a new phase with a new correlator, an expanded collaboration, an enlarged operations team (8.3FTE compared to 4.9 FTE when I started as director in 2018), a firm financial footing with operations funding for the next two years, and with my best wishes for its continued success. As I said in my final presentation to the MWA Collaboration as director, the MWA is a collective success and everyone across the collaboration should take pride in it, but most especially people at Curtin, not just the Ops Team, or indeed the staff and students at CIRA, but everyone at Curtin who has played a role in making the MWA what it is. I look forward to seeing what will happen next!

CIRA's science team **continues to achieve**

Professor James Milller Jones
CIRA Science Director

The CIRA Science group experienced a rollercoaster of a year in 2020, with a number of notable highlights, a tragic loss, and the challenges of dealing with a global pandemic. I am extremely proud of the way that the team faced up to the challenges and supported one another through some very difficult periods, and I extend my thanks to all of our staff and students.

The highlight of the year was the culmination of a decade's worth of work, with Jean-Pierre Macquart and the CRAFT team publishing a lead-author paper in Nature that presented their use of Fast Radio Bursts to measure the density of the intergalactic medium. This attracted significant worldwide media attention at the time, and has continued to have a huge scientific impact within the community over the subsequent months. However, elation turned to tragedy within a few days with the untimely passing of Jean-Pierre. His loss was deeply felt by the group, and indeed by the worldwide astronomical community, and we continue to extend our deepest sympathies to his young family.

The ongoing pandemic restrictions compounded the difficulties of dealing with such a blow, and extended into many other facets of CIRA's activities. While I am grateful to the entire group for their flexibility and forbearance during a rapidly-changing situation, my particular thanks go to our teaching and supervisory teams for transitioning so quickly and effectively to an online delivery mode. Ensuring the wellbeing of our students and the provision of high-quality education is paramount for any University academic, and I'm grateful for the very significant effort that went into ensuring that these key activities could continue as smoothly as they did. To underline the scope (and success) of these efforts, the CIRA Science team continued to remotely supervise almost two dozen HDR students (culminating in three completions) and several undergraduates, and taught into 10 undergraduate coursework units, even winning an award for teaching delivery.

CIRA's scientific research also continued unabated, and it is to the great credit of the staff and students in the group that despite the significant disruptions to our working patterns, we were able to maintain our high level of research output. The team published 124 papers in 2020, with four high-profile media releases demonstrating the impact of the group's research. This excellent work (much of which is summarized in the following pages) was also reflected in awards, both internal and external. Most notably, I congratulate Steven Tingay on being named the joint winner of the prestigious Scientist of the Year category at the WA Premier's Science Awards, in recognition of his many contributions to radio astronomy in WA over the past decade and more.

Another challenging aspect of 2020 was the restriction on movement, which disrupted travel plans and hindered our ability to recruit new staff and students from overseas. Nonetheless, we welcomed several new domestic arrivals, and look forward to others joining us from further afield once restrictions begin to ease. With ARC grant success and the attraction of a Forrest Fellow and a Forrest PhD scholar, the science team will be strengthened over the coming months, and can look forward to continuing its excellent work across the full suite of its teaching, research and engagement activities over the year ahead.

Revealing the large population of accreting **white dwarfs**, **neutron stars** and **black holes** in Galactic globular clusters

ARASH BAHRAMIAN
Research Fellow

Globular clusters are dense old spherical collections of millions of stars orbiting revolving around the center of galaxies over billions of years. The high population density and old age of these clusters makes them ideal environments for compact dead remnants of stars (like white dwarfs, neutron stars and black holes which have strong gravitational fields) to run into other stars in the cluster and form exotic binary star systems in which the compact object can accrete matter from the companion star. The study of these systems is exciting for two main reasons: First, these compact objects are among the most elusive and poorly understood objects in the universe, particularly neutron stars and black holes. Second, formation and evolution of these binaries vary from cluster to cluster, linked to clusters' evolution history. This connection helps us better understand the history of star formation and cluster evolution in our Galaxy going back billions of years. These exciting questions motivated us to start a thorough observational study of these binaries in the star clusters in our Galaxy. Over 150 GCs are known in our Galaxy, providing us with a rich sample to explore. Through our study, we managed to discover and catalog more than 1000 such binaries and candidates in a sample of 38 Galactic globular clusters and characterize some of their behaviors for the first time. This included discovery of new black hole candidates and unusual spinning neutron stars. We also showed that some of these exotic binaries are extremely short-lived (perhaps only tens/hundreds of thousands of years, compared to the billion year lifespans of other binaries) and that energetic white dwarf binaries are substantially less common than previous studies predicted. Our published study and catalog has now paved the path to a large-scale exploration of these compact objects and how star clusters evolve over billions of years.

Source: ui.adsabs.harvard.edu/abs/2020ApJ...901...57B

Below, left: M54, Credits: ESA/Hubble & NASA.
Below, right: M62, Credits: NASA, ESA, STScI, and S. Anderson (University of Washington) and J. Chaname (Pontificia Universidad Católica de Chile).

These are two of dozens of star clusters from this study. M62 is a rather large star cluster hosting numerous accreting binaries. M54 is a very unusual cluster that over its long life has interacted with one of Milky way's satellite dwarf galaxies and the impact of those interactions on the cluster and its population of neutron stars and black holes is an exciting prospect. In our study, we identified multiple energetic (i.e., bright X-ray emitting) binaries that may host black holes.

SCIENCE

> “The detection of extragalactic transients affords us an entirely new and sensitive probe on the huge reservoir of baryons in the intergalactic medium.”

CLANCY JAMES
Senior Research Fellow

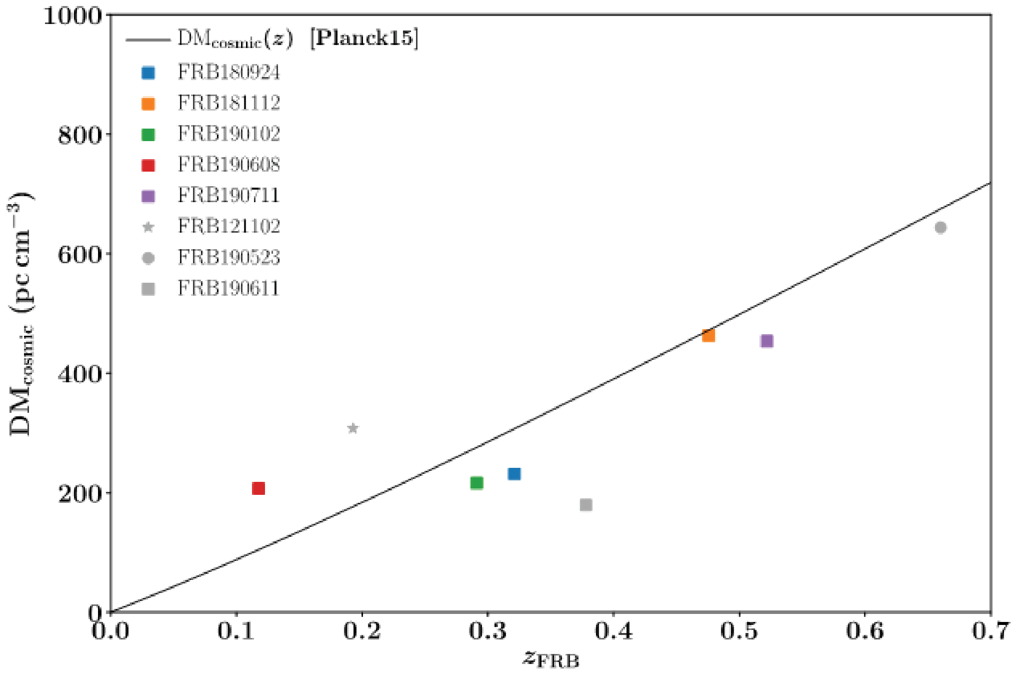
So wrote A/Prof Jean-Pierre Maquart in a submission to the ASKAP survey science projects, published in 2009. At that point in history, the only known sub-second extragalactic radio transient was the Lorimer Burst, discovered in 2007 using data from the Parkes radio telescope recorded in 2001 – and there was much debate about whether or not this was even a real astronomical signal.

Since then, many such bursts – now known as “fast radio bursts”, or FRBs - have been detected. These bursts are identified by their characteristic dispersion measure, or DM. Similarly to how light travels more slowly through water, radio waves travel more slowly through the very diffuse, ionized gas between stars and galaxies. This dispersion delay produces a characteristic sweep where the signal arrives first at high frequencies, then at lower frequencies. Measuring the delay directly probes the total amount of ionized gas between the source and the observer.

At the forefront of FRB research has been the Commensal Real-time ASKAP Fast Transients (CRAFT) survey, using the Australian Square Kilometre Array Pathfinder. Since 2018, CRAFT has been localizing FRBs to sub-arcsecond resolution, allowing their host galaxies to be identified, and their redshifts – and thus their distance – to be measured with optical telescopes such as Keck in Hawaii and the Very Large Telescope (VLT) in Chile. By the beginning of 2020, CRAFT had measured the redshifts of six FRB host galaxies, extending out to z=0.522. And as it turns out, this was enough data to solve the “missing baryon problem”.

Measurements of the microwave background radiation tell us that baryonic matter (i.e. normal matter made of atoms - the same stuff we find around us on Earth) makes up a bit less than 5% of the energy density of the Universe. However, when astronomers try to locate this matter in the local Universe by summing up contributions from stars and gas, tens of percent of it is missing – this is known as the “missing baryons problem”. Previously, microwave and x-ray observations had detected some of this gas in the form of hot, diffuse filaments linking galaxies together. However, the large fraction expected to reside in voids between galaxies remained undetected.

The figure below shows a plot of the dispersion measure – redshift (DM-z) relation found from the host galaxies of FRBs localized by the CRAFT collaboration. CONTINUED-

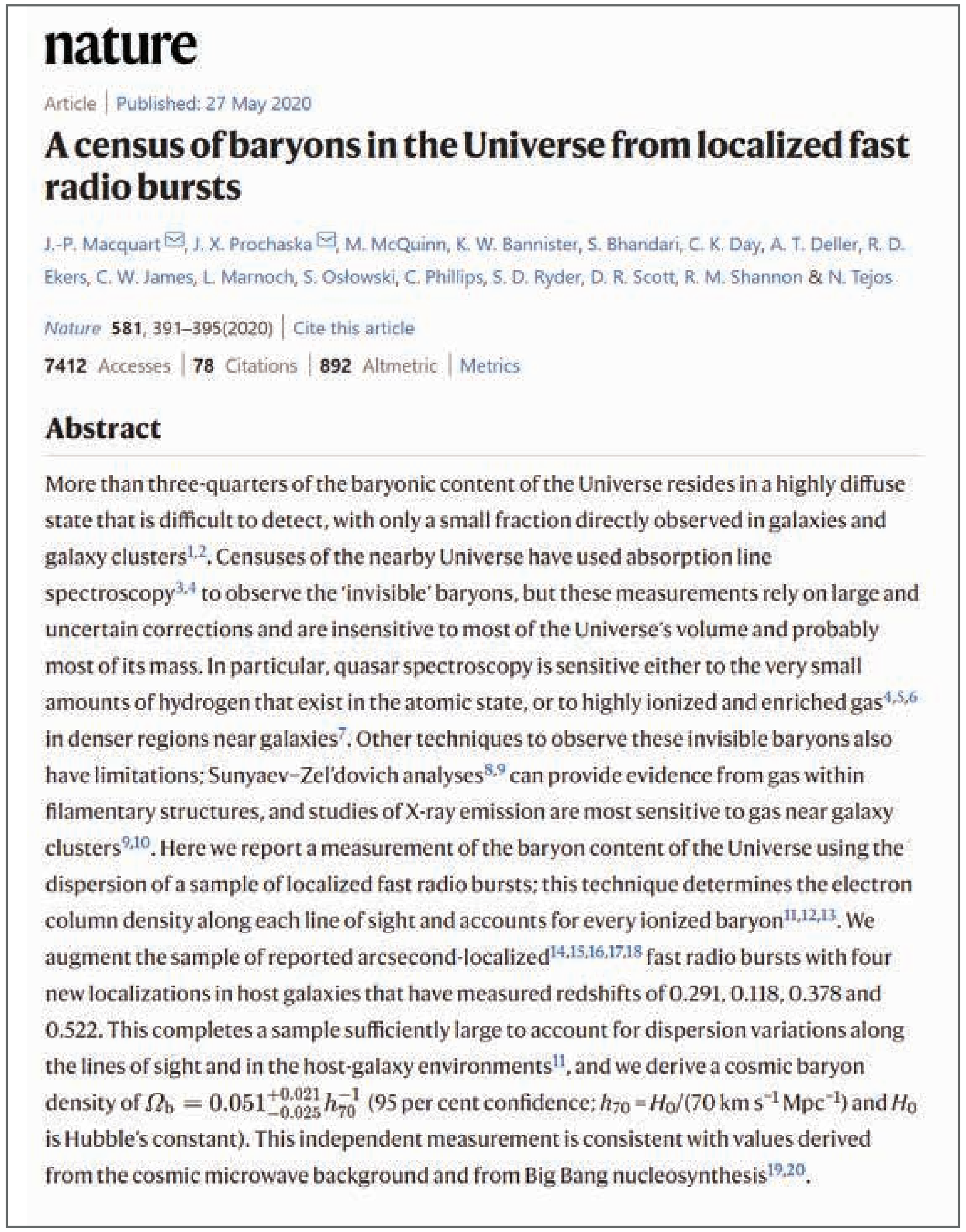


Left: the Macquart (DM-z) relation. Points are localized fast radio bursts – squares are those localized by the CRAFT team. The black line shows the predicted relation from standard cosmology. The FRB host galaxies confirm the prediction.

The amount of matter in the Universe is reflected in the slope of the line – total matter (DM) is simply density multiplied by distance (redshift). The best-fit value found for FRBs matches, to within errors, that predicted by current cosmological models. This DM-z relation – now known as the “Macquart Relation” in honour of its discoverer, Jean-Pierre Macquart – was published on the 27th of May 2020 in the journal Nature, vindicating the prediction made eleven years earlier.

As reported in last year’s Annual Report, Jean-Pierre (J-P as he was known) passed away only two weeks later, on June 9th 2020. His sudden loss gutted the group at Curtin. As well as being a world-leading astrophysicist and driving force behind the CRAFT collaboration, Jean-Pierre was a friend, mentor and personal inspiration for those working with him. In particular, Freya North-Hickey, Mawson Sammons, and David Scott had recently begun their PhD research under his supervision, having worked with J-P since their summer research projects in 2017/2018.

Despite this tragedy, J-P himself would be the first person to want FRB research at CIRA to continue at full pace. His legacy continues to live on - his Discovery Project Solving the origin of ultra-luminous emission from fast radio bursts was funded by the ARC, while a team including him and four other CIRA authors were awarded the prestigious Newcomb Cleveland prize by the American Association for the Advancement of Science for the paper A single fast radio burst localized to a massive galaxy at cosmological distance. We look forward to the many more exciting results remaining to be discovered.


nature

Article | Published: 27 May 2020

A census of baryons in the Universe from localized fast radio bursts

J.-P. Macquart, J. X. Prochaska, M. McQuinn, K. W. Bannister, S. Bhandari, C. K. Day, A. T. Deller, R. D. Ekers, C. W. James, L. Marnoch, S. Osłowski, C. Phillips, S. D. Ryder, D. R. Scott, R. M. Shannon & N. Tejos

Nature **581**, 391–395(2020) | Cite this article

7412 Accesses | **78** Citations | **892** Altmetric | Metrics

Abstract

More than three-quarters of the baryonic content of the Universe resides in a highly diffuse state that is difficult to detect, with only a small fraction directly observed in galaxies and galaxy clusters[1,2]. Censuses of the nearby Universe have used absorption line spectroscopy[3,4] to observe the ‘invisible’ baryons, but these measurements rely on large and uncertain corrections and are insensitive to most of the Universe’s volume and probably most of its mass. In particular, quasar spectroscopy is sensitive either to the very small amounts of hydrogen that exist in the atomic state, or to highly ionized and enriched gas[4,5,6] in denser regions near galaxies[7]. Other techniques to observe these invisible baryons also have limitations; Sunyaev–Zel’dovich analyses[8,9] can provide evidence from gas within filamentary structures, and studies of X-ray emission are most sensitive to gas near galaxy clusters[9,10]. Here we report a measurement of the baryon content of the Universe using the dispersion of a sample of localized fast radio bursts; this technique determines the electron column density along each line of sight and accounts for every ionized baryon[11,12,13]. We augment the sample of reported arcsecond-localized[14,15,16,17,18] fast radio bursts with four new localizations in host galaxies that have measured redshifts of 0.291, 0.118, 0.378 and 0.522. This completes a sample sufficiently large to account for dispersion variations along the lines of sight and in the host-galaxy environments[11], and we derive a cosmic baryon density of $\Omega_{\mathrm{b}} = 0.051^{+0.021}_{-0.025}\,h_{70}^{-1}$ (95 per cent confidence; $h_{70} = H_0/(70\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$ and H_0 is Hubble’s constant). This independent measurement is consistent with values derived from the cosmic microwave background and from Big Bang nucleosynthesis[19,20].

MWA reveals new details of the nearest radio galaxy: **Centaurus A**

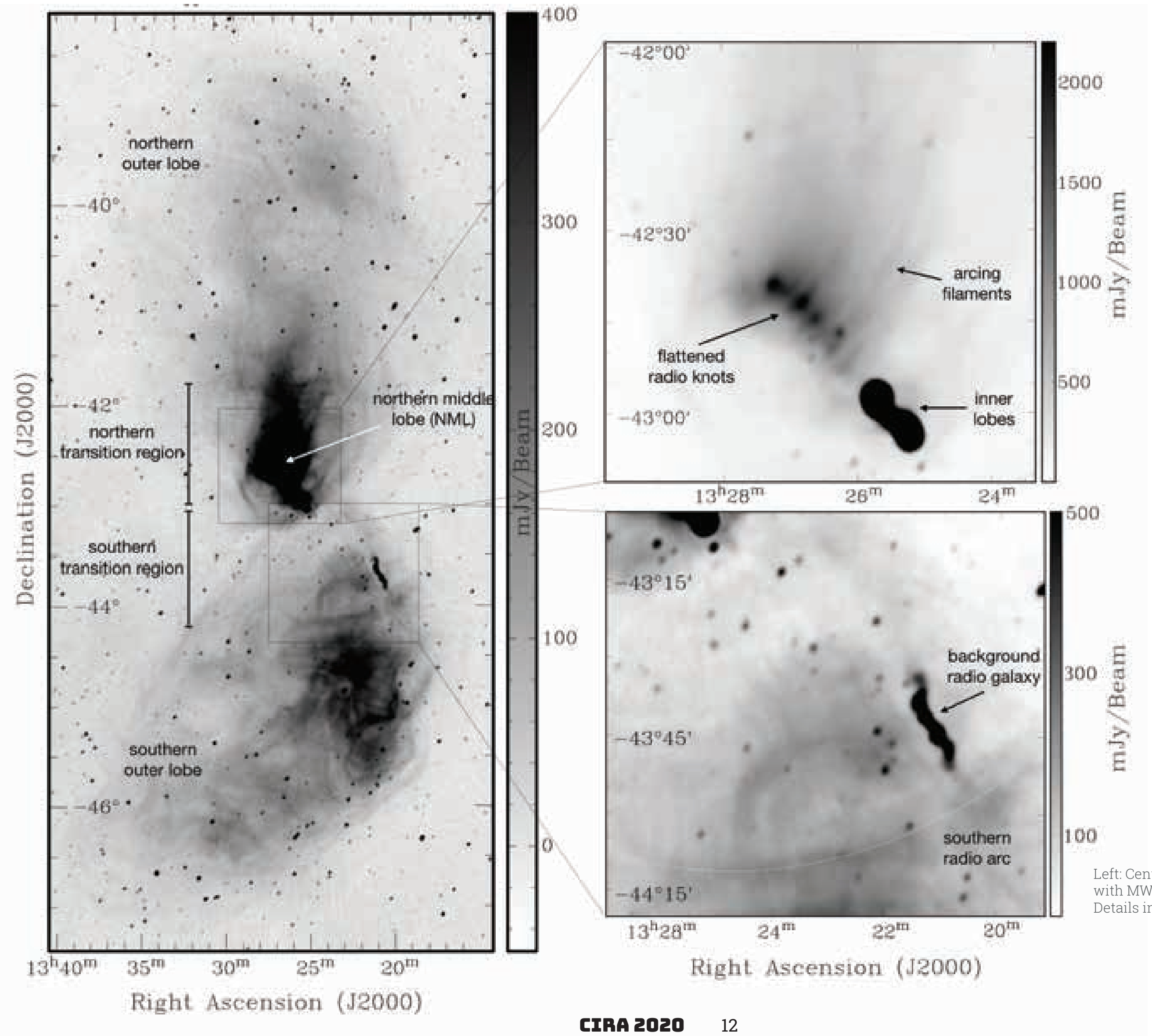
BEN MCKINLEY
Research Fellow

The bright, low-frequency emission from radio galaxies is powered by matter being sucked in toward the central supermassive black hole and spewed back out into space in both fast, narrow jets and wider, slower winds and outflows. These outflows change the way the galaxies evolve and in turn, shape the very structure of the Universe on cosmic scales. Centaurus A is uniquely close to us (at roughly 15 million light years, just a stone's throw away) and appears as a huge structure on the sky, spanning eight degrees at its longest extent (that is 16 full Moons across). This presents both a major opportunity to study the all-important galactic inflows and outflows up close and in extreme detail, and a big challenge caused by the galaxy's angular size and huge range in radio brightness.

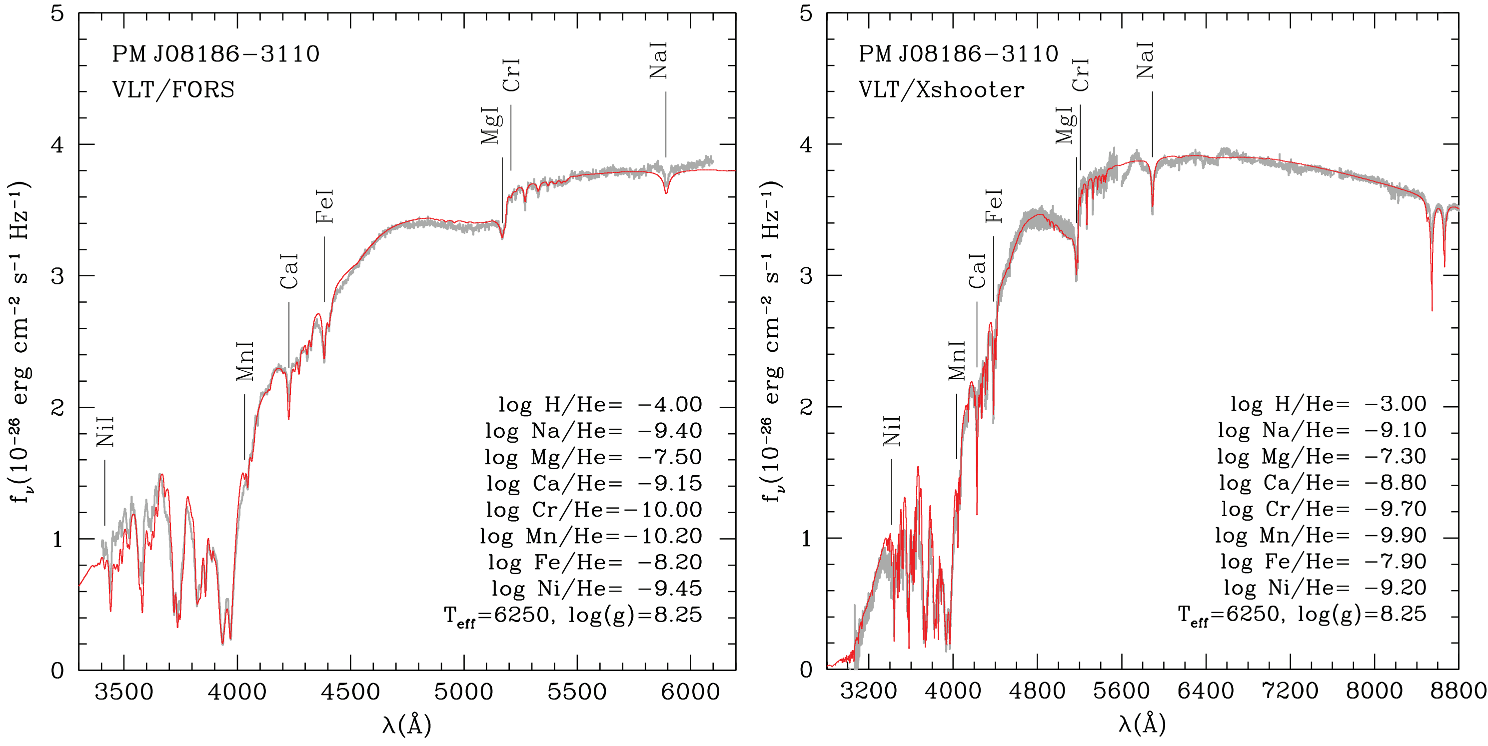
In 2020, a team led by Dr Benjamin McKinley took advantage of the new Phase-2 extended configuration of the Murchison Widefield Array (MWA) telescope to make the most detailed images of Centaurus A (in its entirety) to date. The image, shown below, revealed never-before-seen features of the crucial 'transition regions', where energy is being transported out via a broad outflow from the central black hole. Other telescopes have lacked the wide field of view and antenna coverage on the ground required to accurately capture these new details. By combining MWA data from both Phase 1 (with better sensitivity to large structures on the sky, such as the outer lobes), and Phase 2 (with superior angular resolution), the image shown below was produced. Centaurus A is shown at its full extent in the left panel, showing the faint and complex filamentary structures of the outer lobes. A zoom-in on the Northern Middle Lobe region (top right panel), shows flattened radio knots and arcing filaments that have not been seen before and provide evidence for an outflow towards the north. To the south (bottom right panel), there is a surprisingly empty area bordered by a 'southern radio arc', which likely represents the radius at which the southern component of the outflow is strongly interacting with the surrounding galactic environment.

With the hard work done to produce such a spectacular image, 2021 will be all about trying to extract the astrophysical information that, when studied in combination with other data across a wide range of frequencies and scales, will allow the team to learn about galaxy evolution and the effects of galactic outflows throughout the Universe.

> **"The image revealed never-before-seen features of the crucial 'transition regions.'"**



Left: Centaurus A imaged with MWA during Phase 2. Details in article text.



Above, left: FORS1 spectrum (grey) compared to the best-fitting model spectrum (red) with tabulated model parameters and abundances.
Above, right: Same as left-handed panel but for the X-shooter spectrum (grey)..

A nearby magnetic cool white dwarf with a **polluted atmosphere**

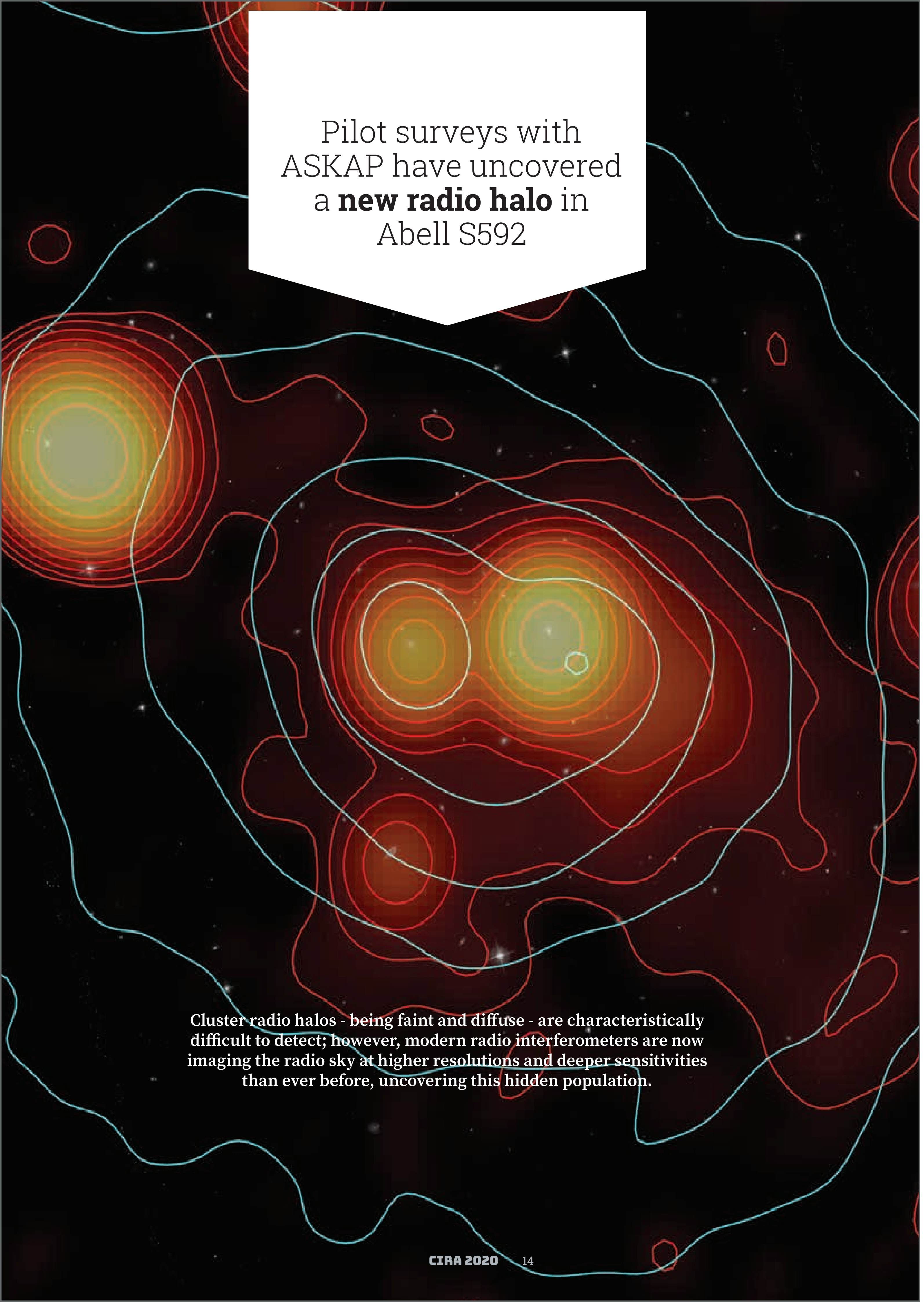
ADELA KAWKA
Senior Research Fellow

White dwarfs are compact stars that are no longer burning any fuel and they are the final phase in the life of most stars. The majority of white dwarfs possess a hydrogen-rich atmosphere while the remainder have a helium-rich atmosphere. Due to the high surface gravity of white dwarfs, heavy elements are expected to sink below the photosphere after a period of time much shorter than evolutionary time-scales. However, about a third of white dwarfs show the presence of elements heavier than helium such as calcium, magnesium, aluminium, and iron. We now know that these elements are accreted from planetary and asteroidal debris.

One of these white dwarfs is the cool and magnetic PMJ08186-3110 for which we conducted an analysis of high signal-to-noise spectra obtained with the FORS2 and the X-shooter spectrographs attached to the 8 m telescopes at the European Southern Observatory. Our spectroscopic analysis found PMJ08186-3110 to have a helium-rich atmosphere polluted with several heavy elements. This analysis required us to include state-of-the-art line opacities for very dense atmospheres including quasi-molecular Ca-He and Mg-He. It has an effective temperature of 6250 K and a mass of 0.72 solar masses. Our spectroscopic analysis also showed that the abundance of heavy elements is variable (Kawka et al. 2021, MNRAS, 500, 2732). A magnetic field of 92 kG was revealed through the Zeeman splitted spectral lines. The abundance variations are most likely due to the magnetic field, which can create abundance spots that are revealed as the white dwarf rotates. PMJ08186-3110 is among a growing number of cool and polluted white dwarfs that also harbour a magnetic field.

By exploring polluted white dwarfs within the Solar neighbourhood, we found that the incidence of magnetism is much higher among cooler stars. Within 20 pc, where the white dwarf population is complete and where PMJ08186-3110 lies, the incidence of magnetism is 40% for white dwarfs with effective temperatures below 7000 K. There are no magnetic counterparts for hotter white dwarfs. When extending this volume to all known polluted white dwarfs, most magnetic cases have an effective temperature below 7000 K, with only a handful up to 8500 K, and no magnetic polluted white dwarfs above this temperature. This deficit of hot and therefore young magnetic and polluted white dwarfs poses a challenge of how these stars acquired a magnetic field. One proposed scenario is that an old white dwarf encounters and collides with a gaseous planet causing differential rotation in the white dwarf envelope generating a weak magnetic field. The chance of a stellar encounter increases with the age of a white dwarf and therefore older white dwarfs are more likely to have had a stellar or planetary encounter than hot, young white dwarfs.

Pilot surveys with ASKAP have uncovered a **new radio halo** in Abell S592



Cluster radio halos - being faint and diffuse - are characteristically difficult to detect; however, modern radio interferometers are now imaging the radio sky at higher resolutions and deeper sensitivities than ever before, uncovering this hidden population.

AMANDA WILBER
Associate Lecturer

Radio observations over the last several decades have revealed that some galaxy clusters host a giant halo of radio emission filling their inner volume. These Megaparsec-scale radio halos are thought to be generated when two galaxy clusters collide and merge into one. Such a merger event produces turbulence that dissipates throughout the intracluster medium, accelerating electrons to relativistic energies and amplifying the cluster magnetic field.

Several factors are still being investigated to explain the vast nature of these radio structures, such as the efficiency of merger-induced turbulence, the strengths of intracluster magnetic fields, and sources of energetic electrons in the intracluster medium. It is predicted that the next generation of all-sky radio surveys, such as the Evolutionary Map of the Universe (EMU) Survey, will reveal an order of magnitude more radio halos than were previously detected. Uncovering and analysing this population of radio halos will allow for abundant statistical studies of galaxy clusters, revealing critical facts about the formation and evolution of matter and Dark Matter in the Universe.

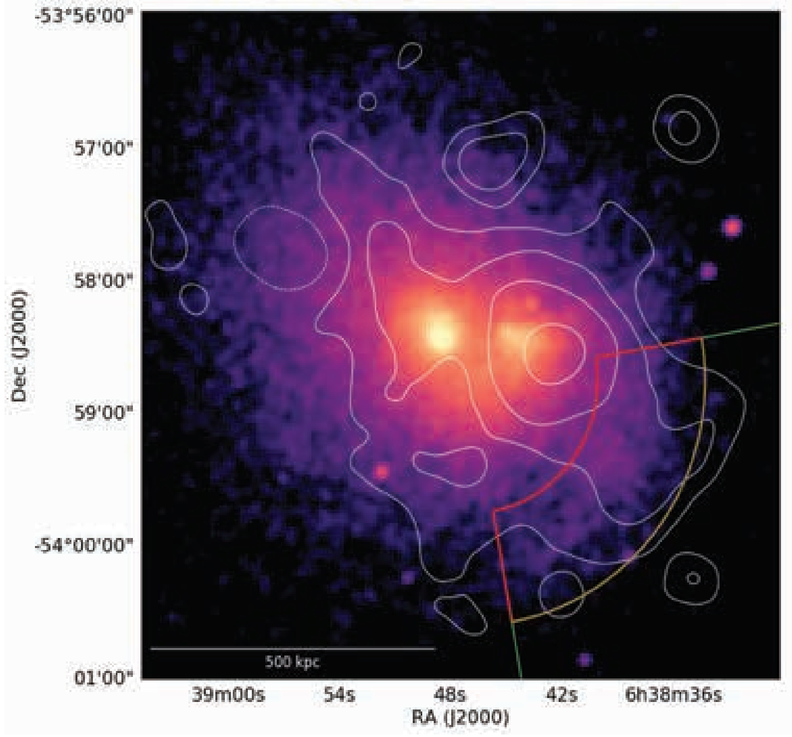
The Australian Square Kilometer Array Pathfinder (ASKAP), located at the Murchison Widefield Observatory, is known for its innovative Phased Array Feeds which make it possible to observe a full 30-square-degree field of the sky at high resolution in just one day. In 2019, ASKAP Early Science and EMU Pilot Survey observations were carried out for a total of ten fields. Our “Clusters & Cosmic Web” team at CIRA browsed these EMU Pilot Survey images to search for faint, diffuse structures associated with galaxy clusters which are diagnostic of radio halos. In Wilber et al., 2020, PASA, 37, e040, we presented an analysis of a radio halo not previously detected in the merging cluster Abell S592 based on clear signs of diffuse emission originating from the intracluster medium.

Chandra X-ray images of Abell S592 revealed that the cluster is undergoing a bullet-type merger (Pandge M. B. et al., 2017, MRNAS, 472, 2042) and showed a large-scale merger shockfront at the southwestern edge of the cluster (Botteon A., Gastaldello F., Brunetti G., 2018, MNRAS, 476, 5591). To perform an enhanced analysis of the diffuse radio emission in this cluster, we carried out direction-dependent calibration and imaging on the publicly available ASKAP data. After this improved calibration, we were able to separate compact components of radio emission from central active galactic nuclei (AGN) to bring out the structure of the underlying diffuse radio emission. We classified this diffuse emission as a newly discovered radio halo and suggested that it is fed by seed electrons originating from cluster AGN. We also uncovered that the radio halo exhibits a sharp edge coincident with the shockfront seen in X-rays.

Discovering a new radio halo in Abell 592 from the ASKAP pilot data illustrates the massive potential ASKAP holds in the analysis of the estimated higher population of radio halos. Furthermore, the results from this study suggest that the upcoming EMU survey may reveal many more examples where diffuse cluster sources are clearly fed by remnant AGN emission. As we utilise the upcoming ASKAP EMU Survey for statistical studies of galaxy clusters, it is encouraging to contemplate what further knowledge we will gain about the large-scale structure of matter and Dark Matter in the Universe.

Far left: Composite image of Abell S592. Red emission represents our ASKAP image after direction-dependent calibration. Several resident galaxies in the cluster have active galactic nuclei, however, there are clear signs of diffuse radio emission emanating from the intracluster medium. Cyan contours represents the X-ray signal of hot gas in the cluster. Credit: Wilber et al., 2020, PASA, 37, e040

Right: X-ray image of Abell S592 shows that the cluster is undergoing bullet-type merger. Contours overlaid represent the underlying signal of the radio halo detected by ASKAP after removing the compact emission of the central active galactic nuclei. Credit: Wilber et al., 2020, PASA, 37, e040



Finding **new supernova remnants** in X-ray and radio

NATASHA HURLEY-WALKER
Senior Research Fellow

Supernova remnants form when massive stars end their lives and collapse, or white dwarfs accrete mass from companion stars; in both cases, an enormous spherical shockwave is created, transmitting huge amounts of energy, neutrinos, and heavy elements into the surrounding interstellar medium. As the shockwave propagates outward, fast-moving electrons spiral around magnetic fields, and produce spheres of radio emission, with a hot interior of ejecta and debris producing prominent X-ray emission. Thus, supernova remnants are most often detected by radio and X-ray surveys.

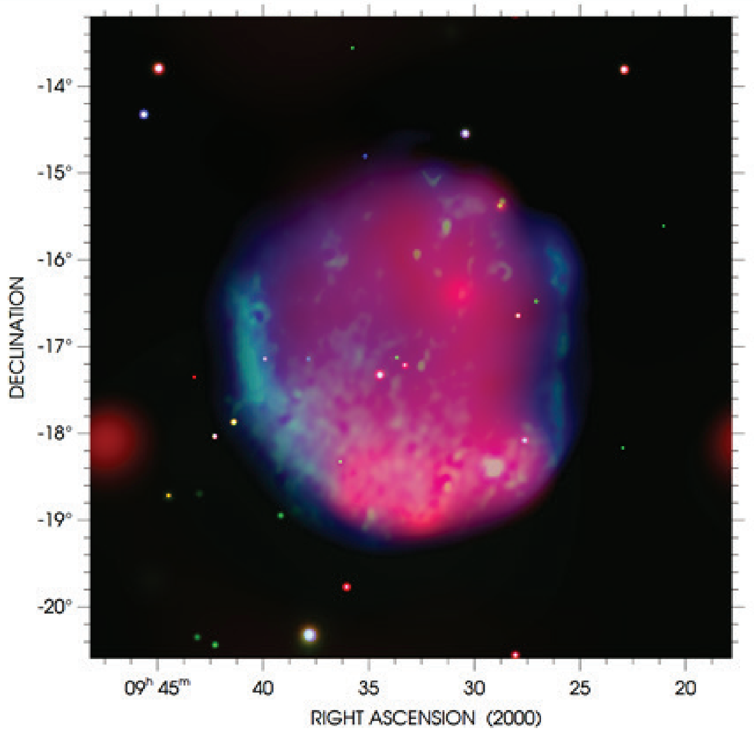
One of the biggest mysteries in Galactic astrophysics is the gap between the expected number of supernova remnants, and those detected by astronomers. From studies of the Magellanic Clouds, and counting massive stars in our own galaxy, we predict that about 1,200 supernova remnants should be visible, tracing the last hundred thousand years of massive star formation and death. However, despite decades of searching, only about 300 supernova remnants are known. It is important to discover and understand these objects, because they contribute so much to the interstellar medium, including the elements which eventually go on to form solar systems like our own.

The eROSITA telescope, which is onboard the Russian-German SRG satellite, is a new X-ray instrument, and is performing an all-sky survey. In 2020, Dr Natasha Hurley-Walker worked with Astronomy Australia Limited (AAL) to form a collaboration with the eROSITA team, including scientists from the Max Planck Institute for Extraterrestrial Physics and the National Institute for Astrophysics. This joint Australian-eROSITA partnership was established to explore our Galaxy using multiple wavelengths, from low-frequency radio waves to energetic X-rays. By combining expertise across multiple wavelengths, the team plans to search for hundreds of supernova remnants. In particular, the GLEAM-X survey offers a very complementary view to that of eROSITA.

Unexpectedly, only a few months into the project, the team were surprised to detect a new supernova remnant; not only that, it is the largest supernova remnant ever discovered via X-rays, in terms of apparent size: about 90 times larger than the full moon. The object, dubbed “Hoinga”, was then found in radio surveys up to ten years old, including some performed by the Murchison Widefield Array. Demonstrating the complementarity of the radio and X-ray data, the radio observations made it possible to work out that it is a middle-aged remnant relatively close to Earth, calculations that would have been far less accurate with the X-ray data alone.

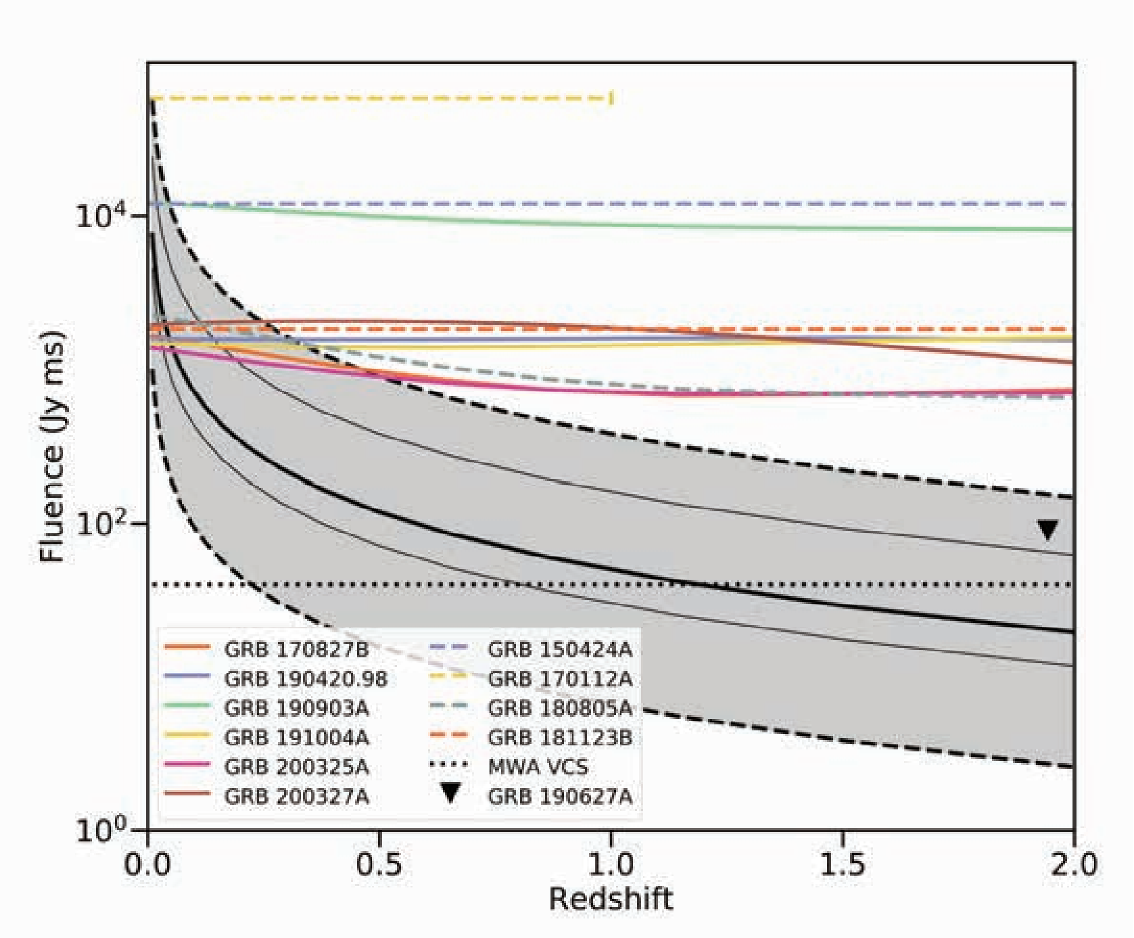
The reason it had been missed by previous searches was its position high above the plane of the Milky Way, and the fact that it is so large, so its flux density is spread out over a large area. Supernova remnants are also not typically expected to be found at high Galactic latitudes so these areas are not usually the focus of surveys, meaning there may be even more of these overlooked remnants out there waiting to be discovered by the Australian-eROSITA collaboration, helping to solve this long-standing astrophysical mystery.

Led by Professor Werner Becker from the Max Planck Institute for Extraterrestrial Physics, with Dr Luciano Nicastro from the National Institute for Astrophysics, the study ‘Hoinga – A Supernova Remnant Discovered in the SRG/eROSITA All-Sky Survey eRASS1’ was published in journal ‘Astronomy & Astrophysics’ and is available online.



Source: ui.adsabs.harvard.edu/abs/2021A%26A...648A..30B

Left: Composite X-ray (red) and radio (blue) image of Hoinga. The X-rays discovered by eROSITA are emitted by the hot debris of the exploded progenitor, whereas the radio antennae detect synchrotron emission from relativistic electrons, which are decelerated at the outer remnant layer. Credit: eROSITA/MPE (X-ray), CHIPASS/SPASS/N. Hurley-Walker, ICRAR-Curtin (Radio)



Above: The predicted range in brightness (fluence) of radio flashes from short GRBs (black curves and grey shaded region). Over-plotted are the brightness upper limits on radio flashes as a function of distance (redshift) from short GRBs observed by MWA (and also LOFAR; GRBs 170112A and 181123B). The best limit on this emission to date is from MWA observations of GRB 190627A (black triangle), which has a known redshift of z=1.9.

Based on results in Anderson et al. (2021), PASA, accepted (arXiv:2104.14758) and Tian et al., in prep.

Rapid observations of **cosmic explosions** with the MWA

GEMMA ANDERSON
Research Fellow

JUN TIAN
PhD Candidate

The exploding or “transient” Universe is an extremely dynamic, where massive stars explode as supernovae to form unusual remnants. In order to study the very earliest radio light emitted by “transient” astronomical events, we need to ensure we have telescopes observing them before their radiation fades away forever. When space-based telescopes detect a transient, they broadcast its coordinates down to Earth. We have set up the Murchison Widefield Array (MWA) to automatically and rapidly repoint at an explosion within 20 seconds of its discovery.

The MWA “rapid-response mode” triggers observations on bursts of bright gamma-ray light known as short gamma-ray bursts (GRBs), which are detected by the space telescope Swift. Short GRBs, which outshine their galaxy and are observable from across the Universe for just a few seconds are produced by the merger of two neutron stars. Neutron stars are the dense remnants left over from supernovae (exploding massive stars) that are made entirely of neutrons. They are the size of a small city but weigh nearly twice as much as our Sun – one teaspoon of neutron star material would weigh 4 billion tons! When two neutron stars merge, we also expect them to emit a bright flash of radio light within the first seconds to minutes. Using the MWA rapid-response mode, we can search for these radio signals from short GRBs. Such a detection would tell us that neutron stars can be much bigger than we originally thought possible before they then collapse into a black hole, thus giving us previously unknown insight into the behaviour and nature of dense matter on the quantum level.

We have used the MWA rapid-response mode to search for these radio flashes from 10 short GRBs and have developed a new data analysis technique that make us more sensitive to these signals, which become smeared out over time and frequency just like fast radio bursts. While no signal has been detected in these data, up to 8 of the short GRBs studied should have been detected based on current theoretical models, shown in the image above. This in itself is an exciting result as it may indicate that many of our theories of dense matter may be wrong. Future MWA rapid-response observations will still use the high time-resolution mode (the Voltage Capture System or VCS), which will be much more sensitive to any radio flashes associated with short GRBs.

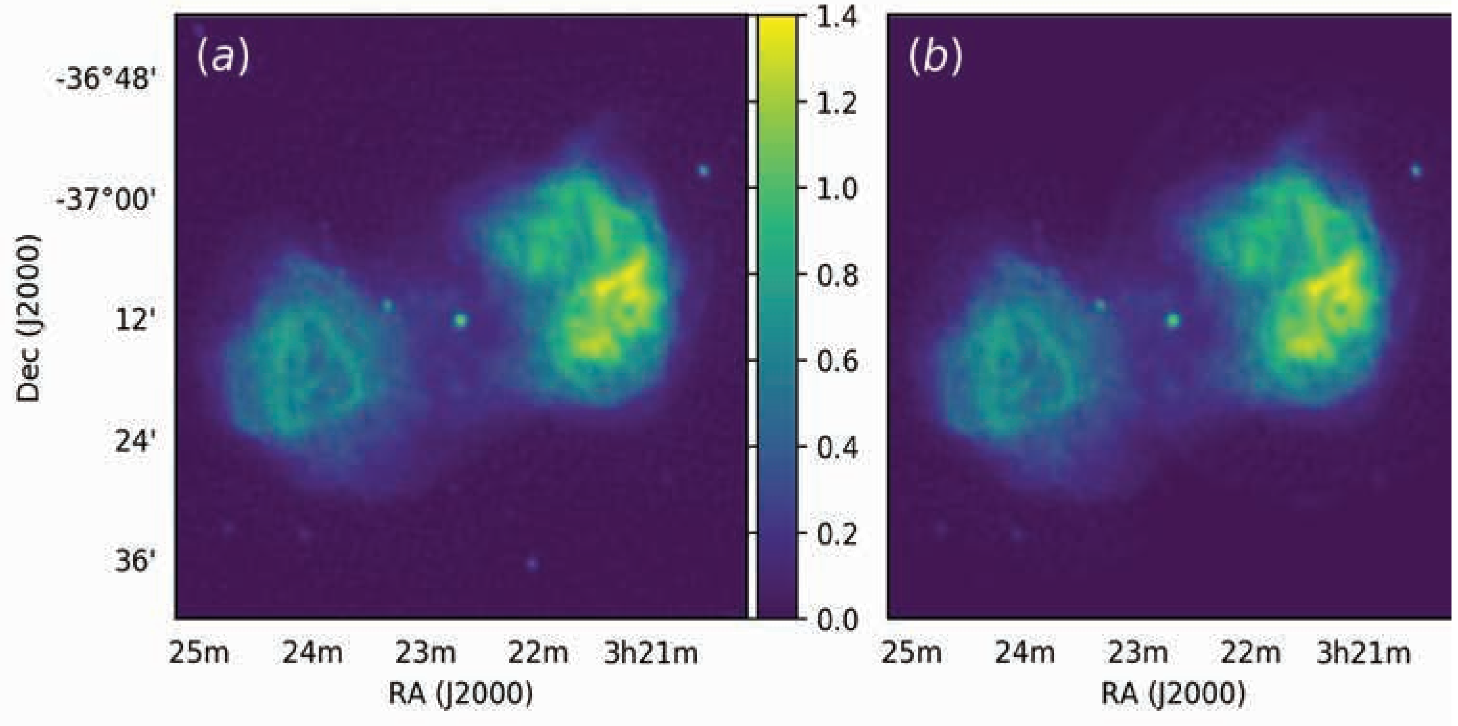
For more than a decade, astronomers have been trying to witness the effects of the very first stars to exist in the Universe. Trouble is, **the rest of the Universe in the way**.

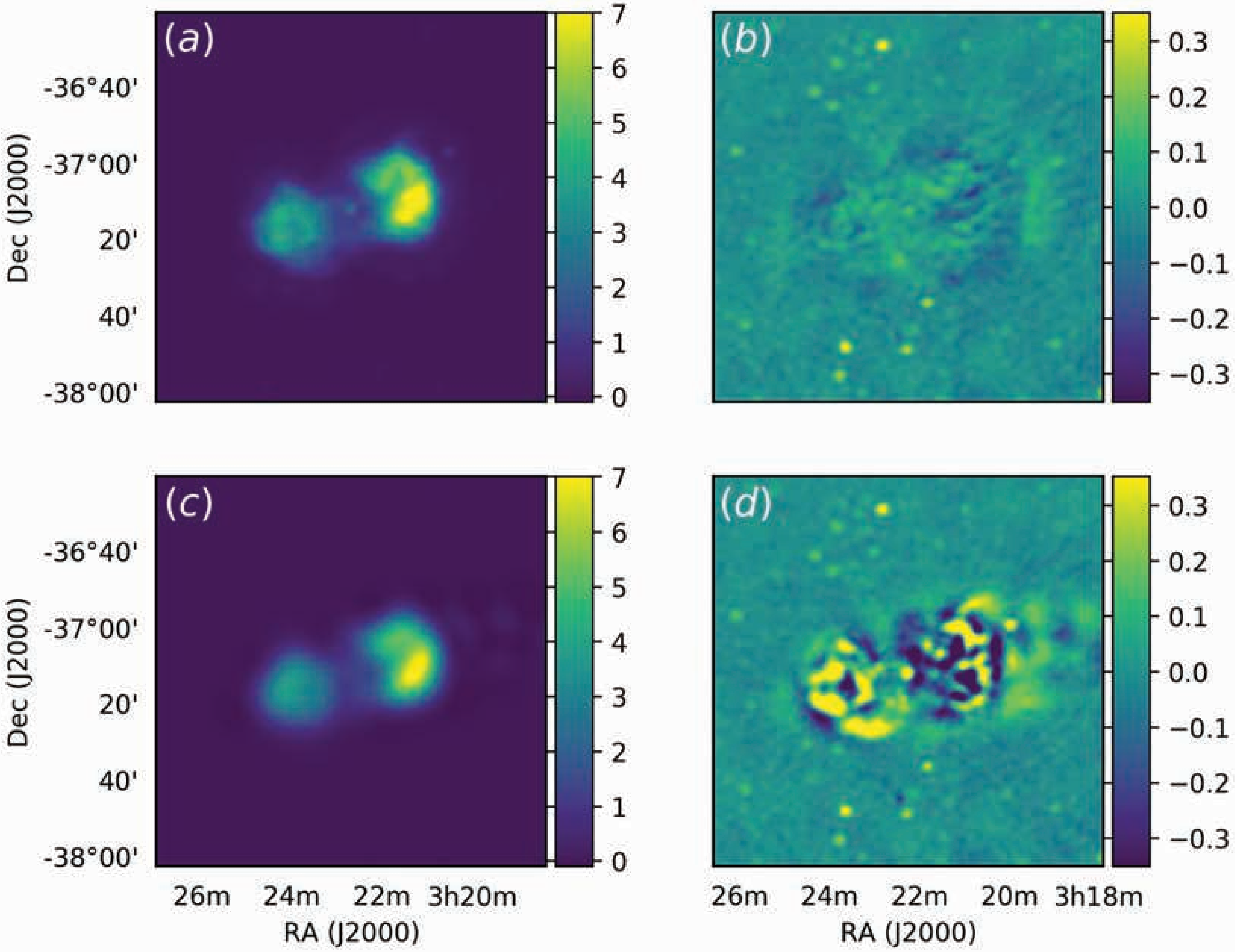
JACK LINE
Research Fellow

The period of time when the first stars switched on is called the Epoch of Reionisation (EoR), because those first luminous sources were embedded in neutral hydrogen, which they began to ionise by emitting UV radiation. As neutral hydrogen emits at 21-cm, if we can observe a lack of this radiation, we can infer the presence of these first stars.

Unfortunately, this all happened around 13 billion years ago. During this time the Universe evolved to contain a wealth of complicated structures, many of which block the emission from neutral hydrogen. One such source is Fornax A (see Figure 1). To observe the EoR 21cm signal, sources like this must be expunged from our data. We do this via subtraction, which requires an extremely accurate model of the galaxy. In work published in 2020, we produced such a model using 'shapelets', which is a departure from standard point source / gaussian modelling, using large predefined 2D layers to build up a model. You can see the improvement on our old model in Figure 2.

Below: Figure 1 – (a) Fornax A as imaged by the MWA in Phase I and II configurations; (b) Our shapelet model. Credit: Line 2020

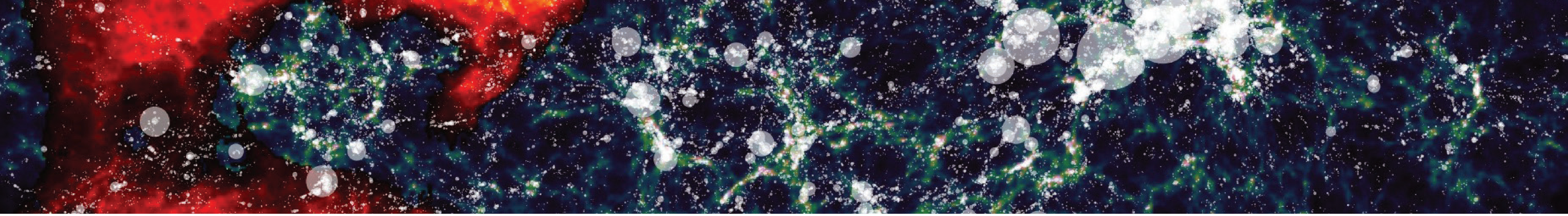




Above: Figure 2 – (a) New Fornax A model as seen by MWA Phase I; (b) New model subtracted from MWA data; (c) Old Fornax A model; (d) Old Fornax A model subtracted from MWA data. Credit: Line 2020

We compared our new model to one produced by the imaging software WSClean, made up of more traditional point source / gaussian model components. We found that the shapelet model consistently subtracted well on the largest angular scales, which is important to the EoR as we expect the 21cm signal to exist there. To test the computational efficiency, we built new GPU based code to simulate MWA observations. We found that generating shapelet models took similar compute resources. Importantly, point source models can be thought of as making up a galaxy from pixels of an image. If you need to make a higher resolution image from that model, you get 'pixelisation effects', where you can see the resolution of the original image. Shapelets don't suffer from this problem. We think this will be important for future telescopes with high angular resolution, such as the upcoming SKA-LOW.

"Point source models can be thought of as making up a galaxy from pixels of an image."



Above: The evolution of the Epoch of Reionisation from the DRAGONS simulations. Credits: Paul Geil & Simon Mutch (The University of Melbourne).

Constraining conditions in the Universe **13 billion years ago** with the MWA

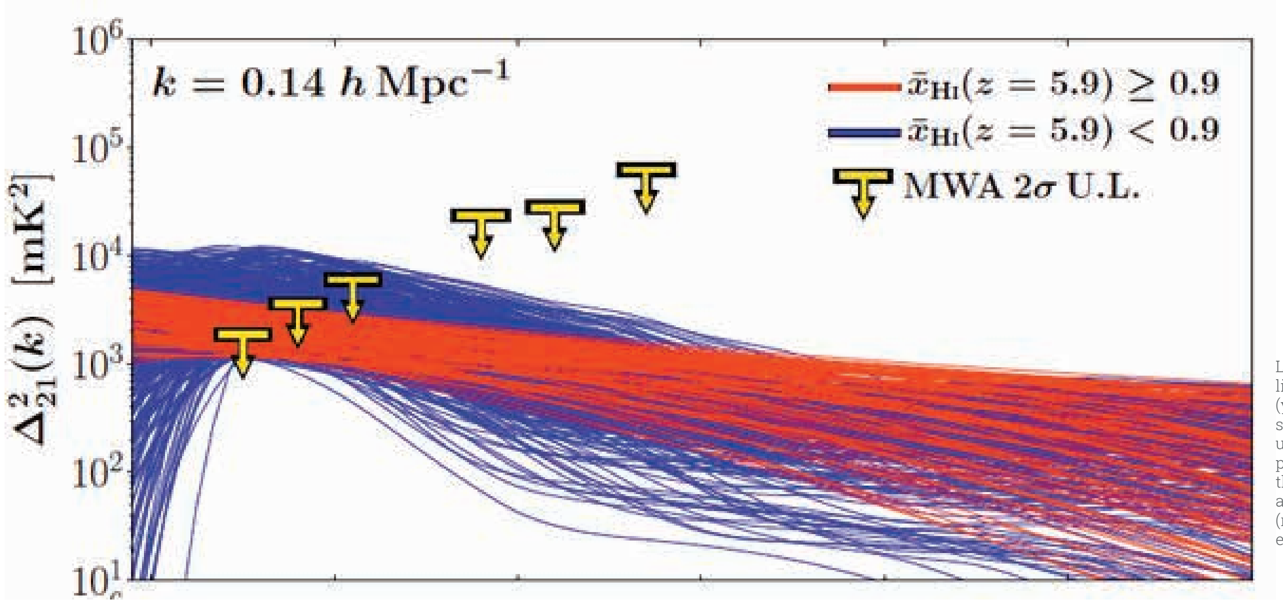
CATHRYN TROTT
Associate Professor

The Epoch of Reionisation marks one of the remaining unexplored periods in the early Universe. Spanning 200 million to 1 billion years after the Big Bang, this period witnessed a transformation of the hydrogen gas that permeated the space between early galaxies from a neutral to an ionised state. Driven by high-energy photons from the first generations of stars and quasars, exploring the distribution and temperature of the reionised hydrogen gas provides key insights into the properties of the Universe almost 13 billion years in our past.

In 2020, the MWA EoR collaboration published the largest suite of low-frequency telescope data exploring this period. By measuring the emission line signal from the nucleus of the hydrogen atom, redshifted to 100-200 MHz from these early times, we constrained models for the radiation and density in the Universe. These measurements placed the deepest limits on the temperature of the signal 700 million years after the Big Bang, and were published in Trott et al (2020, MNRAS).

Despite not yielding a direct detection of the weak signal, the constraints were sufficiently tight to eliminate many models for how the early Universe evolved. In collaboration with theorist Dr Brad Greig from the University of Melbourne, the MWA results were used to estimate key astrophysical information from that early time, including the kinetic temperature of the gas, the radiation field from stars and quasars, the amount of ionising radiation that escapes galaxies, and the luminosity of the earliest galaxies. Dr Greig's algorithms use a Bayesian framework to constrain each of these parameters by assessing their consistency with the MWA's measurements; combinations of parameters that produce measurements that exceed the upper limits are disfavoured. One of the key benefits of the MWA results is that they span a few hundred million years of evolution and contain information on a range of spatial scales. Figure 1 shows example simulated measurements from different parameter combinations for one set of the MWA data. Curves that exceed the yellow arrows are inconsistent with the MWA measurements. The grey shaded region in Figure 2 represents models that are disfavoured by MWA, but are consistent with other tracers of the early Universe, demonstrating that the MWA is already providing new and complementary information.

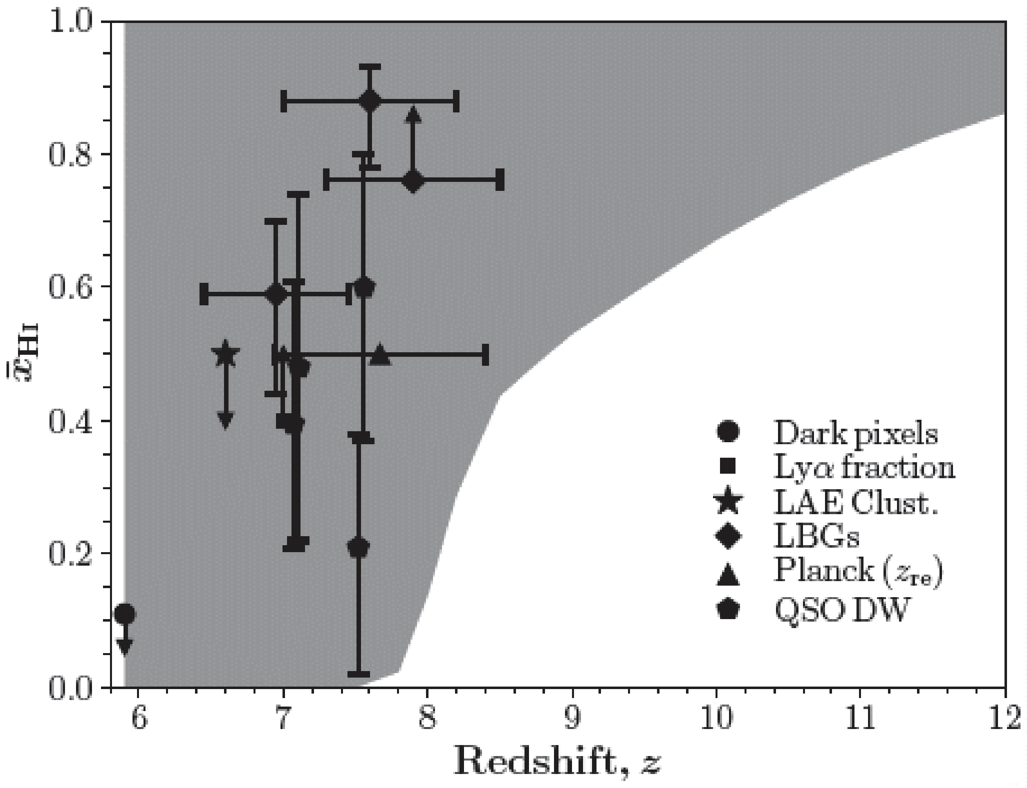
The results show that the intergalactic medium between galaxies must have been previously heated by photons escaping galaxies ("cold" reionisation scenarios are disfavoured) and that the x-ray luminosity of Reionisation-era galaxies has a sufficiently large value. With further improvements in the MWA results, we can provide further constraints to provide a clearer understanding of conditions in the Universe 13 billion years in our past.

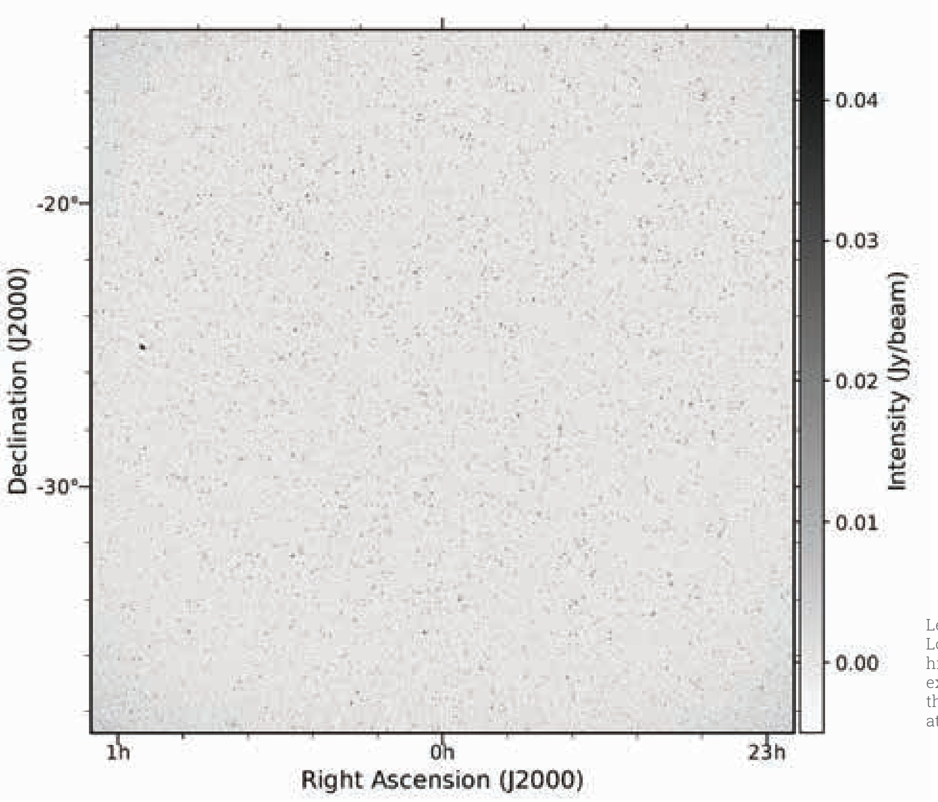


Left: Figure 1. MWA upper limits on gas temperature (yellow arrows) and simulated measurements using combinations of parameters. Measurements that exceed the yellow arrows are disfavoured (reproduced from B. Greig et al (2021)).

Paper: ui.adsabs.harvard.edu/abs/2021MNRAS.500.5322G

Right: Figure 2. Fraction of the medium that is still neutral versus redshift. The shaded area denotes regions for which there are models that are disfavoured by the MWA, which are consistent with all other measurements, demonstrating the complementarity of MWA to others tracers (reproduced from Greig, et al 2021, Figure 2).





Left: Figure 1: Central region of the LoBES EoR0 image highlighting the high image quality of MWA phase 2 extended. The noise at the edge of the field, due to the primary beam attenuation, is apparent.

Improved Source Catalogue for the MWA EoR0 field using the **Long Baseline Epoch of Reionisation Survey (LoBES)**

CHRISTENE LYNCH
Research Fellow

Detecting 21 cm emission from the Epoch of Reionisation (EoR) is a goal for many current and future low-frequency telescopes, including the Murchison Widefield Array (MWA). Within the EoR community, the importance of accurate and complete sky models, used for calibration and foreground source removal, is well established. To imporve the source models for the main two MWA EoR fields, we have conducted the Long Baseline Epoch of Reionisation Survey (LoBES). This survey uses the MWA Phase II extended array to make multi-frequency observations of the main MWA EoR fields and their eight neighbouring fields; it takes advantage of the improved resolution and expected lower confusion noise of the longer baselines in this new configuration of the MWA.

In 2020, we completed the first half of this survey centred on the MWA EoR0 observing field (located at RA(J2000) 0 hr, Dec(J2000) -27 deg). This half of the survey covers an area of 3069 square degrees, with an average rms of 2.1 mJy/beam. This is roughly a factor of five improvement in sensitivity over previous low-frequency radio surveys of these fields. The resulting catalogue contains a total of 80824 sources, with 16 separate spectral measurements between 100 and 230 MHz. Figure 1 shows the 25 x 25 degree central region of the EoR0 field from the LoBES survey; this image was used for source finding and modelling.

Below: Figure 2: Differential source counts from the LoBE survey (filled brown circles) compared to other survey source counts at 100 MHz spanning similar sensitivity ranges. The comparison surveys included are: MWA results from Franzen et al. (2016) (orange open squares) and Franzen et al. (2019) (filled light orange triangles); GMRT results from Intema et al. (2011) (filled light purple stars), Intema et al. (2017) (filled purple triangles), and Williams et al. (2013) (dark purple open diamonds). The LoBES source counts are in agreement with previous surveys and with the upgrades to the MWA, the sources counts are now becoming competitive with the deepest source counts from the GMRT.

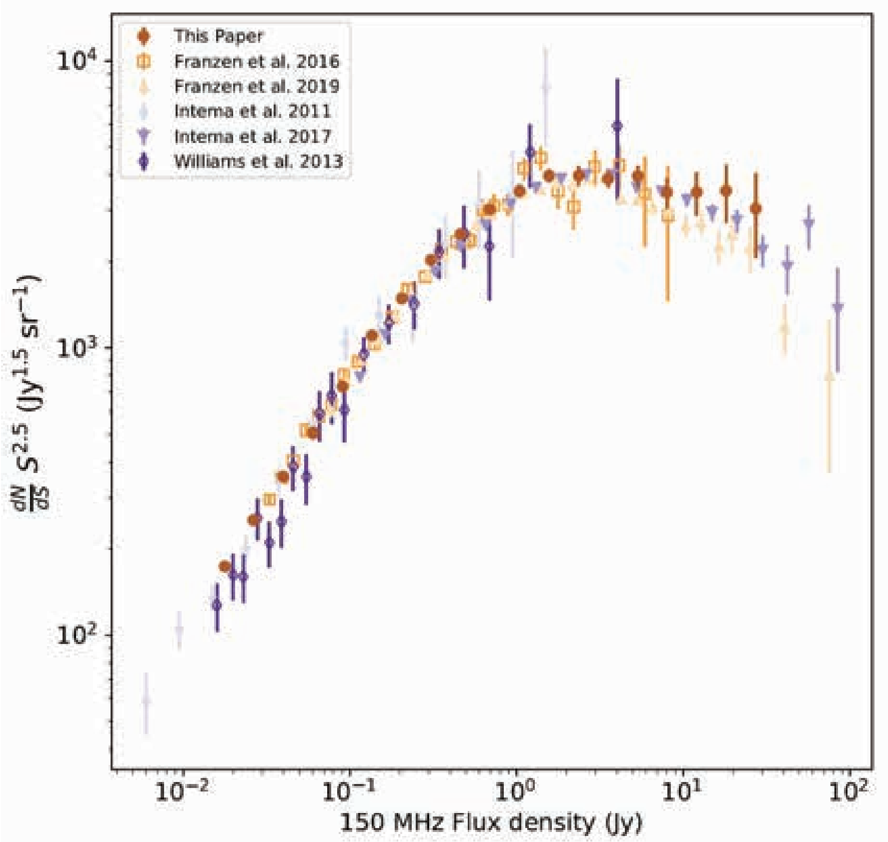


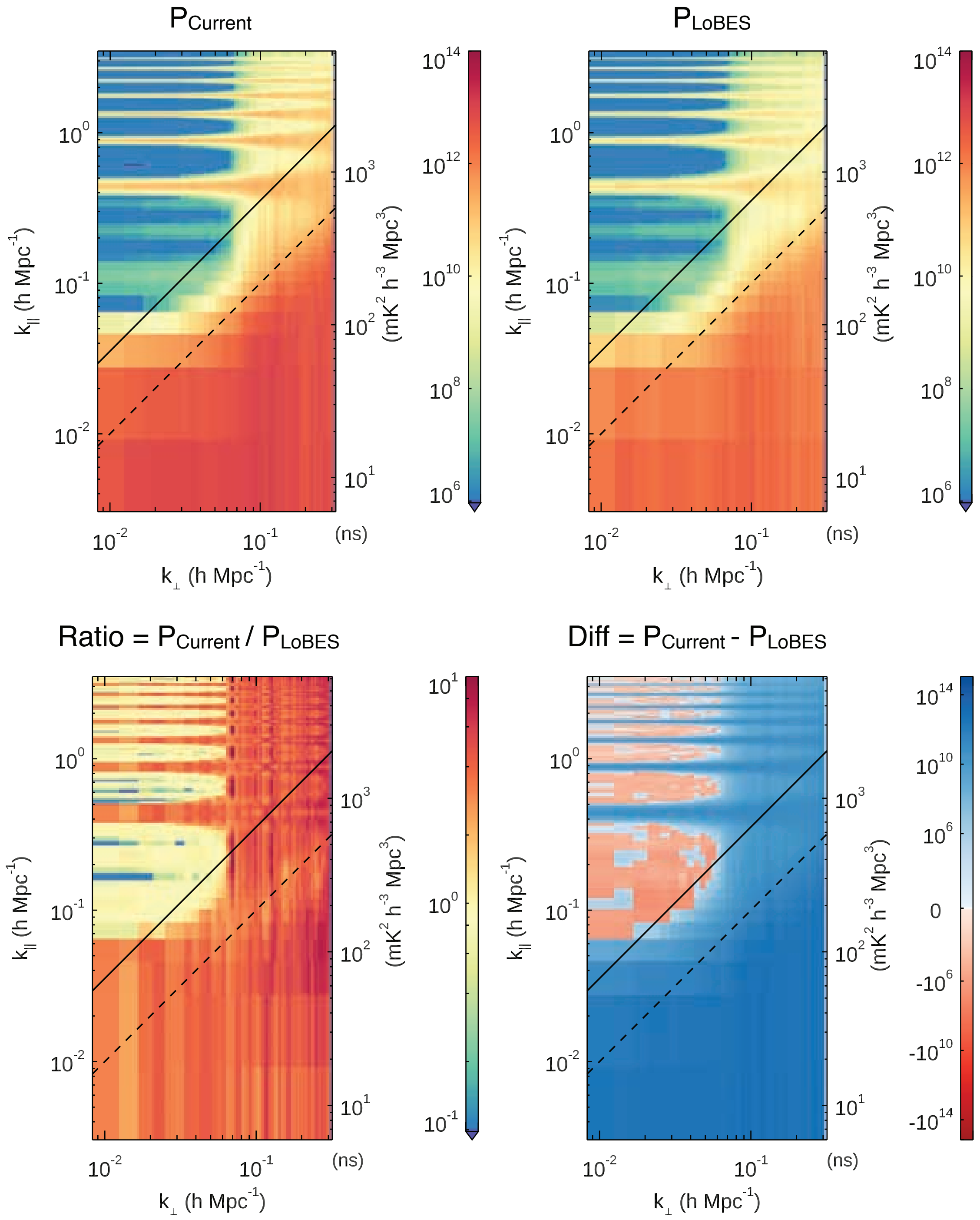
Figure 2 shows the differential source counts from this first half of the LoBE survey as compared to other low-frequency surveys. The LoBES source counts are in good agreement with these previous surveys at similar sensitivities. Additinally, it is clear that the upgrades to the MWA have resulted in greater imaging capabilities, reaching sensitivities now comparable to the deepest surveys from the Giant Metrewave Radio Telescope at similar frequencies.

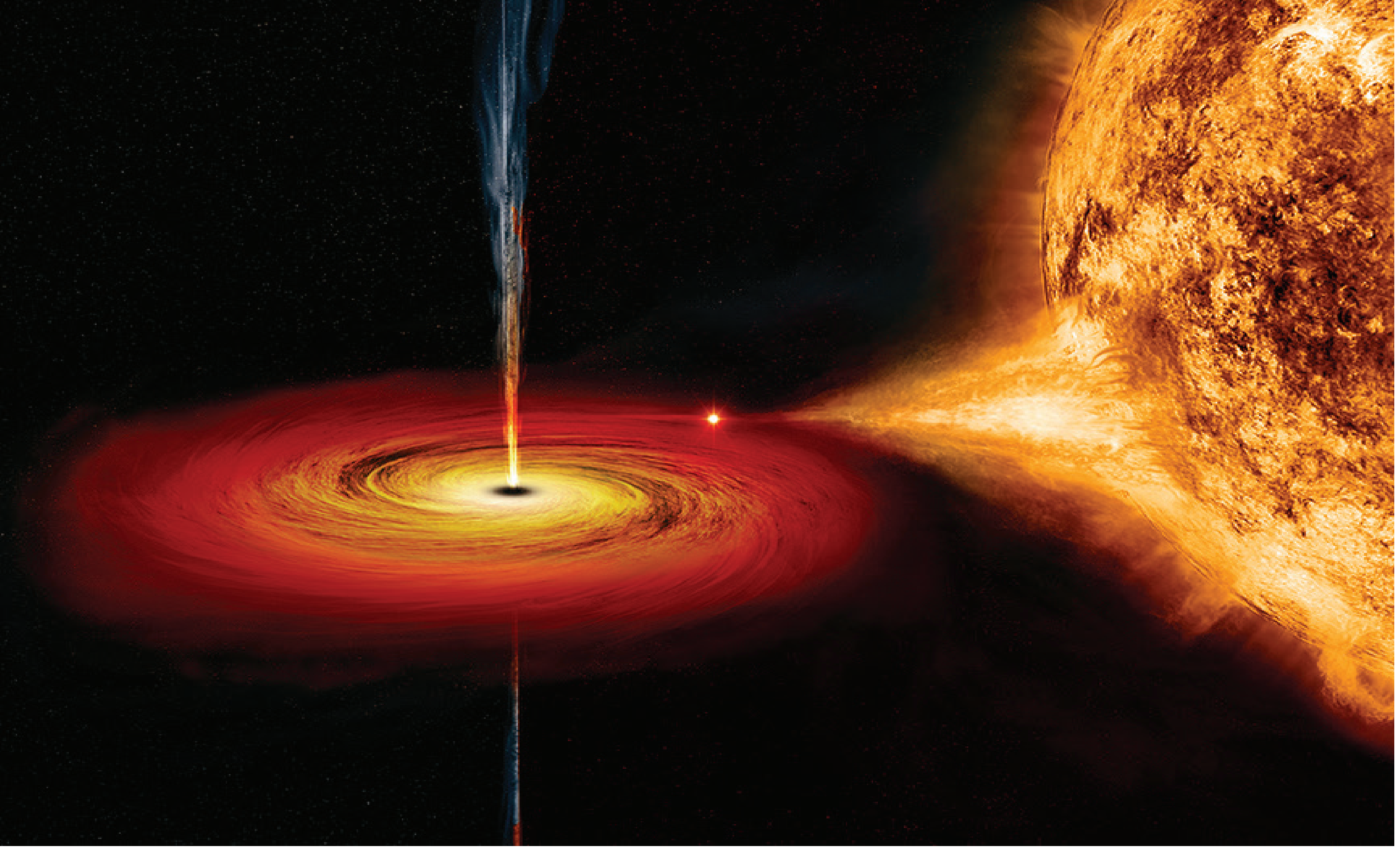
We tested the source modelling from the first half of the LoBE survey by calibrating and removing foreground sources in MWA data using the new LoBES models and the source models currently used by the Australian MWA EoR group. We find that the new LoBES source models produce lower residual rms values for peeled sources, particularly for extended sources, as compared to the current sky model. We also test the new source models using similated MWA Phase I data, finding an overall factor of 3 improvement in the removal of foreground power on all angular scales in a 2-dimensional power spectrum (Figure 3).

The first half of the survey has been submitted to PASA for publication. We plan to release the full LoBES catalogue with the publication of the second paper (focused on EoR1 field) later in 2021.

Below: Figure 3: The resulting 2D PS from using the current Australian MWA EoR sky model (top left) and LoBES sky model (top right) to peel sources from a single simulated MWA phase I observation. The bottom row shows the ratio (left) of the residual power from the current model to the LoBES model, and difference (right) in residual power between the current model and LoBES. In the ratio plot orange/red shades indicate where LoBES is an improvement; similarly blue shades in the difference plot show the regions where LoBES removes more foreground power. It is clear that there is a significant difference in the residual power between these two models for the simulated data. The LoBES sky model removes roughly a factor of 3 more power than the current sky model on all angular scales.

All figures will be published in C. Lynch, T. J. Galvin, J. L. B. Line, C. H. Jordan, C.M. Trott, J. K. Chege, B. McKinley, M. Johnston-Hollit, S. J. Tingay, 2021, PASA (submitted)





Far left: Artist's impression of the black hole X-ray binary system MAXI J1820+070. With observations from the infrared to the radio band, we studied the jets launched from close to the black hole. Credit: NASA/CXC/M.Weiss

Right: Radio images of the jets moving away from the black hole X-ray binary system MAXI J1820+070 over a period of six months. Images were made with the eMERLIN, MeerKAT and VLA radio telescopes. Credit: J.S. Bright et al., 2020, Nature Astronomy, 4, 697

A panchromatic perspective on **black hole jets**

JAMES MILLER-JONES
Professor

Stellar-mass black holes are formed from the deaths of the most massive stars. As black holes emit no light of their own, we see them only through their effect on their surroundings. Although there are thought to be around 100 million stellar-mass black holes wandering through our Milky Way galaxy, only a few dozen have been discovered to date. Most of those reside in X-ray binary systems, where the black hole is in a close enough orbit with a more normal star to capture gas from the stellar surface. As the captured gas falls in towards the black hole, it condenses into a disk and heats up, emitting strong X-ray radiation.

While we think of black holes as cosmic vacuum cleaners, the twisted magnetic fields pervading the disk of matter swirling around the black hole can be responsible for launching particles outwards in energetic beams of radiation known as jets, which carry energy away to very large distances.

Every so often, the rate at which matter is able to fall inwards through the disk increases, causing the disk to heat up, and increasing the power channelled into these energetic jets. These outburst episodes provide an excellent opportunity to study the relationship between the infalling matter and the outflowing jets.

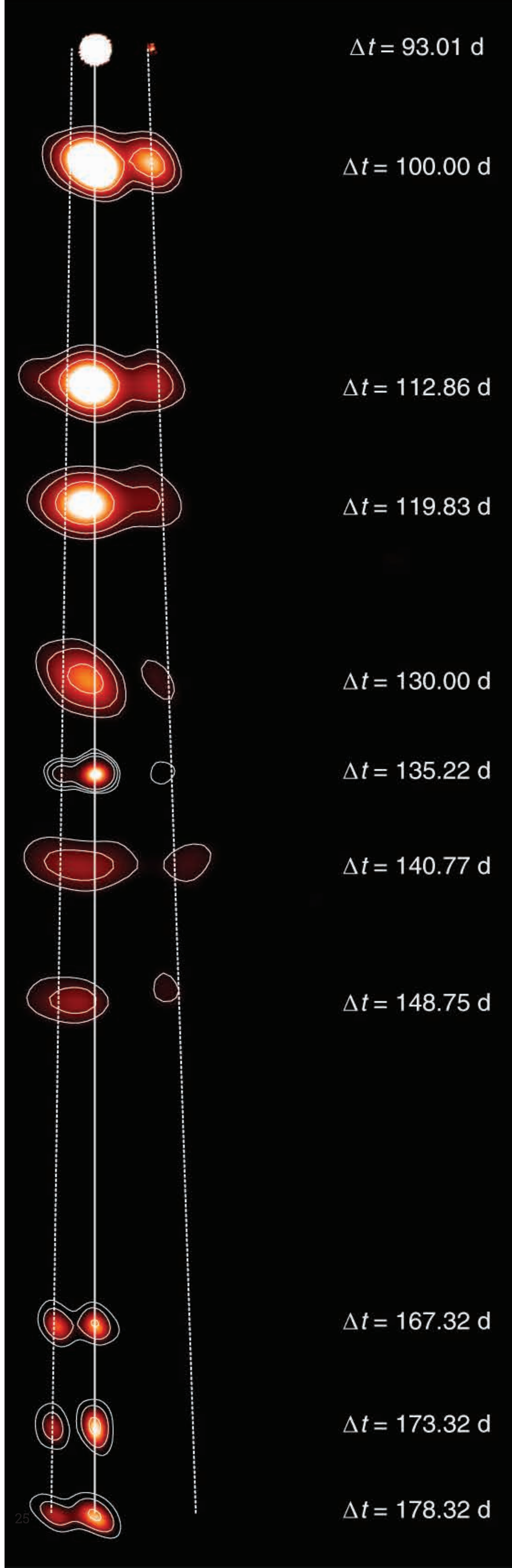
In early 2018, X-ray satellites detected a new outburst from a previously unknown system known as MAXI J1820+070. This outburst lasted for several months, allowing us to study the jets with a range of facilities across the electromagnetic spectrum.

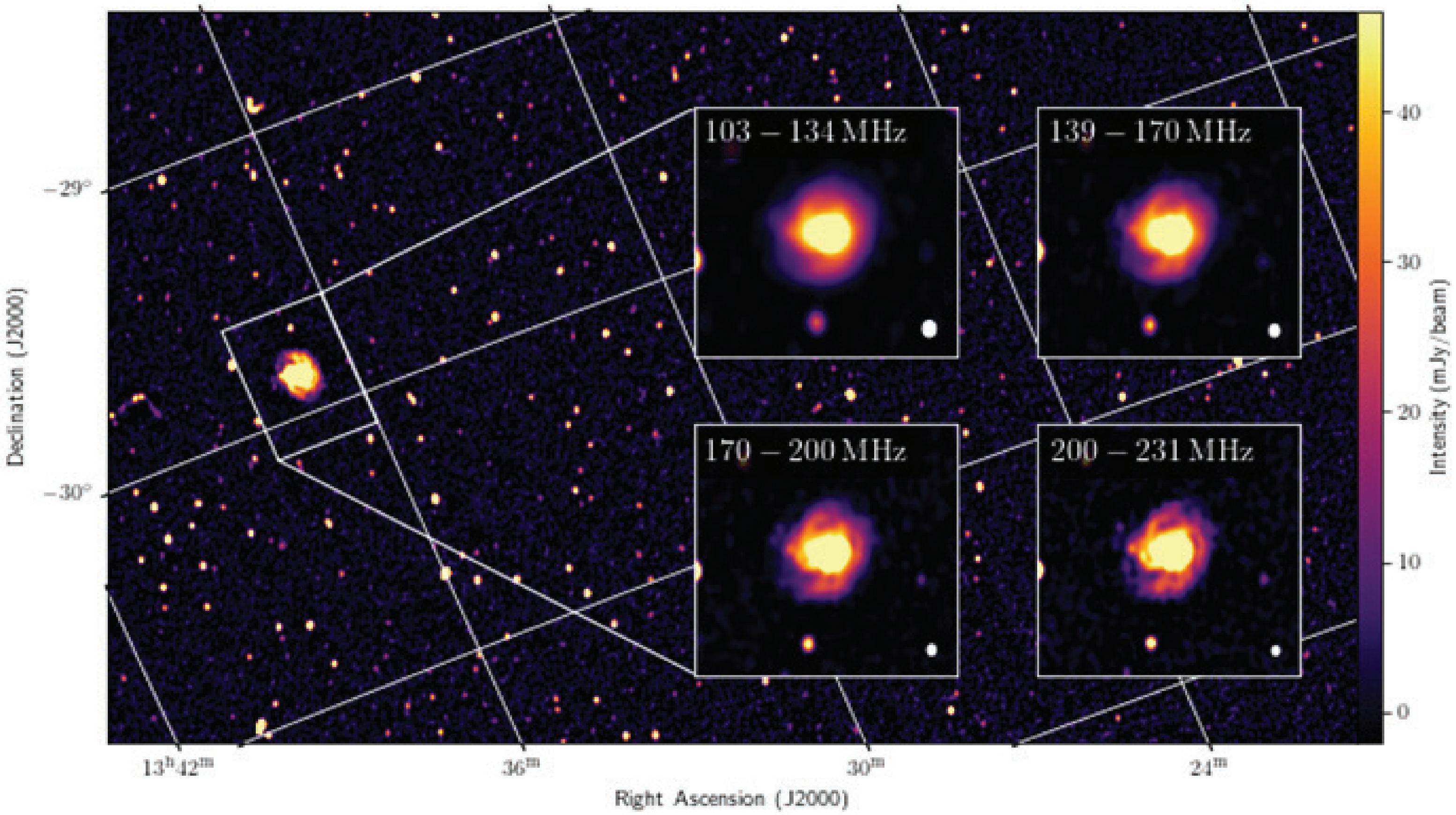
Using the GRAVITY instrument on ESO's Very Large Telescope to observe MAXI J1820+070 in the early phases of the outburst, we were able to make the first infrared interferometric detection of an X-ray binary jet. While the jets were unresolved, we were nonetheless able to place an upper limit of 0.1 milliarcseconds on their size (equating to 40 million km at the distance of the system), demonstrating the potential of this technique for black hole jet studies.

A few months later, a pair of powerful jets were ejected at the peak of the outburst. We tracked these jets for over six months as they moved away from the system, using the US Very Long Baseline Array and Very Large Array, the eMERLIN telescope in the UK, and South Africa's SKA precursor facility MeerKAT. The jets were moving at close to the speed of light, and their longevity demonstrated that particles were being accelerated in situ. Furthermore, a comparison of the emission observed on different angular scales showed that the jets had to be carrying more energy than standard techniques would infer. Eventually, the collision of the jets with the dense surrounding medium was detected with NASA's Chandra X-ray Telescope, further supporting our finding that the jets were extremely energetic.

Finally, with a year's worth of high-precision measurements of the position of MAXI J1820+070 on the sky, CIRA PhD student Pikky Atri led a team that determined the source's distance from Earth by measuring its parallax; the apparent positional wobble due to the Earth's motion around the Sun. This accurate distance allowed the conversion of observables into real physical parameters, thereby refining our estimates of the jet's speed and orientation, and the black hole's mass.

By deploying a suite of world-leading facilities across the electromagnetic spectrum, we were able to determine the key physical properties of the powerful jets launched from this newly-discovered stellar-mass black hole.





Far left: An extract of a 200-230MHz region produced from the co-addition of four nights of GLEAM-X observations. We also highlight the spiral galaxy M83 at four of the five GLEAM-X bands. The synthesised beam of each zoomed M83 image is shown as a white ellipse in the lower right hand corner.

The Galactic and Extra-Galactic All-Sky MWA Extended Survey **(GLEAM-X)**

TIM GALVIN

NATASHA HURLEY-WALKER

On behalf of the GLEAM-X team, including CIRA members John Morgan, Stefan Duchesne, Kat Ross, Ben Quici

In 2020, Dr Natasha Hurley-Walker commenced an ARC Future Fellowship to carry out a new survey with the Murchison Widefield Array (MWA): the GaLactic and Extragalactic All-sky MWA survey: eXtended (GLEAM-X). As part of this effort, Dr Tim Galvin joined CIRA, to streamline and run the processing pipeline on the Pawsey supercomputers. Together with a team of excellent researchers across MWA partner institutions, they endeavour to create an all-sky image of the sky that is twice the resolution and ten times as sensitive as the original MWA flagship survey, GLEAM.

Over a period of three years a collection of ~40,000 observations have been made by the MWA under the GLEAM-X banner. This represents approximately 2.4 Petabytes of raw telescope data -- an enormous computational challenge requiring supercomputer facilities to manage. If multi-processing computing platforms were not available, some 4 million hours would be required to transform the entirety of the raw GLAM-X data files into science ready data products. To enable this the GLEAM-X team have developed an end-to-end processing pipeline with key software components now being stored within a container based framework. This allows the processing pipeline to be effortlessly deployed on almost any modern high-performance computing platform. To date we have processed data using clusters available from the Pawsey supercomputer center and Shanghai Astronomical Observatory (SHAO). With access to these facilities we estimate that approximately two months of continuous processing would be needed to complete the GLEAM-X survey.

When completed the GLEAM-X survey will enable a broad set of science projects, including further refinement of studies initially performed using GLEAM data. Key science projects planned include a detailed low-frequency analysis of the Galactic plane (Hurley-Walker, 2018, 2019PASA...36...47H), identification of variability and transient behaviour in extra-galactic populations (Ross, 2021, 2021MNRAS.501.6139R), detailed analysis of near-by galaxies (Kapinska, 2017, 2017ApJ...838...68K), active galactic nuclei studies and investigations into their lifecycles (Quici, 2021, 2021PASA...38....8Q), exquisite rotation measure studies (Riseley, 2020, 2020PASA...37...29R) and detailed

CONTINUED-

analysis of the spectral energy distribution of star forming galaxies (Galvin, 2018, 2018MNRAS.474..779G). Where possible, the GLEAM-X pipeline has been optimised to facilitate these projects, with project-specific data products being produced and archived in typical processing. In particular, we are coordinating with CSIRO to provide fully calibrated measurement set to carry out polarisation analysis.

To-date we have processed 12 nights of data focusing on the extra-galactic sky for observations made at a declination of -27 degrees, with corresponding night long mosaic, and are currently investigating the optimal method of combining these into a single science-ready deep data product. Initial tests that combined one third of the data have indicated that our in-field and ionospheric de-distortion strategies are working well, allowing us to combine our image data into deep images without any apparent systematic or image-fidelity issues.

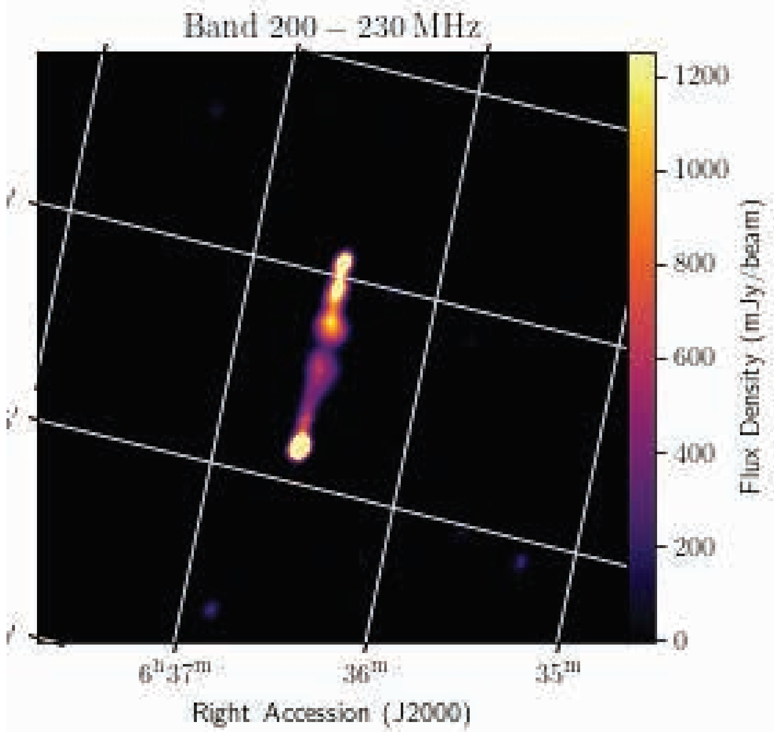
We highlight an extract of one of these deep image products that is directed towards the nearby face-on spiral galaxy M83. At the highest GLEAM-X frequency bands the spiral arms of the system are clearly distinguishable from its core. Moving away from M83, the improved resolution enabled by the long-baseline configuration of the MWA have enabled us to dive below what was the confusion limit of GLEAM, revealing a wealth of faint, unresolved objects.

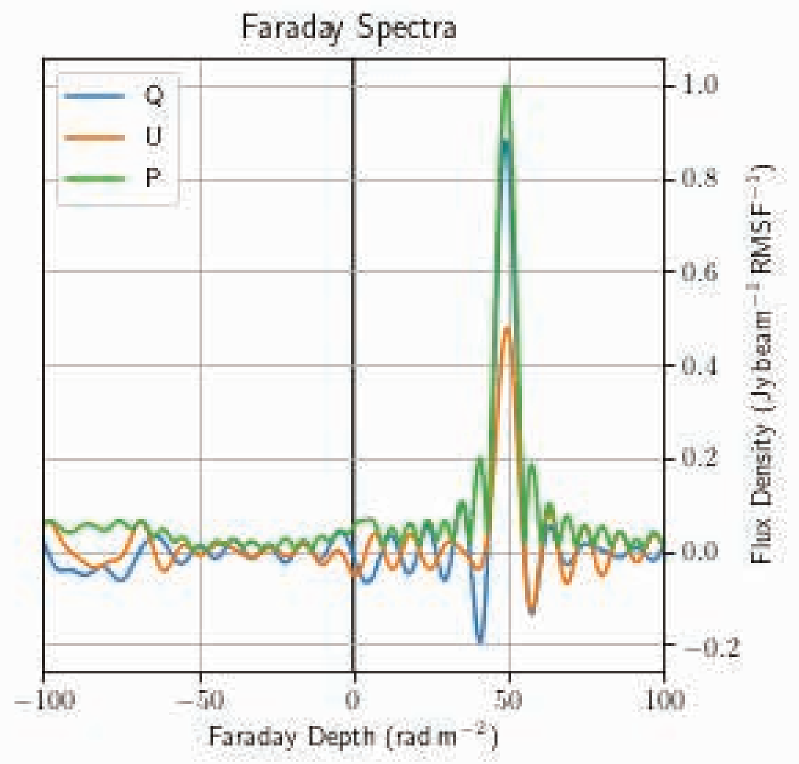
Initial analysis of the polarisation products from the typical GLEAM-X processing reveals a wealth of polarised sources. Rotation measure synthesis has leveraged the extraordinary lambda-squared coverage of the MWA to produce exceptionally precise Faraday spectra of polarised sources. We show the uncleaned Faraday spectra of the southern lobe of the FRII object PKS J00636-2037 - nicknamed ‘the exclamation mark’ based on its resolved radio morphology! The Faraday spectra highlights a Faraday thin component located at a Faraday depth of ~50 rad m^2.

Once all GLEAM-X data have been processed we will achieve an RMS 1 — 2 mJy/beam with an angular resolution of ~45 arcseconds in the highest frequency band across most of the Southern celestial sphere, detecting upwards of seven million radio galaxies. When completed, science data products will be made accessible to the public through Data Central (datacentral.org.au) and other virtual observatory interfaces. We hope to process the majority of data by the end of 2021.

Below, left: The continuum image from 200-230MHz of PKS J00636-2037 -- the exclamation mark.

Below, right: The Faraday spectrum of PKS J00636-2037’s southern lobe. Credit to Xiang Zhang and George Heald at CSIRO for kindly providing the reference Faraday spectra.





The GLEAMing of the **first supermassive black holes**

GUILLAUME DROUART, JESS BRODERICK, NICK SEYMOUR & TIM GALVIN

Current observations reveal active galactic nuclei (AGN) containing billion-solar-mass black holes out to a redshift of z = 7.64, when the Universe was only 670 million years old. Time is therefore very short for a black hole to grow this massive, implying that extreme physical processes were at work in the early Universe, involving highly efficient accretion and/or large black hole seeds (up to a million solar masses). Observable phenomena from these extreme processes include powerful radio jets, which are detectable across cosmic time in the new generation of all-sky low-frequency radio surveys such as GLEAM from the Murchison Widefield Array (MWA).

The strong synchrotron emission from the jets has several unique properties to enable the study of galaxy and black hole evolution in the first billion years of the Universe: (i) it is insensitive to dust obscuration, (ii) it provides a strong continuum to probe the intergalactic medium through the absorption of the redshifted 21-cm neutral hydrogen (HI) line, and (iii) it identifies the progenitors of the most massive galaxies and their central supermassive black holes at the earliest times. Distant powerful radio galaxies (i.e. high-redshift radio galaxies; HzRGs; redshift z > 2) are intrinsically rare, however (of order a few hundred). We need an efficient technique to isolate them from the millions of radio sources detected in the sky!

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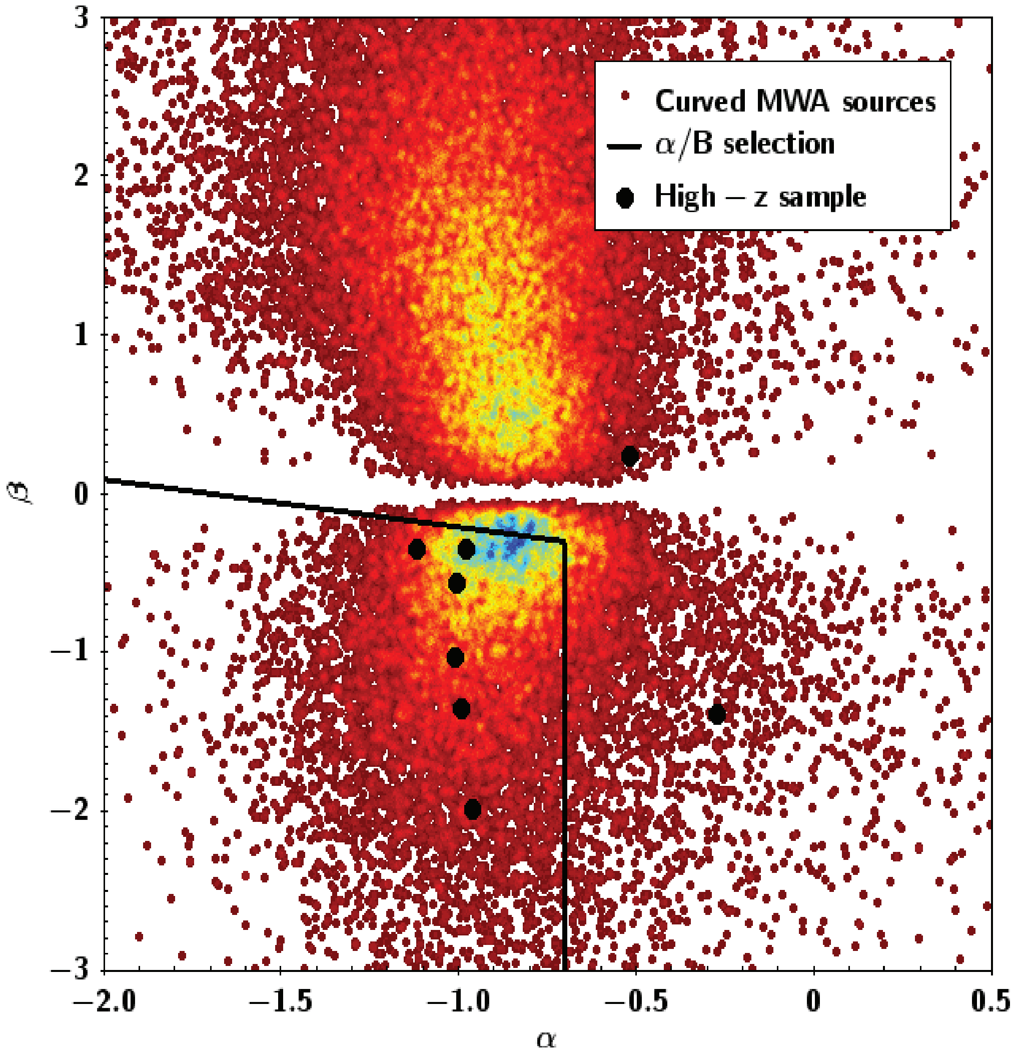
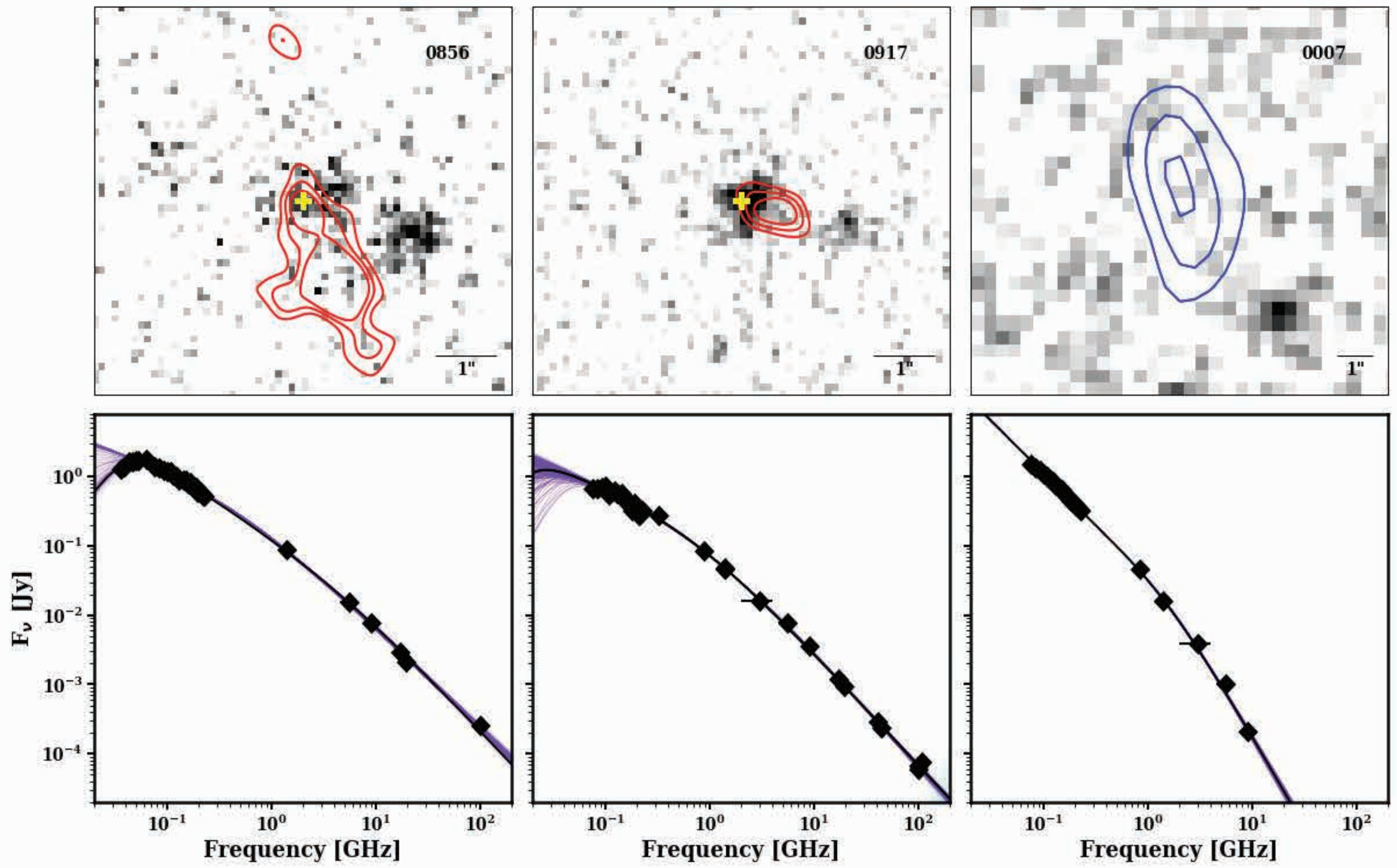
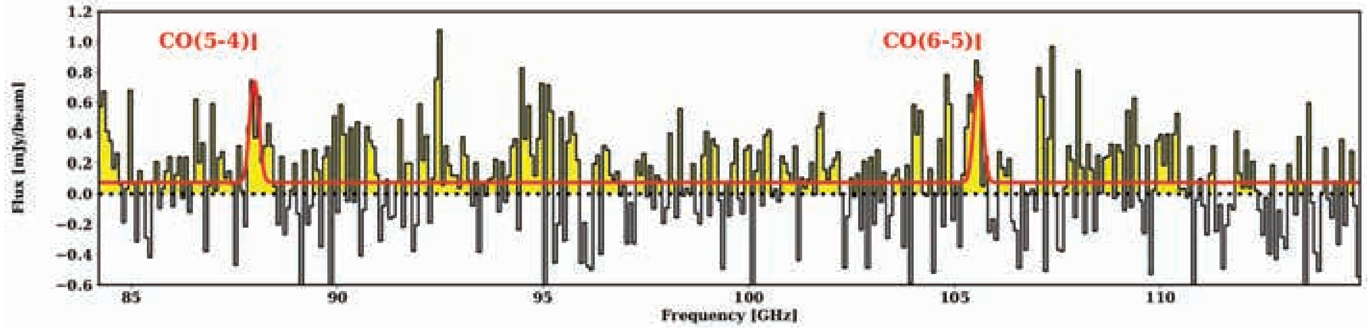


Above: Fig. 1: The radio spectral steepness (α) – curvature (β) parameter space for all extragalactic sources in GLEAM (Declination < +30°) that have low-frequency radio spectra with a statistically significant curvature component. HzRG candidates were selected in the region in the lower left of the plot, delineated by the black lines (α < −0.7 and β < −0.3α − 0.51). Known z > 4 radio galaxies with GLEAM data are shown with black circles; we can see that our selection includes the majority of these distant sources.



Above: Fig. 2: Plots showing radio contours overlaid on K-band images (top row), and broadband radio spectra (bottom row). Left panels: our z = 5.55 discovery. Middle panels: our z > 5 candidate radio galaxy. Right panels: one of the sources from our new, expanded HzRG candidate sample. Left and middle overlay plots: grey-scale: deep VLT/HAWKI K-band image; red: ALMA 100-GHz continuum emission; yellow cross: where the ALMA spectrum was determined at the position of the host galaxy. Right overlay plot: grey-scale: deep SHARKS K-band image; blue: Australia Telescope Compact Array (ATCA) 5.5-GHz radio contours. The host galaxy is not seen in the SHARKS K-band image, and deeper VLT imaging is needed to obtain a detection. Left and middle radio spectra: The broadband spectrum over more than three orders of magnitude in frequency, fitted with a triple-power-law model. Uncertainties per data point are smaller than the symbols. The uncertainty in the fit is represented by the scatter in the purple lines. Right radio spectrum: The broadband spectrum over two orders of magnitude in frequency. A double power law has been fitted. For the radio spectra, the next step is to use the fitting information along with the general radio properties to determine jet ages and powers, as well as the physical mechanism(s) responsible for the spectral steepening at higher frequencies.



Above: Fig. 3: ALMA 100-GHz spectrum for our z = 5.55 discovery. There are two CO molecular line detections at signal-to-noise ratios of 3.2 (CO 5–4) and 4.1 (CO 6–5), whose observed-frame wavelengths were used to determine the redshift.

Broadband, low-frequency surveys such as GLEAM allow us to search for the most distant HzRGs. Given that GLEAM has 20 data points over the frequency range 70–230 MHz, we can combine broadband spectral steepness and curvature to isolate high-redshift candidates (Fig. 1). Our team also uses a novel and efficient multiwavelength follow-up campaign. In particular, deep near-infrared K-band imaging from the Very Large Telescope (VLT) allows us to pinpoint the very faint host galaxy of each radio source, and we can use observations from the Atacama Large Millimeter/submillimeter Array (ALMA) to determine the spectroscopic redshift via the detection of molecular emission lines (as opposed to more classical near-infrared spectroscopy, which can be significantly challenging at very high redshifts).

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We conducted a pilot study in the 60 deg2 GAMA-09 field. From only four targets, we demonstrated the success of our new selection technique by identifying a powerful radio galaxy at z = 5.55 (Fig. 2 left; Fig. 3). This discovery was made with a small amount of observing time (4 h on the VLT and 6 h on ALMA for the entire pilot programme). While, as previously stated, AGN have been discovered out to z = 7.64, our z = 5.55 discovery is one of only two HzRGs which have recently broken the radio galaxy distance record that stood for 20 years! The results of our pilot study are presented in Drouart et al. (2020).

A second source from the pilot study also has a very faint K-band detection (Fig. 2 middle), along with faint 100-GHz continuum emission. However, no molecular emission lines were detected in the ALMA data. In the radio domain, the source is compact (0.3–1.2 arcsec size), partially scintillating (as determined from MWA data) and unpolarised. Using a combination of public data from across the electromagnetic spectrum (optical to radio) and deeper follow-up observations from the Jansky Very Large Array (JVLA) at 40 GHz and ALMA at 100 GHz, our favoured interpretation is that this source is also at z > 5 (Fig. 4). We note that even in the case of a lower-redshift solution, this source will then be so peculiar that thoroughly characterising it will lead to interesting discoveries. A paper has now been submitted on this enigmatic source (Drouart et al. 2021) and we are continuing to follow it up with other facilities.

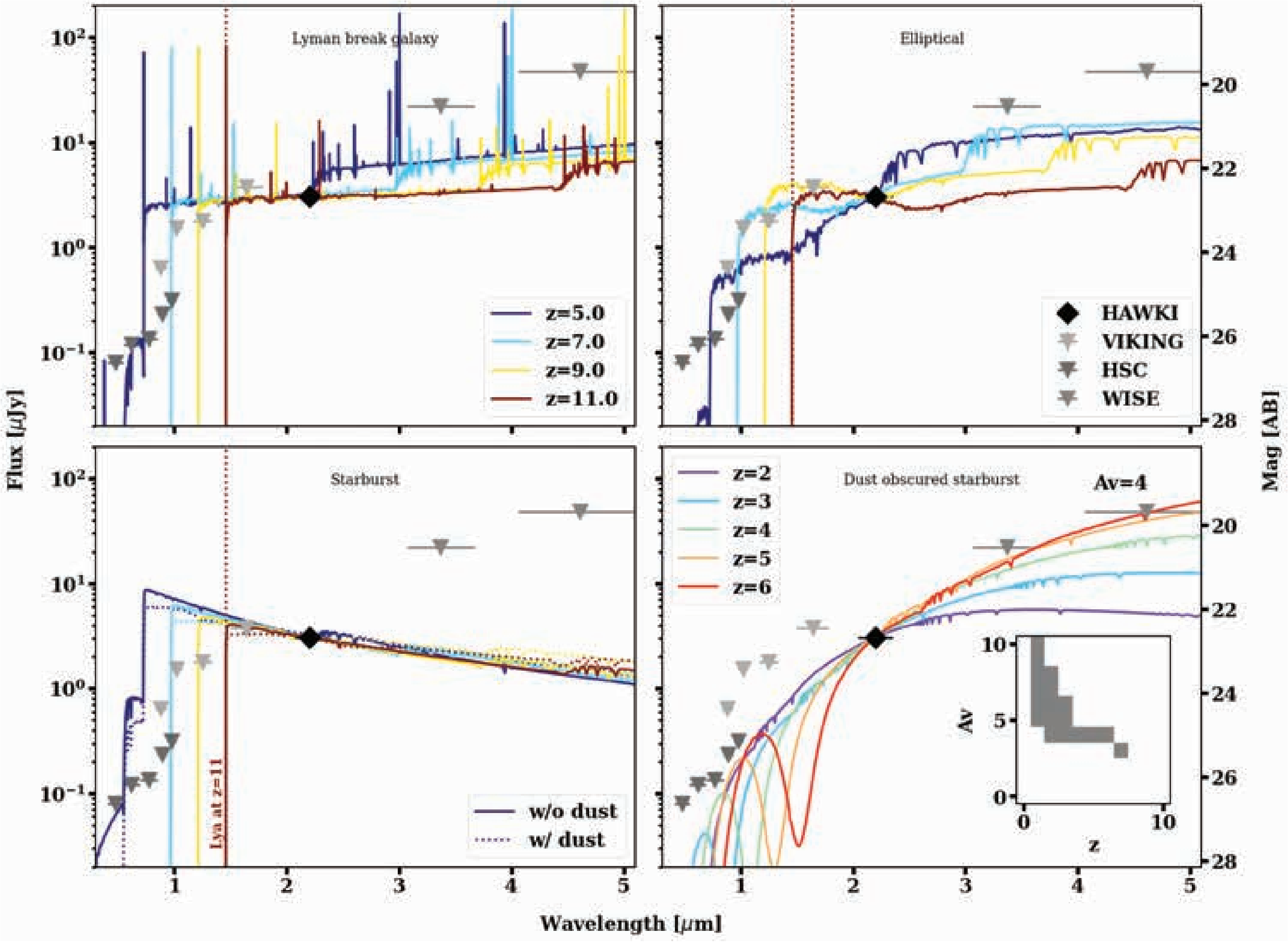
Given the above results, we have developed a selection technique that shows very encouraging prospects of efficiently selecting HzRGs above z = 5, when the Universe was less than 1.2 billion years old: up to a 50 per cent success rate! The following step in our project was to apply this same technique, but over a sky area twenty times larger, and to radio flux density levels an order of magnitude fainter. Our goal is to build a sample of powerful HzRGs at z > 6.5 during the Epoch of Reionisation (EoR), when the first stars and galaxies formed. Such a sample would provide us with unique laboratories to study the co-evolution of the host galaxy and central supermassive black hole during the first billion years of the Universe.

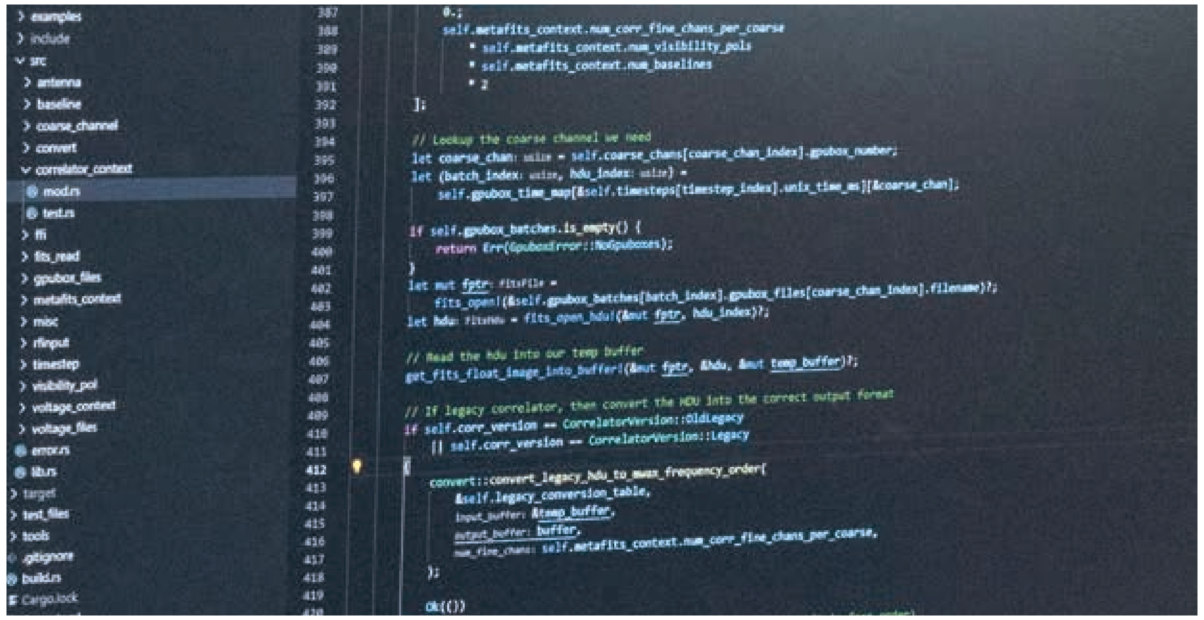
We used the full 1200 deg2 VIKING near-infrared survey (as well as deeper data within this region from the SHARKS near-infrared survey, where available), and considered all GLEAM sources within this region with 151-MHz flux densities > 40 mJy. We then applied refined radio spectral steepness and curvature selection criteria (Fig. 1), as well as a range of other selection criteria to narrow down the list of sources to the best HzRG candidates. CONTINUED-

Our final candidate sample comprises 55 compact radio sources that are very faint in the near-infrared (Fig. 2 right): ideal targets for multiwavelength follow-up. A sample definition paper is currently being written up for publication (Broderick et al. 2021, in preparation). This includes an initial analysis of the radio properties of the sample.

We will follow up this HzRG sample with a selection of world-class telescope facilities. As in the pilot study, we will propose for time on the VLT to obtain deep near-infrared K-band imaging, and with ALMA to determine the spectroscopic redshift of each target. Other potential follow-up includes Lyman-alpha halo studies, detailed ALMA observations of molecular gas and dust, protocluster searches, and the characterisation of the intergalactic medium during the EoR via the observation of redshifted HI absorption. An HI detection in absorption with the current generation of low-frequency radio telescopes, such as the MWA, would be a very exciting, high-impact result: Square Kilometre Array science, but with a precursor!

Below: Fig. 4: Optical to near-infrared SED of our z > 5 candidate. We have overlaid different galaxy templates over a range of redshifts, where each template has been normalised to the K-band detection (denoted by the diamond). The downward-pointing triangles are the 3-sigma upper limits from VIKING, as well as the HSC and WISE surveys. The vertical dotted line shows the wavelength of the redshifted Lyman-alpha emission line if z = 11. The grey shaded area in the bottom-right panel inset indicates the permissible solutions for the dust extinction given the constraints provided by our K-band detection and the upper limits at other wavelengths.





```
            0.;
        self.metafits_context.num_corr_fine_chans_per_coarse
            * self.metafits_context.num_visibility_pols
            * self.metafits_context.num_baselines
            * 2
    ];

    // Lookup the coarse channel we need
    let coarse_chan: usize = self.coarse_chans[coarse_chan_index].gpubox_number;
    let (batch_index: usize, hdu_index: usize) =
        self.gpubox_time_map[&self.timesteps[timestep_index].unix_time_ms][&coarse_chan];

    if self.gpubox_batches.is_empty() {
        return Err(GpuboxError::NoGpuboxes);
    }
    let mut fptr: FitsFile =
        fits_open!(&self.gpubox_batches[batch_index].gpubox_files[coarse_chan_index].filename)?;
    let hdu: FitsHdu = fits_open_hdu!(&mut fptr, hdu_index)?;

    // Read the hdu into our temp buffer
    get_fits_float_image_into_buffer!(&mut fptr, &hdu, &mut temp_buffer)?;

    // If legacy correlator, then convert the HDU into the correct output format
    if self.corr_version == CorrelatorVersion::OldLegacy
        || self.corr_version == CorrelatorVersion::Legacy
    {
        convert::convert_legacy_hdu_to_mwax_frequency_order(
            &self.legacy_conversion_table,
            input_buffer: &temp_buffer,
            output_buffer: buffer,
            num_fine_chans: self.metafits_context.num_corr_fine_chans_per_coarse,
        );

        Ok(())
```

MWA's Next Generation of **Data Processing Pipelines**

CHRIS JORDAN
Senior Research Fellow

For many years, the MWA Epoch of Reionisation (EoR) team has used the Real-Time System (RTS) software to perform its calibration, which is critical for their science. However, over time, it has become apparent that many small issues within the RTS have hindered progress. Broadly, these stem from the design of RTS usage being quite different from the needs of the EoR team. For this reason, a re-write and thorough testing of this critical code was agreed upon and tasked to Chris Jordan.

Early in 2020, Jordan started working on hyperdrive; purpose-built calibration software for the EoR team but generally applicable for MWA observations. Along the way, the new MWAX correlator format on the horizon became an increasing problem to handle; existing tools were not capable of reading it and reading existing MWA data was not an insignificant amount of work. After consulting with Greg Sleap on this issue, mwalib was born: a library available for all programming languages allowing the reading of MWA data from any correlator format without assumptions.

Derwent McElhinney – or Dev as they like to be known – joined the MWA team in January 2021 as software developer with the goal of helping improve the existing EoR data processing pipeline in order to help build the requirements for the Australian SKA Regional Centre. Their first piece of work was to create a suitable workflow for flagging the new MWAX correlator format, leveraging mwalib. Previously, flagging and pre-processing of MWA data had been done with cotter, a bespoke C++ application which marshals MWA correlator visibility data into a suitable format for the popular AOFlagger flagging library. Enter Birli, a modern replacement for cotter, which processes both legacy MWA and MWAX correlator visibilities, optionally flagging with AOFlagger and packaging the corrected data into a common container format (measurement set or uvfits). Birli is the Wajarri word for lightning, a common cause of outages at the MWA, and a great descriptor for the speed which this library intends to deliver.

At the time of writing, hyperdrive and Birli are not yet ready for general usage, although hyperdrive is estimated to be twice as fast as calibrate, and Birli is able to perform flagging with AOFlagger in the simplest flagging configuration. With this software in place, MWA science teams will require significantly less effort to reach their goals, thanks to modern software development practices, including numerous unit tests and continuous integration.

A **Calibration and Imaging Strategy** with the Murchison Widefield Array

JAIDEN COOK
Masters Student

At relatively high radio frequencies, highly sensitive grating sidelobes occur in the primary beam patterns of low frequency aperture arrays (LFAA) such as the Murchison Widefield Array (MWA). This occurs when the observing wavelength becomes comparable to the separation of dipole radio antennas within MWA tiles; this happens at approximately 300 MHz for the MWA. The presence of these grating sidelobes has made calibration and image processing for 300 MHz MWA observations difficult. As a result, observations of the entire sky at 300 MHz have remained unprocessed.

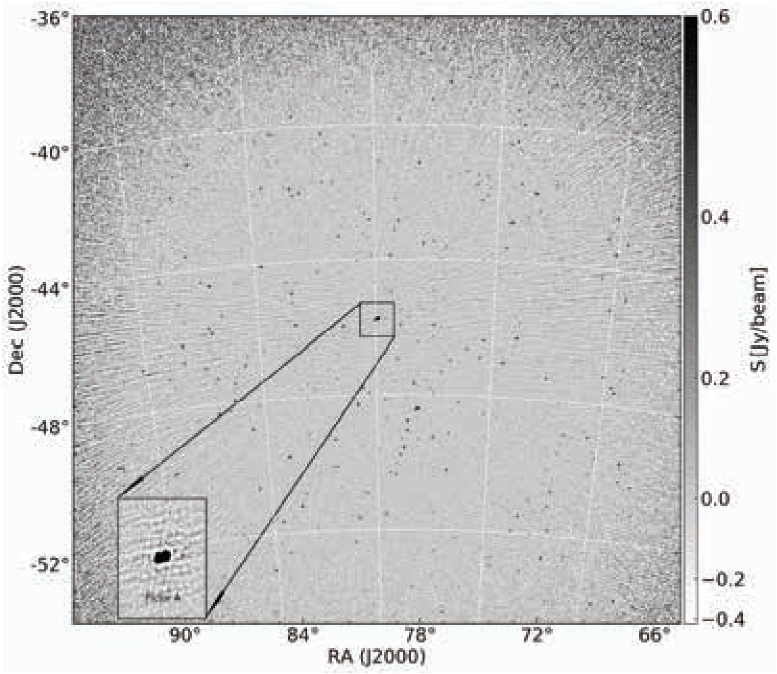
This work presents a new calibration and imaging strategy which employs existing calibration and imaging techniques to process two example 300 MHz MWA observations. The first observation is of a field centred on the bright calibrator radio galaxy Pictor A, and the second observation is of an adjacent field taken during the same observing night. The calibration strategy presented in this work uses bright radio galaxies such as Pictor A, to calibrate relatively benign observing fields.

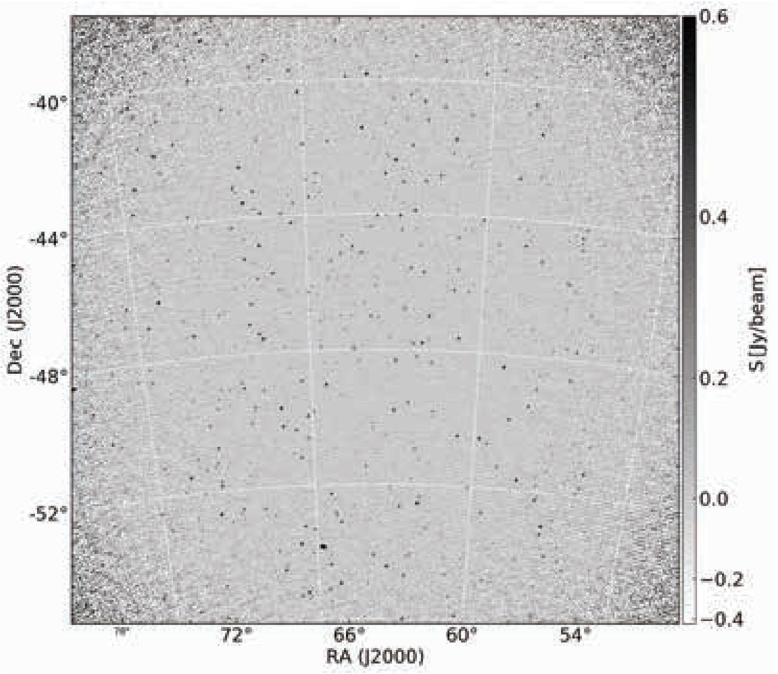
Calibrator observations are initially calibrated using a new 300 MHz sky-model which has been interpolated from low frequency and high frequency all-sky radio surveys. Using this 300 MHz model in conjunction with the accurate MWA tile primary beam model, we calibrated both example observations. After initial calibration a self-calibration loop is performed by all-sky imaging each observation with the WSCLEAN radio interferometer imaging software. Using the output all-sky image, we mask the main lobe of the image to isolate the contribution of the grating sidelobes. Using this masked image we perform a sky-subtraction by estimating the masked image visibilities using WSCLEAN. We then reimage the main field of view of the observations with WSCLEAN. This results in high dynamic range images of the two example observation main lobes (see Figures below). These images have a resolution of 2.4 arcminutes, with a maximum sensitivity of approximately 31 mJy/beam.

The calibration and imaging strategy presented in this work, opens the door to performing science at 300 MHz with the MWA, which was previously an inaccessible domain.

Below, left: 300MHz MWA image of Pictor A, blown up image shows Pictor A which is partially resolved.

Below, right: 300MHz MWA image of the observing field adjacent to the Pictor A observation.



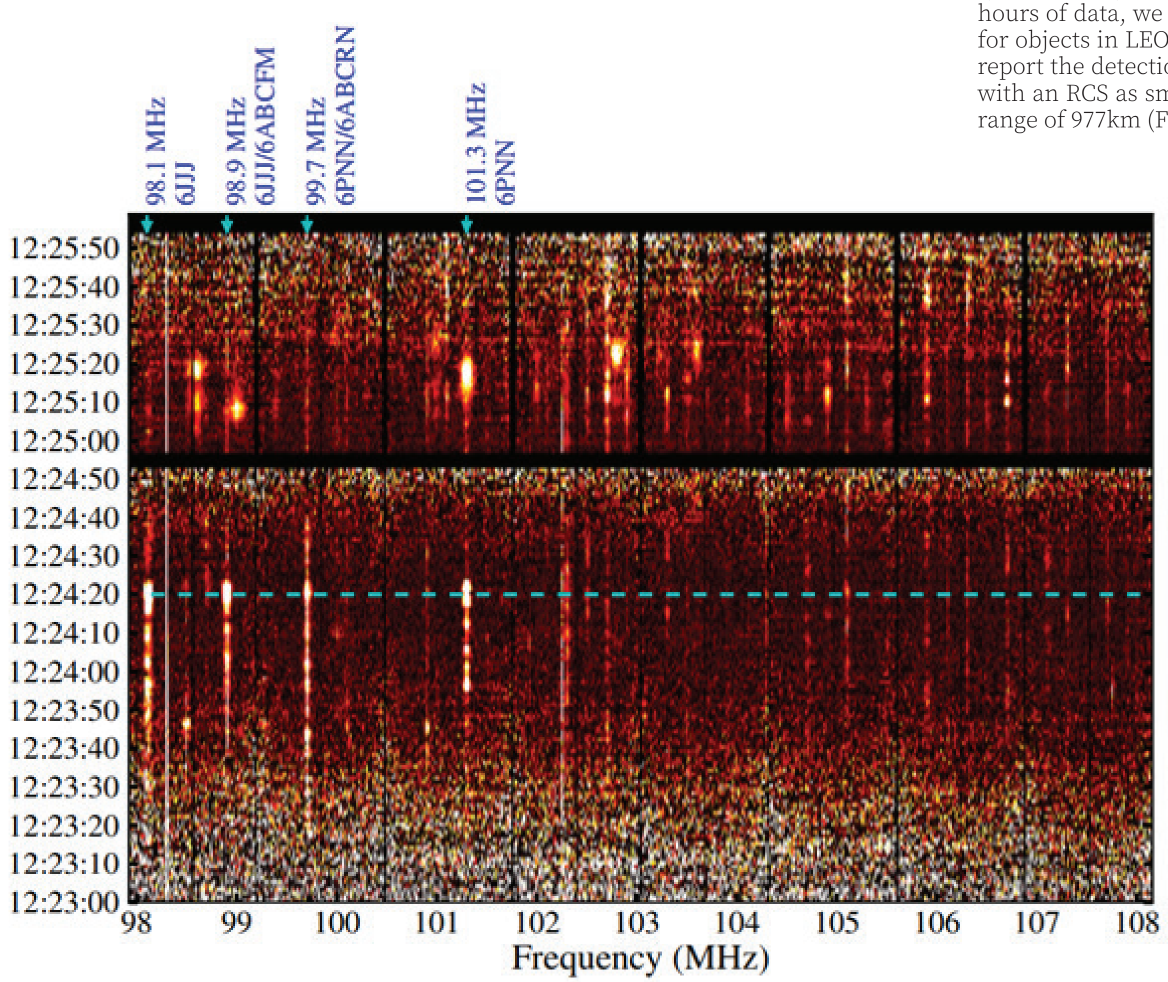


The detection of **satellites and debris in low Earth orbit** with the MWA

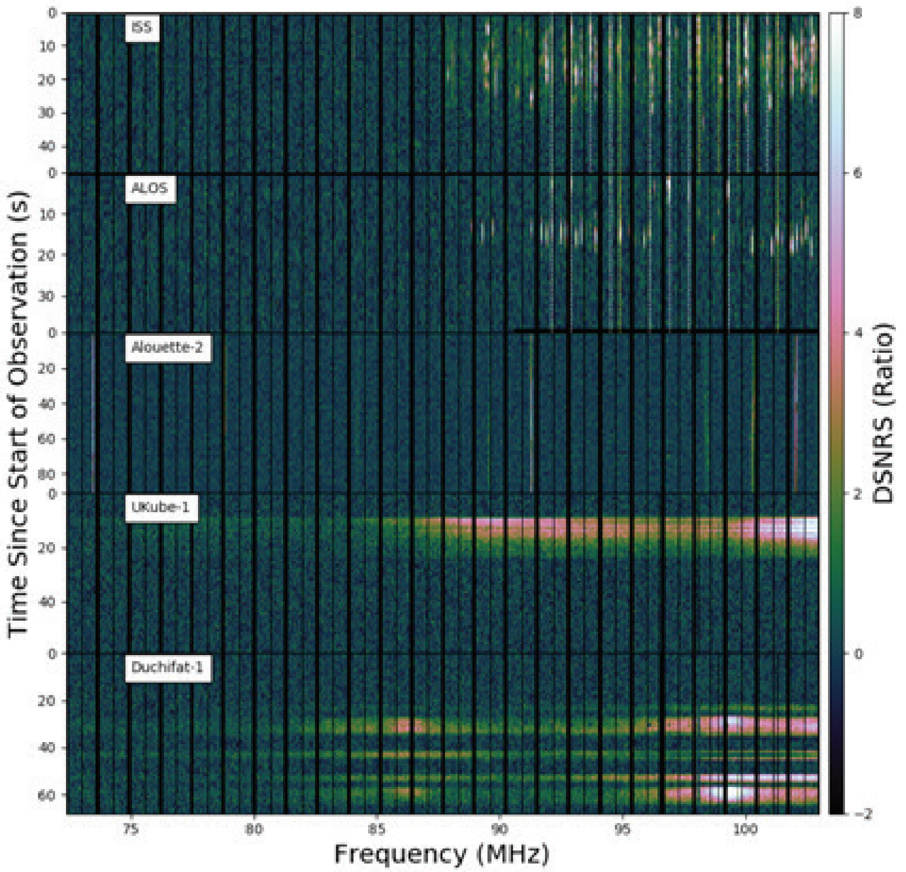
PAUL HANCOCK, STEVE PRABU & STEVEN TINGAY

In 2013 the MWA observed the International Space Station (ISS) as it transited over Western Australia (Figure 1). This work used just 32 tiles of the MWA while it was in it's commissioning phase, and used imaging software designed for narrow field of view instruments. The bright and easily detectable reflections from the ISS at frequencies coincident with known FM broadcast stations proved that the MWA could detect and track objects in Low Earth Orbit (LEO). From this work, Tingay et al 2013 predicted that objects with a radar cross section (RCS) as small as 0.79m2 could be detected up to a range of 1000km in images created from 1s of data at 50kHz resolution. This processing method is based on imaging the sky using correlated data products - the data are averaged in time and frequency and thus only the total received power is observed.

Since 2013 the MWA has been completed and seen upgrades that deployed a total of 256 tiles. We have seen advances on the data processing front as well, the most significant advancement being the creation of an imaging tool that is optimised for wide field of view instruments like the MWA, and the creation of multiple automated calibration and imaging workflows. In 2018, Zhang et al developed an image differencing based detection method that increases the effective sensitivity of the MWA to objects that move through the sky. Work by Prabu et al 2020a took this difference imaging method and adapted it to identify objects in LEO. Figure 2 shows the detection of objects at a range of sizes from the ISS (RCS~400m2), to the weather satellite ALOS (RCS ~13.5m2), and the defunct Alouette-2 (RCS ~1m2), via reflected FM transmissions in multiple bands. Also shown is the detection of two cubesats via what appears to be out-of-band transmissions. These new detection and measurement methods represent an effective increase in the sensitivity of the MWA system. Applying these new methods to 20 hours of data, we conducted a blind survey for objects in LEO. In Prabu et al 2020b, we report the detection of a further 74 objects, with an RCS as small as 0.1m2 and out to a range of 977km (Figure 3).



Left: Figure 1: The initial demonstration of the MWA's ability to work as a passive radar. Here a dynamic spectrum is formed at the location of the ISS as it transits the MWA. Reflected radio stations are identified as vertical streaks, with FM radio stations identified above. From Tingay et al 2013.



Left: Figure 2: Multiple objects in Low Earth Orbit have been detected using the Dynamic Signal to Noise Ratio Spectrum (DNSRS) developed by Prabu et al. 2020a. The upper three objects are detected via reflected terrestrial FM broadcasts (narrow vertical lines), while the lower two objects are seen to be transmitting out of band (wide horizontal bands). Both methods can be used to detect and monitor objects in Low Earth Orbit.

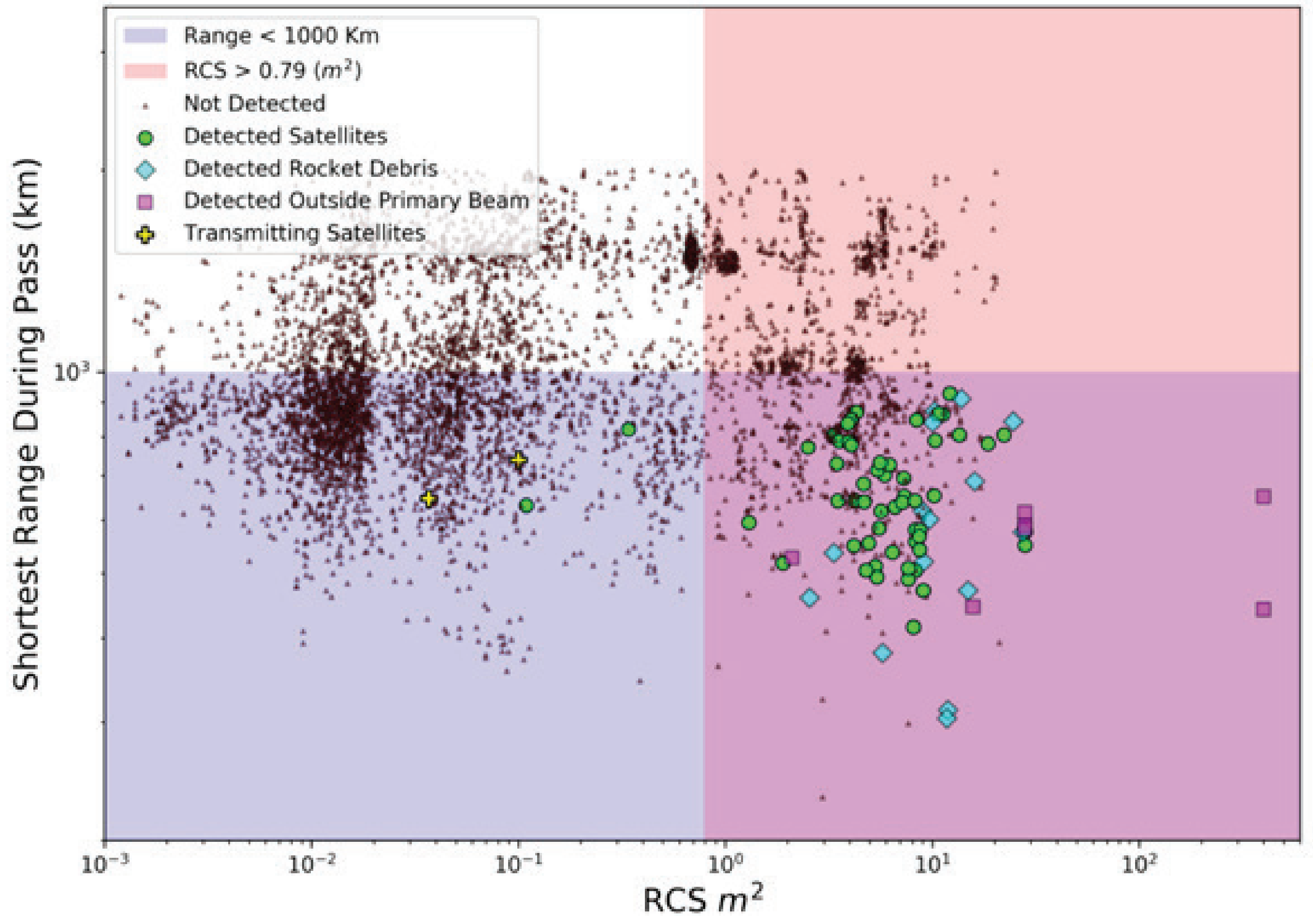
[1] Tingay et al., 2013. ui.adsabs.harvard.edu/abs/2013AJ....146..103T

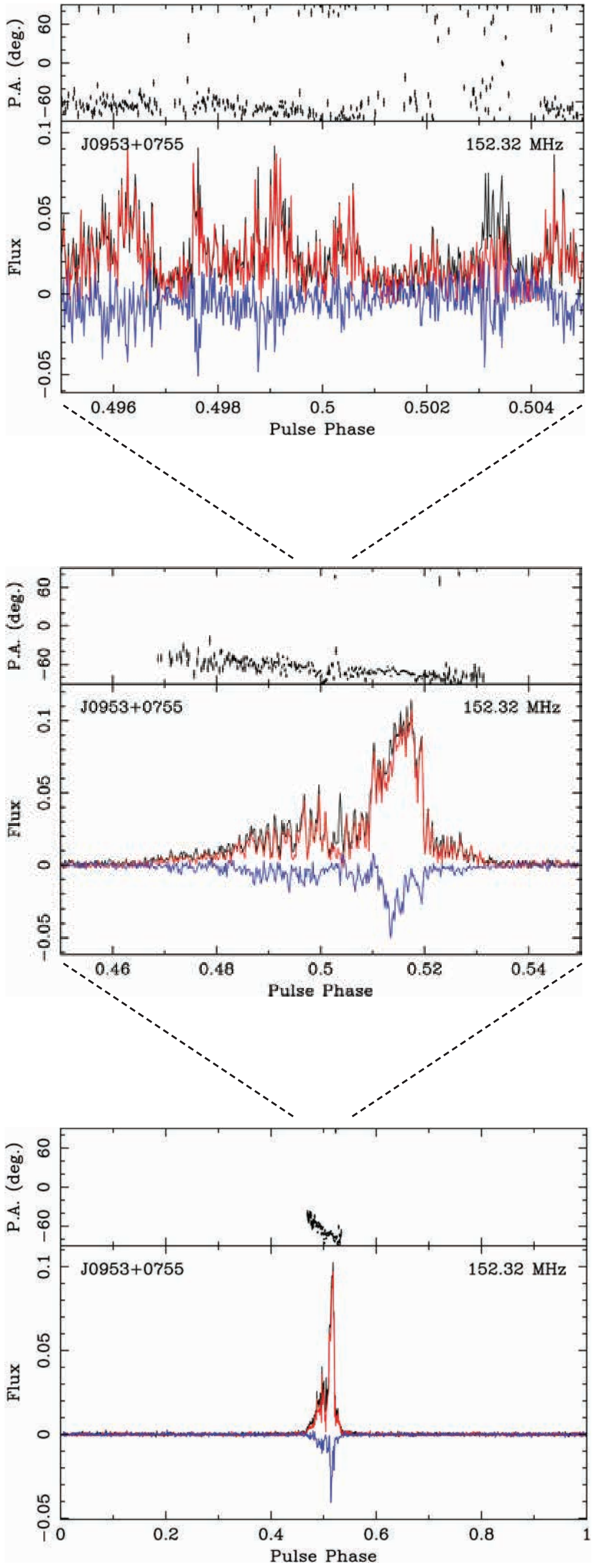
[2] Zhang et al., 2018. ui.adsabs.harvard.edu/abs/2018MNRAS.477.5167Z

[3] Prabu et al., 2020a. ui.adsabs.harvard.edu/abs/2020PASA...37...10P

[4] Prabu et al., 2020b. ui.adsabs.harvard.edu/abs/2020PASA...37...52P

Below: Figure 3: Objects in LEO that were above the horizon during the 20 hour survey. Black triangles show all objects, whilst colored markers show detected objects. The intersection of the blue and pink shaded regions represents objects which are expected to be detectable based on Tingay et al. 2013. This figure from Prabu et al. 2020b.





Far left: A single pulse of PSR B0950+08, observed with the MWA, shown in three zoom levels. The finest structure visible in the top plot is pulsar microstructure, which contains information about the structure of pulsar magnetospheres on length scales on the order of kilometres. Observing and studying it with the MWA is only possible thanks to the newly-installed high time resolution beamforming mode.

Increasing the time resolution of the MWA for expanding **pulsar and cosmic ray science**

SAMUEL JAMES MCSWEENEY
Associate Lecturer

The Murchison Widefield Array (MWA) was originally conceived as an instrument for generating images of the radio sky, and only later were the necessary hardware and software systems installed to enable the study of rapid time-varying phenomena like pulsars. The first implementation of these systems delivered telescope readings with a time resolution of 100 µs, and this system has been the bedrock of almost all MWA pulsar studies that have been published over the last several years. However, some pulsars rotate on the order of milliseconds, and show interesting behaviour on microsecond timescales. Many of the most pressing science questions of the day that relate to pulsars (e.g. the detection of nanohertz gravitational waves, more stringent tests of General Relativity), depend crucially on being able to obtain high quality, low frequency data on rapidly rotating pulsars of the kind that the MWA can potentially offer, if only the time resolution could be pushed higher. In addition, efforts to use the MWA as a tool for detecting cosmic rays---which would appear as detection events on nanosecond timescales---are also under way. All of these considerations motivated the development of a system that can reconstruct higher time resolution than what the original system offers.

Fortunately, upgrading the system to include a high time resolution mode did not require any changes to the existing hardware. The reason for this is that high time resolution samples can be reconstructed (the technical term is “resynthesised”) from the coarser time resolution data by virtue of the fact that the coarser time resolution data is recorded in multiple frequency channels simultaneously. There is a fundamental principle in communications science which states that the amount of information contained in a message (or, in this case, an astrophysical signal!) is proportional to the product of the time resolution and the frequency resolution. Thus, it is possible in principle to trade frequency resolution for time resolution without losing information. We exploited this principle to convert the available 3072 (small bandwidth) frequency channels into 24 (larger bandwidth) channels, thereby decreasing the frequency resolution by a factor of 128, and increasing the time resolution by the same factor. Thus, the original 100 µs time resolution is effectively upsampled to give a time resolution of less than 1 µs!

However, there is a small catch. Although systems can be (and often are) designed so that there is no loss of information when trading frequency information for time information, in practice some information loss cannot always be avoided. It is important, therefore, to be able to quantify how much information loss may occur. Two causes for signal loss were identified: (1) the deliberate choice to reduce the number of bits stored per sample, and (2) a side effect of the upstream (unalterable) channelisation algorithm. The combination of both causes result in a signal power loss of only ~3 - 5%, which is near the optimal recovery rate for this system.

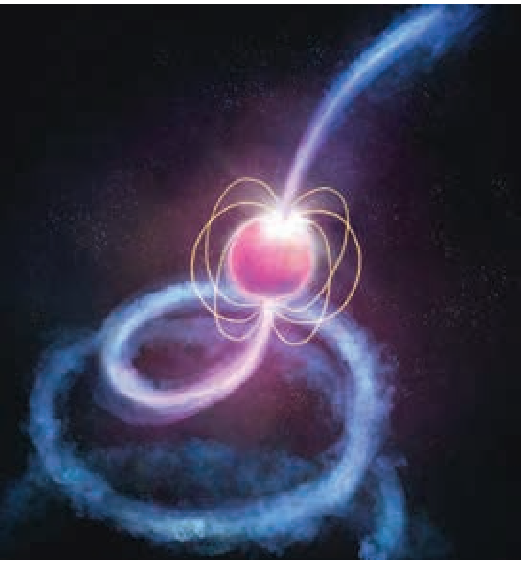
The new system was road-tested on three pulsars, PSRs J0437-4715, J2241-5236, and B0950+08. The first two are millisecond pulsars which are high-priority targets for timing array experiments. In their cases, the high time resolution mode revealed new fine structure at low frequency that had never been seen before. The third is a particularly bright, long-period pulsar (rotation period of about 250 milliseconds) which is known to exhibit extraordinary fine structure on microsecond timescales. In this case, the high time resolution system revealed this fine structure in exquisite detail (see accompanying figure), an impressive vindication of the validity and utility of the system. These spectacular examples, along with details of the algorithm and implementation of the high time resolution mode, are reported in McSweeney et al. (2020).

With this new system in place, the range of possibilities for pulsar studies with the MWA, as well as studies of other fast transients, has been considerably widened. Already it has been used to probe the frequency dependence of propagation effects in the interstellar medium (ISM), and to detect cosmic rays. Future plans include a program of characterising the low frequency behaviour ISM for many more pulsars---especially millisecond pulsars with a view to improving the prospects for gravitational wave detection---as well as campaigns to observe pulsar microstructure in order to study the dynamics of pulsar magnetospheres on length scales as small as a few kilometers. The future is bright (and fast!) for MWA pulsars.

First pulsar discovery for the MWA

RAMESH BHAT and the SMART Collaboration

Below: An artist's impression of a pulsar — a dense and rapidly spinning neutron star sending radio waves into the cosmos. Credit: Kaur



The Murchison Widefield Array (MWA), originally designed and built as an imaging telescope, has come a long way in its journey towards becoming a pulsar-capable telescope. Its high-time resolution functionality was developed around the voltage capture system (VCS), which meant dealing with large data rates and substantial software development and processing challenges to push this next-generation telescope into the fascinating world of pulsar astronomy. Thanks to the enthusiasm and support of the first cohort of PhD students who joined the group, the team was able to overcome these challenges and make major strides in this endeavour.

Over the past years the sustained effort in this direction has resulted in a series of capability developments for pulsar science with the MWA, culminating in the successful graduation of the first cohort of PhD students by 2020. The advances in the VCS suite of software and processing pipelines, the commendable progress made with early pulsar science, and the advent of the Phase 2 MWA, all presented new opportunities and led to the conception of the **S**outhern-sky **M**WA **R**apid **T**wo-metre (SMART) pulsar survey project – an ambitious all-sky pulsar survey that is designed to take advantage of the MWA's low-frequencies and prodigiously large field of view, as well as its unique voltage-capture functionality, which allows high-time resolution sampling of a large patch of the sky. It was well-motivated by the fact that pulsar discovery and science is a headline science theme for the SKA telescope, of which the MWA is an official Precursor.

A novel feature of the SMART survey is that the data are collected in the form of raw voltage samples instead of pre-processed data, which has been the standard for all past and ongoing pulsar surveys. However, it also poses two major challenges. First, the large data rates mean every single observation (1.5 hour long) would result in 42 Terabytes of data and nearly three Petabytes of data collection for the full survey, which will need to be stored and archived for the lifetime of the project. Second, the computational demands of processing these data are enormous, because of both the large field of view and the large parameter space that need to be exhaustively searched in order to find pulsar signals. The team courageously embraced these challenges, working towards their goal to gear up the MWA for pulsar searches.

As a first step, Curtin PhD candidate Nick Swainston augmented the tied-array beam-former software with a functionality that allows the simultaneous generation of several dozens of "pencil" beams. This new 'multi-pixel' beam-former was integrated with the software to search for pulsar signals. The pipeline was then road-tested on Pawsey's Galaxy supercomputer before porting and benchmarking on Swinburne's OzSTAR supercomputer, where time was secured via merit allocation through the Astronomy Supercomputing Time Allocation process. The enormity of data processing, however, warranted a double-tier strategy: first, processing just the first ten minutes of every observation (a "shallow" search), and only later processing the full 1.5 hours ("deep" search). The shallow search allows us to search the sky ~10 times faster, albeit at a reduced sensitivity of about one third of the deep search.

The strategy paid off through the discovery of a new pulsar, after processing only about one percent of the data collected to date! The pulsar, which goes by the name PSR J0036-1033, was found to have a rotation period of 0.9 seconds and a dispersion measure (DM) of 23.1 parsecs per cubic centimetre, placing it at a distance of approximately 1 kiloparsec. The team immediately swung into action and initiated extensive follow-up studies using multiple facilities including the Parkes 64-metre telescope (recently given the indigenous name Murriyang) and Giant Metrewave Radio Telescope, as well as the MWA, collectively covering a frequency range from ~150 MHz to 4 GHz. The investigations uncovered a number of characteristics of the new pulsar: 1) it has a steep spectrum, meaning it is 100 times brighter in the MWA band than in that which Parkes operates, 2) it has a very low luminosity, placing it in the lowermost two percentile of the currently known population of long-period pulsars, 3) its apparent brightness changes by a factor as much as 5-6 on timescales of several weeks to months, and 4) it has an estimated characteristic age of 67 Myr and a magnetic field of $4.4 x 10^{11}$ Gauss, confirming that it is a non-recycled pulsar. A paper reporting the discovery and results was recently published in the Astrophysical Journal Letters.

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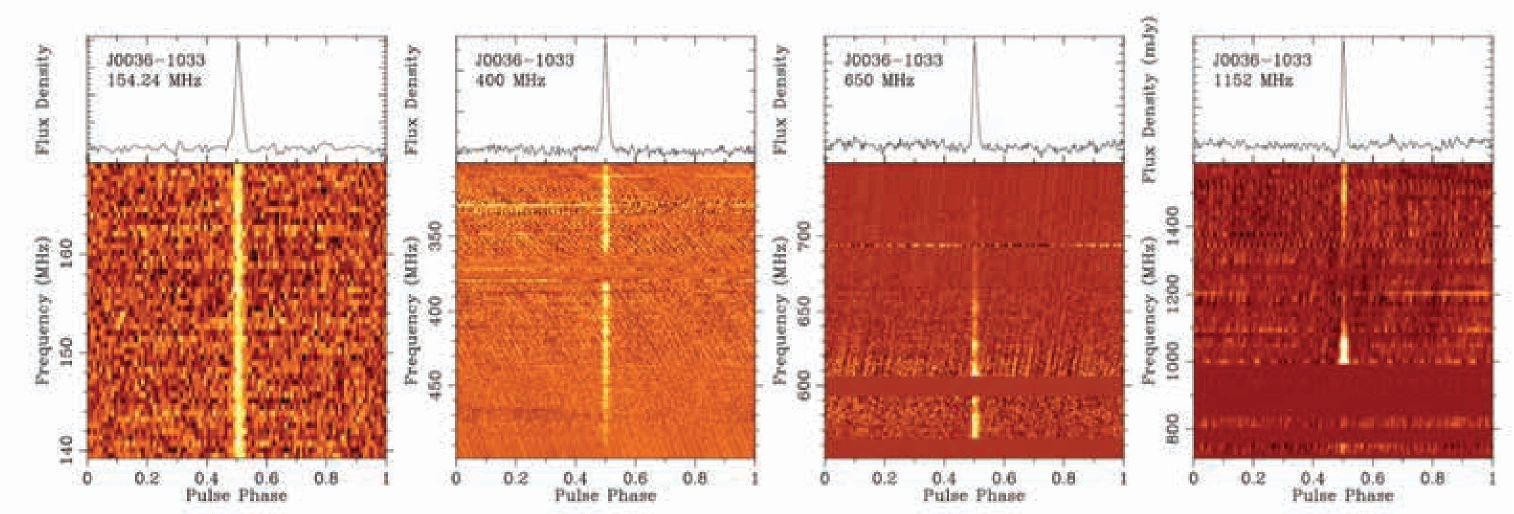
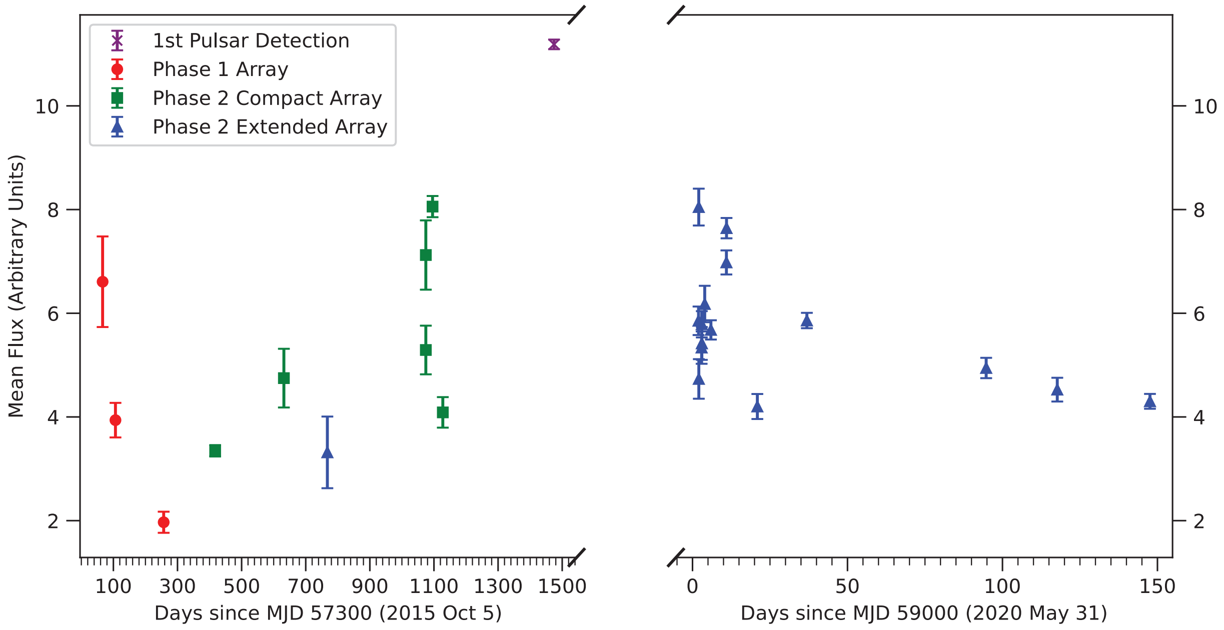


Above: Detection plots of the newly discovered pulsar PSR J0036–1033 with the Murchison Widefield Array (left panel), the Giant Metrewave Radio Telescope (two central panels), and the Parkes 64-metre (Murriyang) telescope (right panel): the top panels are the integrated pulse profiles and the waterfall plots below show the pulse strength versus pulse phase and frequency. MWA observations were made with the compact configuration of the Phase 2 array.

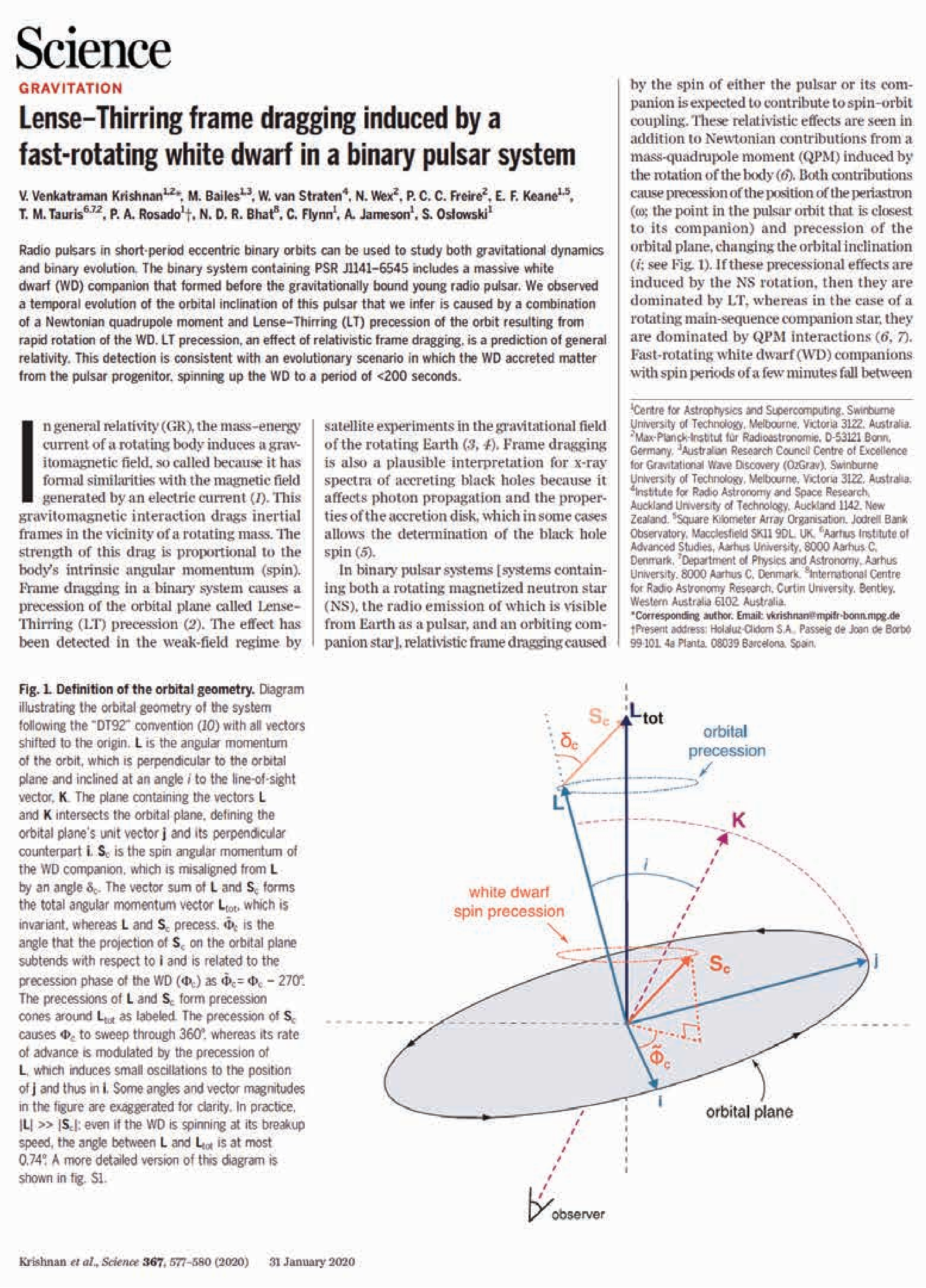
The discovery marks a significant milestone for pulsar science activity with the MWA, as this SKA precursor telescope puts its first foot into the pulsar searching space. However, going forward involves tackling further challenges. The first and foremost is the computational cost – an estimated 7 million core hours will be needed for the completion of the first pass shallow processing. Secondly, the daunting 'class imbalance' problem in pulsar searching, where finding a 'genuine' pulsar candidate involves sifting through zillions of spurious candidates (false positives) generated by the search algorithms, akin to finding a needle in a haystack! The new pulsar discovery at this early stage of the project is therefore extremely encouraging. The forecast from our simulation analysis is the survey will likely discover as many as 300 pulsars when the data are fully (and thoroughly) processed and analysed, heralding many new discoveries to come.

This leap was made in the year that was marked with many uncertainties and challenges arising from the COVID pandemic, as well as the distributed work arrangements due to the refurbishment work at CIRA. A significant setback was also the loss of a dear and much-valued colleague, J-P Macquart, whose presence is greatly missed by the group members. His insightful comments and constructive criticisms often served as important checkpoints for students and colleagues alike. The CIRA pulsar team remembers J-P very fondly and continues to draw inspiration from his unmatched passion and enthusiasm for science, as they work to push the MWA for doing impactful science in pulsar astronomy – a headline science theme for the SKA project.

Below: Observed variability in the mean flux density (brightness) of PSR J0036–1033, over a four year time span. The data shown on the left segment are from archival MWA observations dating back to 2016, whereas those on the right segment are from new observations (i.e. since 2020 June) made with the extended configuration of the array.



An artist's impression of one of 256 tiles of the Murchison Widefield Array radio telescope observing a pulsar — a dense and rapidly spinning neutron star sending radio waves into the cosmos. Credit: Dilpreet Kaur



Science

GRAVITATION

Lense–Thirring frame dragging induced by a fast-rotating white dwarf in a binary pulsar system

V. Venkatraman Krishnan[1,2,*], M. Bailes[1,3], W. van Straten[4], N. Wex[2], P. C. C. Freire[2], E. F. Keane[1,5], T. M. Tauris[6,7,2], P. A. Rosado[1]†, N. D. R. Bhat[8], C. Flynn[1], A. Jameson[1], S. Osłowski[1]

Radio pulsars in short-period eccentric binary orbits can be used to study both gravitational dynamics and binary evolution. The binary system containing PSR J1141−6545 includes a massive white dwarf (WD) companion that formed before the gravitationally bound young radio pulsar. We observed a temporal evolution of the orbital inclination of this pulsar that we infer is caused by a combination of a Newtonian quadrupole moment and Lense–Thirring (LT) precession of the orbit resulting from rapid rotation of the WD. LT precession, an effect of relativistic frame dragging, is a prediction of general relativity. This detection is consistent with an evolutionary scenario in which the WD accreted matter from the pulsar progenitor, spinning up the WD to a period of <200 seconds.

In general relativity (GR), the mass–energy current of a rotating body induces a gravitomagnetic field, so called because it has formal similarities with the magnetic field generated by an electric current (*1*). This gravitomagnetic interaction drags inertial frames in the vicinity of a rotating mass. The strength of this drag is proportional to the body's intrinsic angular momentum (spin). Frame dragging in a binary system causes a precession of the orbital plane called Lense–Thirring (LT) precession (*2*). The effect has been detected in the weak-field regime by satellite experiments in the gravitational field of the rotating Earth (*3*, *4*). Frame dragging is also a plausible interpretation for x-ray spectra of accreting black holes because it affects photon propagation and the properties of the accretion disk, which in some cases allows the determination of the black hole spin (*5*).

In binary pulsar systems [systems containing both a rotating magnetized neutron star (NS), the radio emission of which is visible from Earth as a pulsar, and an orbiting companion star], relativistic frame dragging caused by the spin of either the pulsar or its companion is expected to contribute to spin-orbit coupling. These relativistic effects are seen in addition to Newtonian contributions from a mass-quadrupole moment (QPM) induced by the rotation of the body (*6*). Both contributions cause precession of the position of the periastron (ω; the point in the pulsar orbit that is closest to its companion) and precession of the orbital plane, changing the orbital inclination (i; see Fig. 1). If these precessional effects are induced by the NS rotation, then they are dominated by LT, whereas in the case of a rotating main-sequence companion star, they are dominated by QPM interactions (*6*, *7*). Fast-rotating white dwarf (WD) companions with spin periods of a few minutes fall between

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Fig. 1. Definition of the orbital geometry. Diagram illustrating the orbital geometry of the system following the "DT92" convention (*10*) with all vectors shifted to the origin. **L** is the angular momentum of the orbit, which is perpendicular to the orbital plane and inclined at an angle i to the line-of-sight vector, **K**. The plane containing the vectors **L** and **K** intersects the orbital plane, defining the orbital plane's unit vector **j** and its perpendicular counterpart **i**. $\mathbf{S}_c$ is the spin angular momentum of the WD companion, which is misaligned from **L** by an angle δ_c. The vector sum of **L** and $\mathbf{S}_c$ forms the total angular momentum vector $\mathbf{L}_{tot}$, which is invariant, whereas **L** and $\mathbf{S}_c$ precess. $\tilde{\Phi}_c$ is the angle that the projection of $\mathbf{S}_c$ on the orbital plane subtends with respect to **i** and is related to the precession phase of the WD (Φ_c) as $\tilde{\Phi}_c = \Phi_c - 270°$. The precessions of **L** and $\mathbf{S}_c$ form precession cones around $\mathbf{L}_{tot}$ as labeled. The precession of $\mathbf{S}_c$ causes Φ_c to sweep through 360°, whereas its rate of advance is modulated by the precession of **L**, which induces small oscillations to the position of **j** and thus in **i**. Some angles and vector magnitudes in the figure are exaggerated for clarity. In practice, $|\mathbf{L}| >> |\mathbf{S}_c|$; even if the WD is spinning at its breakup speed, the angle between **L** and $\mathbf{L}_{tot}$ is at most 0.74°. A more detailed version of this diagram is shown in fig. S1.

ENGINEERING

Gearing up for the **Square Kilometre Array.**

Professor David Davidson
CIRA Engineering Director

The first year fully into the ICRAR-III programme continued the trajectory started in 2018, with a strong focus on the SKA-LOW prototype system, Aperture Array Verification System 2 (AAVS2). Several industrial projects were undertaken, speaking to early success in the Translation and Impact space. The team continued to work productively throughout the massive and unplanned disruption occasioned by COVID-19 in the second quarter of the year, and the more orderly disruption caused by the renovations to building 610 in the last quarter. I would like to express my appreciation of the positive approach maintained by the engineering team throughout all the challenges of the year.

In 2019, in collaboration with our Italian partners INAF, a very challenging program had been completed, with the deployment of a 256-element SKA-LOW station on the MRO. The station used the new SKALA4.1 antenna developed by INAF from the SKA reference design, and is known as AAVS2. Analysis, simulation and commissioning work on this prototype station continued throughout 2020. This resulted in a number of publications in journals and refereed conference proceedings. These papers documented sensitivity results obtained by both simulation and measurement and compared these to SKA-LOW specifications. The engineering group made a substantial contribution to the SKA-LOW AAVS2 Test Results and Simulation Meeting on 23-24 June 2020, held by teleconference.

The COVID-19 pandemic resulted in effectively all major conferences in antenna, radio frequency and microwave engineering being either postponed or migrating to online format. This included the EuCAP’20, IEEE APS and URSI GASS meetings. CIRA staff contributed to all these major meetings, organizing sessions and presenting papers, as well as more specialist meetings such as ICCEM’20.

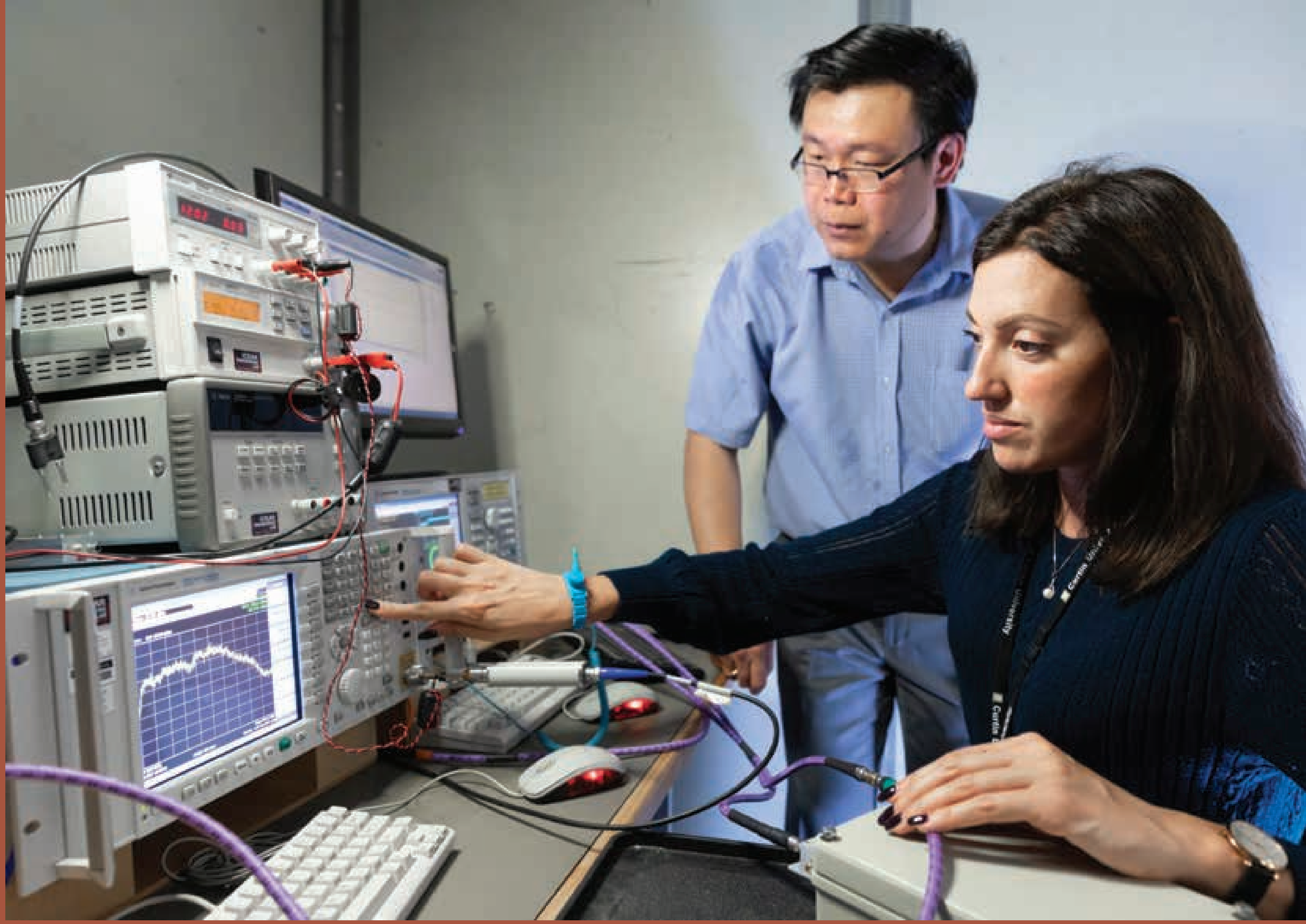
Regarding personnel, a new appointment was made in the Engineering group; Dr Danny Price joined us from Swinburne University of Technology. He is an expert in radio astronomy instrumentation, having worked at the Harvard-Smithsonian Center for Astrophysics and University of California Berkeley prior to joining Swinburne. He has a particular interest in SETI, and is currently the Australian Project Scientist for Breakthrough Listen.

As noted in the introduction, the engineering group also contributed to T&I. A report on the first phase of an investigation into high power microwave effects on electronic circuits was prepared for Defence Science and Technology; DST then commissioned a second phase which has continued into 2021. An EOI to develop a white paper on phased arrays for submarine communications for Lockheed Martin Australia was submitted, and LMA subsequently awarded a contract for this. A third project is in progress for the Defence Science Centre on a rapidly deployable space surveillance system. In terms of other smaller projects, we contributed to software development for a new correlator for the MWA (MWAX); another project addressed Global EoR science.

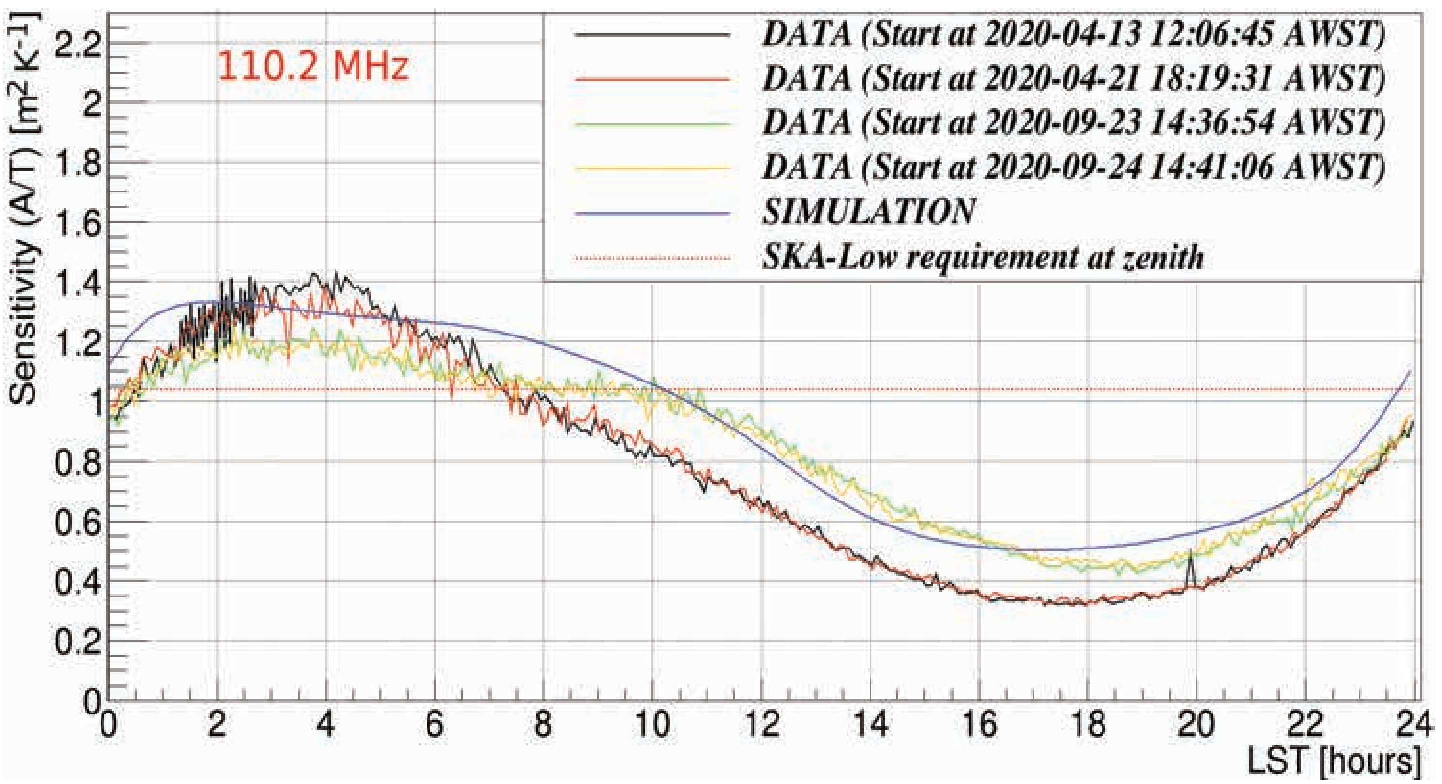
Additionally, we continued our traditional teaching within electrical and electronic engineering, being responsible for three undergraduate courses and supervising around thirty final year Electrical Engineering and capstone Computer Science projects. A further contribution was the presentation of a new course at Curtin entitled “Satellite Communications”. It was presented as part of the taught Master’s program in electrical engineering by members of the engineering group.

In November, we took delivery of our new Keysight 32 channel PXI vector network analyser. This permits the simultaneous characterisation of up to 32 antennas and should prove very useful as we progress our work on aperture arrays for radio astronomy and phased arrays for industry applications.

With the SKA Observatory Convention ratified during the course of the year, 2021 promises to be equally busy as we gear up for the first stages of SKA construction, presently scheduled for mid-2021.



Above: Research Engineer Dr Budi Juswardy and Associate Lecturer Maria Kovaleva in the CIRA radio laboratories. Credit: ICRAR



Above: The measured and simulated sensitivity in "Y" polarisation at 110 MHz, compared with the SKA requirement (for one station) at zenith, for varying local sidereal times (LSTs).

Far right: SKA-Low prototype stations, AAVS2 (top image) and EDA2 (bottom image). The key difference between them is the antenna type: AAVS2 uses 'Christmas-tree'-style log-periodic antennas, whereas EDA2 uses the well-known MWA-style 'bowtie' dipole antennas, making it easier to characterise system performance. Credit: ICRAR

Commissioning and verification of the SKA-Low bridging arrays

RANDALL WAYTH
Associate Professor

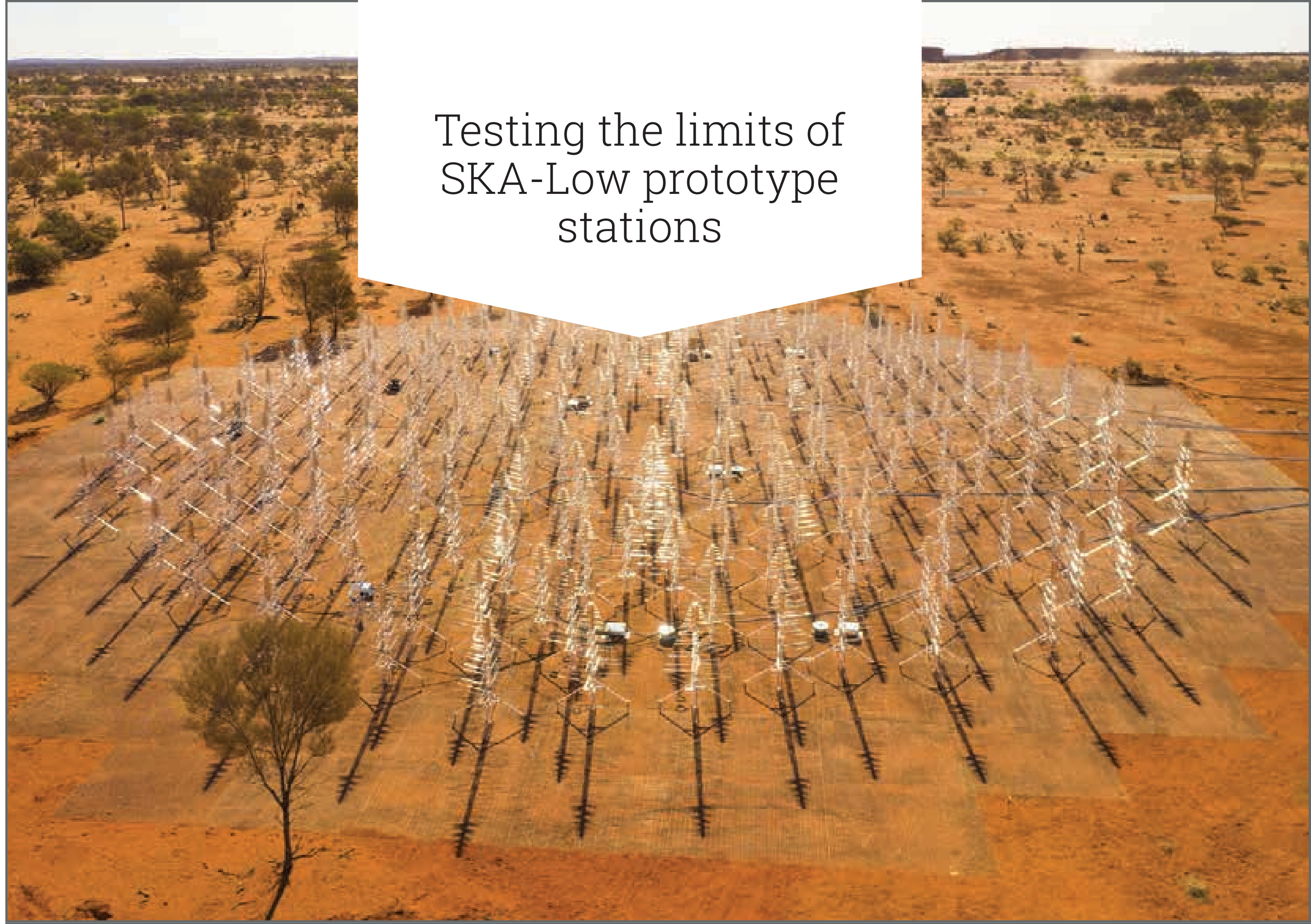
CIRA's Engineering and Astronomical Instrumentation groups have continued critical commissioning and verification work on the SKA-Low prototype stations Aperture Array Verification System 2 (AAVS2) and Engineering Development Array 2 (EDA2), which were deployed in 2019. The EDA2 and AAVS2 arrays are single prototype stations for SKA-Low, and include upgraded signal transport links and ever improving backend software and firmware. The stations are comprised of 256 antennas: AAVS2 uses SKALA4.1 log periodic dipole antennas, and the EDA2 uses 256 MWA-style dipoles. The signals from all antennas in the array are combined electronically, so that the station works as a single large radio antenna that can be steered electronically with no moving parts. Radio antennas that use many antennas whose signals are combined electronically like this are generically called "Aperture Arrays".

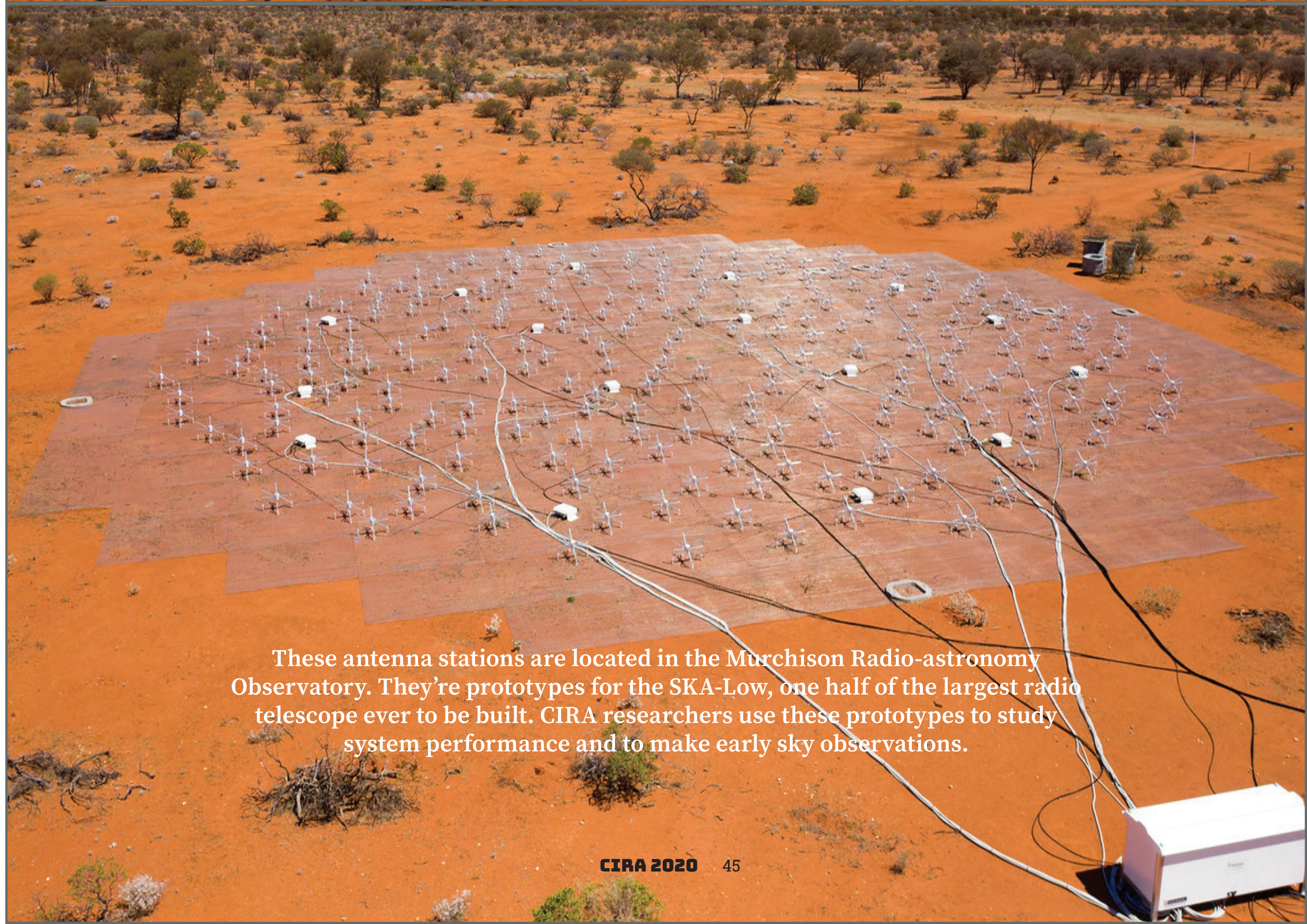
The foremost performance metric of a radio telescope is its sensitivity, hence measurement and verification of the on-sky sensitivity of the telescope is an essential milestone in the commissioning process. The sensitivity of a station is determined by A/T (collecting area divided by noise temperature - usually pronounced 'A on T'), which is complicated to predict for large aperture arrays like the EDA2 and AAVS2, hence verification is essential.

The sensitivity of the prototype arrays was measured by using the arrays as small interferometers with 256 antennas, rather than single large antenna station. In this way, all-sky images could be formed where the noise in the images is a direct measure of the station sensitivity. Preliminary results of this work for AAVS2 were published in 2020 for the 2021 EuCAP Antennas and Arrays Conference (Sokolowski et al.), an example result is shown above for the AAVS2 station.

An under-appreciated aspect of SKA-Low's performance is the variable level of background radio noise, which changes as the sky (and in particular the Galactic Plane) rotates. This manifests itself as a changing on-sky sensitivity, which is clearly seen in both the predicted and measured sensitivity of the station. This work was one of the first examples of actual measured sensitivity over a full sidereal day plotted against predicted performance. The agreement between the predicted and measured sensitivity is very good over the entire LST range. The difference between the plots is due to a temperature-dependent gain effect that was also discovered during the process to measure sensitivity.

Testing the limits of SKA-Low prototype stations





These antenna stations are located in the Murchison Radio-astronomy Observatory. They're prototypes for the SKA-Low, one half of the largest radio telescope ever to be built. CIRA researchers use these prototypes to study system performance and to make early sky observations.

A southern-hemisphere **all-sky radio transient monitor** for SKA-Low prototype stations

MARCIN SOKOLOWSKI

RANDALL WAYTH

RAMESH BHAT

DANNY PRICE

JESS BRODERICK

In 2019, the Engineering Development Array 2 (EDA2) and Aperture Array Verification System 2 (AAVS2), two prototype stations of the low-frequency Square Kilometre Array (SKA-Low) were deployed and commissioned at the Murchison Radio-astronomy Observatory (MRO). Since then, they have been used for various engineering tests ranging from testing of hardware components under the MRO conditions to verification of stations performance, such as real-time beamforming and station sensitivity, by comparisons with the electromagnetic simulations and SKA specifications. As the only major difference between the stations is the antenna design (AAVS2 uses SKALA4.1 antenna and EDA2 the same bow-tie dipoles as the Murchison Widefield Array (MWA)), the performance of the two stations can be compared and contrasted. These tests have shown that the real-time station beamforming and station sensitivity agree very well with the predictions of the simulations;the preliminary results were presented and published in the conference proceedings [1].

The prototype stations have also been used for transient monitoring using all-sky images, i.e. horizon to horizon images of the entire visible hemisphere (Figure 1): a unique capability unavailable to any other radio-telescope in the southern hemisphere! We analysed a few hundreds hours of 2-second cadence all-sky images using a real-time transient search pipeline. The pipeline finds transient candidates in difference images from both stations, requires spatial and time coincidence of the transient candidates from the both stations and excises non-astrophysical events, such as RFI due to satellite or aircraft reflections and transmissions, by cross matching positions of transient candidates with positions of known objects in the Earth orbit and pre-defined aircraft flight paths in the vicinity of the MRO.

So far, the most intriguing detections are extremely bright transients from the pulsar PSR B0950+08 on 2020-04-10/11, with the radio-transients detected in the 2-second images reaching flux densities of order160 Jy (Figure 2). The cumulative distribution of the observed pulse fluences follows a broken power-law, suggesting that the bright pulses may be analogous to giant pulses such as those observed from the Crab pulsar; that is, they arise from effects intrinsic to the pulsar and not propagation effects. Similar bright pulses from PSR B0950+08 were also reported last year by the AARTFAAC group using LOFAR low-band antennas to form all-sky images at frequencies 58.3 and 61.8 MHz, and were interpreted as Crab-like giant pulses. The limitations of our current system (only 1.28 MHz bandwidth and time resolution of 2 seconds), however, prevented us from firm conclusions on the physical explanation of these bright pulses, and there is still a possibility that the observed activity is due to a complex combination of propagation effects. We have analysed nearly 360 hours of data spread over nearly 6 months and found that the night 2020-04-10/11 was very unusual and the pulsar was the most active (over 200 transients detected by each station).

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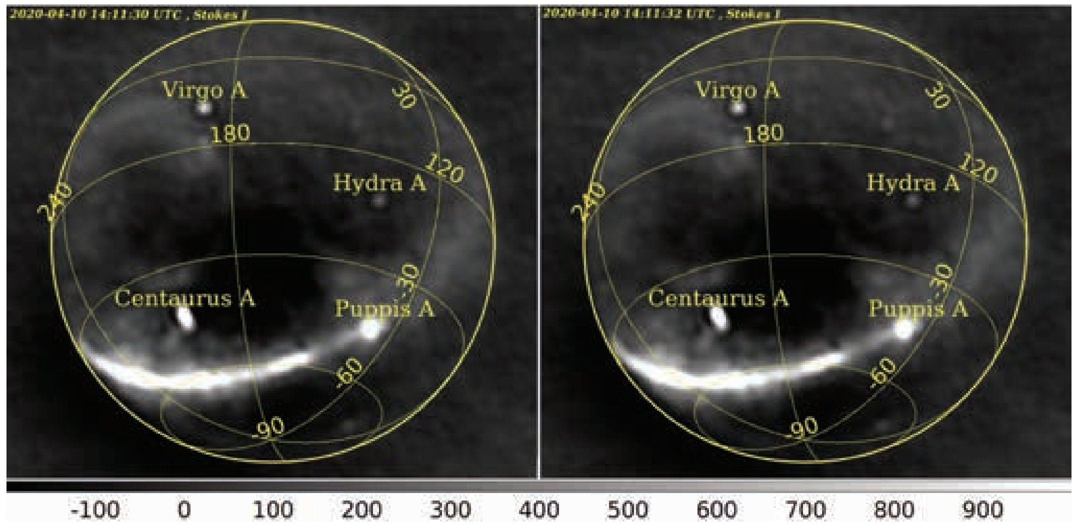


Right: Figure 1. Examples of two consecutive 2 second all-sky images from the EDA2 at 159.375 MHz collected on 2020-04-10 at 14:11:30 UTC (left) and 14:11:32 UTC (right). Both are Stokes I images, i.e. average of the beam corrected images in X and Y polarisations. The thicker yellow circle represents the horizon and the brightest radio-sources in the field are labelled. The difference of these images is shown in Figure 2.

> **“We have also discovered similarly bright transients from an unknown object, which is currently under investigation.”**

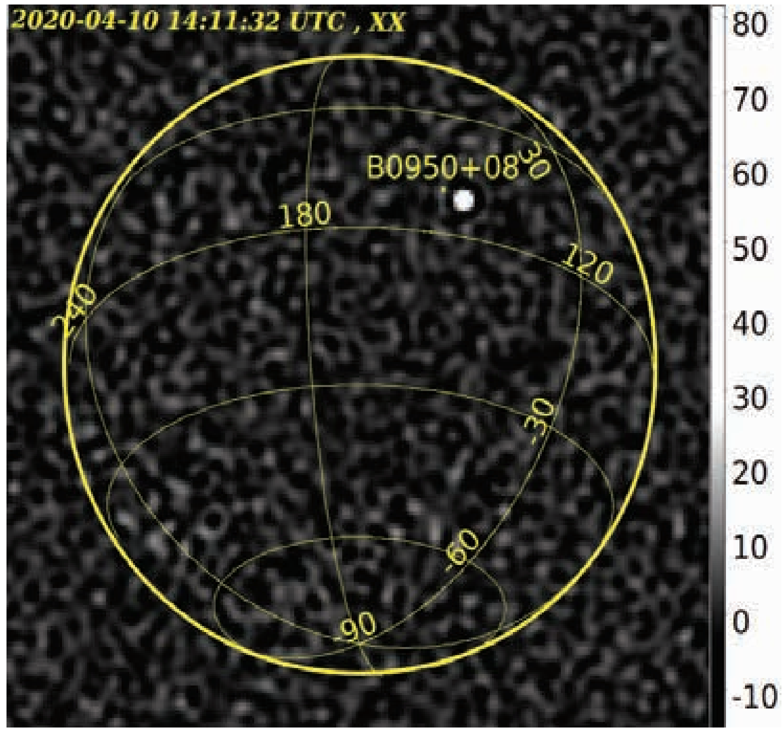
However, relatively bright transients from PSR B0950+08 were also observed on two other nights, but with fewer and fainter pulses. Besides these detections, we have also discovered similarly bright transients from an unknown object, which is currently under investigation.

We have also analysed nearly 130 hours of data when EDA2 observed at 160 MHz and AAVS2 at 230 MHz, and did not find any astrophysical radio-transients. This enabled us to derive a new upper limit on the surface density (SD) of transients brighter than 42 Jy at a timescale of 2 seconds of SD < 1.32×10−9 deg−2. This new limit fills a gap in a relatively unexplored region of the parameter space between upper limits at timescales of 1 and 5 seconds published by the AARTFAAC and the Long Wavelength Array (LWA) respectively.

Finally, we have recorded 2-second all-sky images at the time when three FRBs went-off: one detected by ASKAP and two other by the Deeper Wider Faster (DWF) project. Unfortunately, we did not detect low-frequency counterparts of these FRBs, but the derived upper limits on flux densities of FRBs 200914 and 200919 (of the order of 25-33 kJy ms) at frequencies 160 and 230 MHz from EDA2 and AAVS2 respectively were distributed as an Astronomy Telegram (ATEL #14044). All these results have been summarised in a publication [2]. In the future we are planning to increase the EDA2 observing bandwidth by at least a factor of 40, and start searching for FRBs in all-sky images at 10 ms resolution, which will increase sensitivity to FRBs by two orders of magnitude and enable detections of tens to hundreds FRBs per year.

[1] M. Sokolowski, J. W. Broderick, R. B. Wayth, D. Davidson et al. “Preliminary sensitivity verification of the SKA-Low AAVS2 prototype”, 15th European Conference on Antennas and Propagation (EuCAP 2021), March 2021

[2] M. Sokolowski, R. Wayth, N. D. R. Bhat, D. Price, J. W. Broderick et al., “A Southern-Hemisphere all-sky radio transient monitor for SKA-Low prototype stations”, PASA, 2021



Above: Figure 2. An example of 2-second Stokes I difference all-sky image obtained by subtracting image started on 2020-04-10 at 14:11:30 UTC from the next image started at 14:11:32 UTC. The very bright (approximately 80 Jy) transient from the pulsar PSR B0950+08 is clearly visible under the B0950+08 label. The thicker yellow circle represents the horizon.

Holography

RANDALL WAYTH
Associate Professor

In 2019, international student Uli Kiefner undertook and Engineering internship project to investigate if the SKA-Low prototype stations could be calibrated via an unusual technique call holography. This technique has traditionally been used to measure the surface accuracy of conventional "dish" radio telescopes. In the conventional holographic method, a separate antenna is used to generate a reference signal, then the antenna under test (AUT) is steered to many pointing directions on the sky to do the holographic measurement.

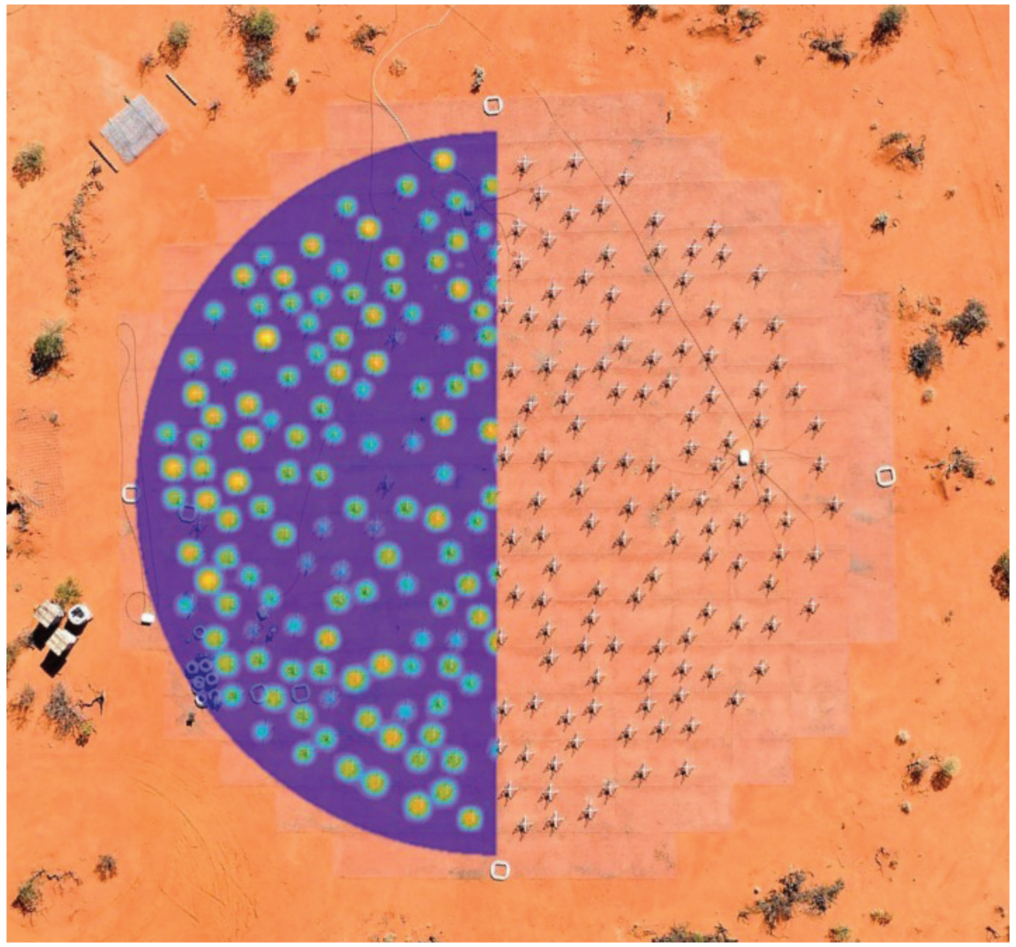
Following from some preliminary work performed by colleagues at ASTRON, this project investigated whether the aperture arrays of the prototype stations could be used to generate their own reference beams to perform a form of novel self-holography.

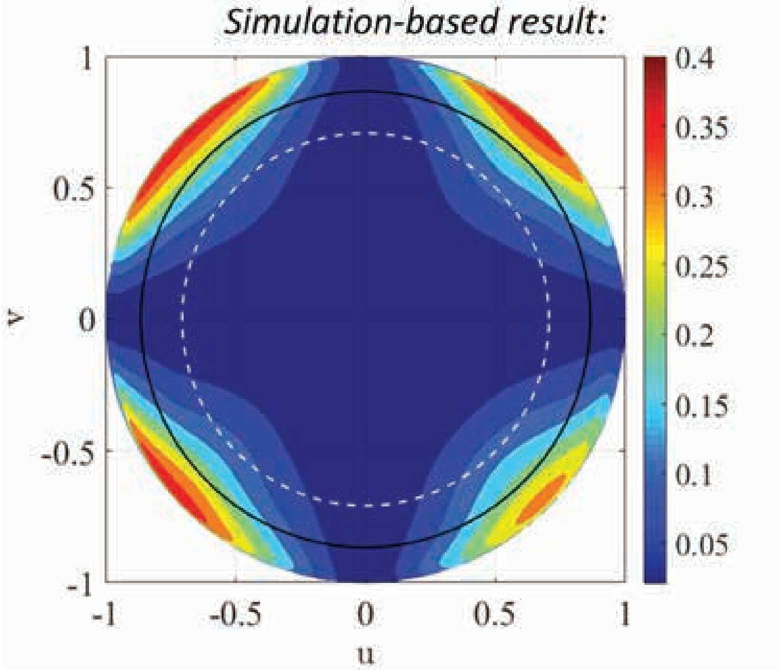
The result of the project was a definite "yes" - with the holographic technique generating high accuracy information about the station calibration, similar to a conventional calibration technique.

The image below shows a combined overlay of a drone-based image of the EDA2 with the actual aperture illumination image created by the holographic technique. The colour scale of the aperture image is proportional to the raw uncalibrated antenna gain (amplitude). This technique therefore provides a direct visual map of the electrical gain of each antenna in the array.

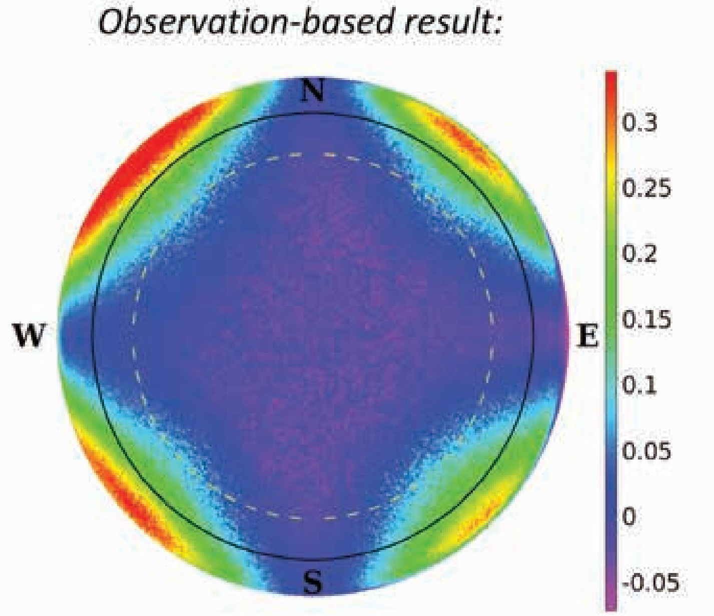
This work was published in the journal Radio Science by Kiefner, Wayth, Sokolowski and Davidson.

Below: Photo of EDA2 overlaid with aperture illumination image (left-hand-side) from holographic technique.
Credits: ICRAR, Kiefner





Relative difference between the derived formula and the narrow FoV formula for an embedded MWA dipole in a tile based on simulation. The black solid line is at zenith angle ZA=60 degrees, while the white dashed line is at ZA=45 degrees.



Relative difference between the derived formula and the narrow FoV formula for an embedded MWA dipole in a tile based on observation. The black solid line is at ZA=60 degrees, the yellow dashed line is at ZA=45 degrees, and the letters N, E, S, W show cardinal directions.

Sensitivity of a Low-Frequency Polarimetric **Radio Interferometer**

ADRIAN SUTINJO, MARCIN SOKOLOWSKI & MARIA KOVALEVA

Sensitivity of a radio telescope is a measure of the faintest source that can be observed by the telescope. The telescope sensitivity is proportional to the antenna area and inversely proportional to the total noise power during observation, including the sky noise and instrumental noise.

Modern low-frequency radio telescopes such as the Murchison Widefield Array (MWA), LOFAR, and the SKA-Low are designed to detect the state of polarization of celestial sources under observation. We refer to this as polarimetry. Also, these same telescopes consist of many smaller entities (called stations or tiles) that observe the sky by collecting data pair by pair over thousands or tens of thousands of pairs of such entities. This process is referred to as interferometry. Furthermore, these telescopes are sensitive to large swathes of the sky, which we refer to as wide field of view (FoV). In addition, these radio telescopes consist of antennas that are fixed to the ground and point electronically such that the antenna beam changes with pointing.

The said characteristics of a wide FoV polarimetric interferometric radio telescope suggest that there could be key differences between the low-frequency radio telescopes and dish-based radio telescopes. Indeed, dish-based telescopes are generally narrower in FoV and are mechanically pointed such that the sky is illuminated with the same antenna beam regardless of pointing. Therefore, certain figure-of-merit formulas for a low-frequency radio telescope which were derived assuming dish-based radio telescopes should be re-examined. Indeed, we found that the sensitivity of an interferometric and polarimetric radio telescope with a wide FoV requires generalization of the formula for which the narrow FoV is a special case.

In the published paper [1], we carefully derived a sensitivity formula valid for a low-frequency radio telescope without limiting the FoV nor assuming the polarization state of the source. The resulting formula is correct over all sky whereas the narrow FoV formula contains errors in the diagonal plane and low elevation angles. The formula was verified based on simulation and observation data. The figure shows a great agreement between simulation-based and observation-based verification. We are currently extending the work from a single-element interferometer to a phased array interferometer. We find that the extended formula is very similar to the single antenna case. This formula will be validated using astronomical observation data.

[1] arxiv.org/abs/2012.08075

Paving the way for commensal real-time **FRB and SETI searching** with the MWA

IAN MORRISON, GREG SLEAP, BRIAN CROSSE, MARCIN SOKOLOWSKI, CLANCY JAMES & DANNY PRICE

The hunt for Fast Radio Bursts (FRBs) and other radio transients is ramping up worldwide, particularly so with new-generation array telescopes, which enable localisation of the host source of emission. Telescopes like ASKAP, MeerKAT, UTMOST, CHIME and DSA-10 are now finding large numbers of FRBs, and CIRA researchers are at the forefront. For example, ASKAP recently achieved the first localisation of a non-repeating FRB [1]. Macquart et al used FRBs to probe the intergalactic medium and solve the missing baryon problem [2]. James et al used FRBs to discover that most rarely repeat [3].

The majority of FRBs have been detected at frequencies around 1 GHz, but recent discoveries have shown they emit energy at frequencies as low as 110 MHz [4]. With SKA-Low on the horizon, there is intense interest in using it to detect FRBs at low frequencies. It is important to prove that this is possible, which is where deploying an FRB search capability for the Murchison Widefield Array (MWA) will be invaluable.

In 2019 and 2020, we implemented a detection pipeline to co-exist with the forthcoming high-time-resolution front end that supports both voltage capture and real-time processing of MWA coarse-channel data (24 channels each of bandwidth 1.28 MHz).

The pipeline starts by capturing the MWA data stream, which creates a flow of "sub files" that contain the voltage signals from all MWA tiles over each 8-second sub-observation within each observation. These sub files are processed by a real-time beamformer that combines the signals from all tiles to provide increased sensitivity over a specified patch of the sky.

Incoherent beamforming, where powers from each tile are summed, retains the MWA tile's field-of-view (FoV), which is around 25o x 25o at 150 MHz. This is great for increasing the rate of FRB detection because we don't know where they will happen on the sky. By contrast, coherent (or "tied-array") beamforming sums the voltages, taking care to establish phasing relationships between all signals such that the result is a narrow pencil beam (of the order of 1-2 arcmin) on the sky in a specified direction. The smaller FoV is a disadvantage, however this is offset by higher sensitivity and hence the ability to detect fainter, more distant sources. Also, the reduction in FoV can be offset by generating, in parallel, multiple beams in different directions and searching for sources in each of the beams. The number of beams is constrained by available processing power, which in our case is determined by the GPU board fitted within the computer used to run the pipeline.

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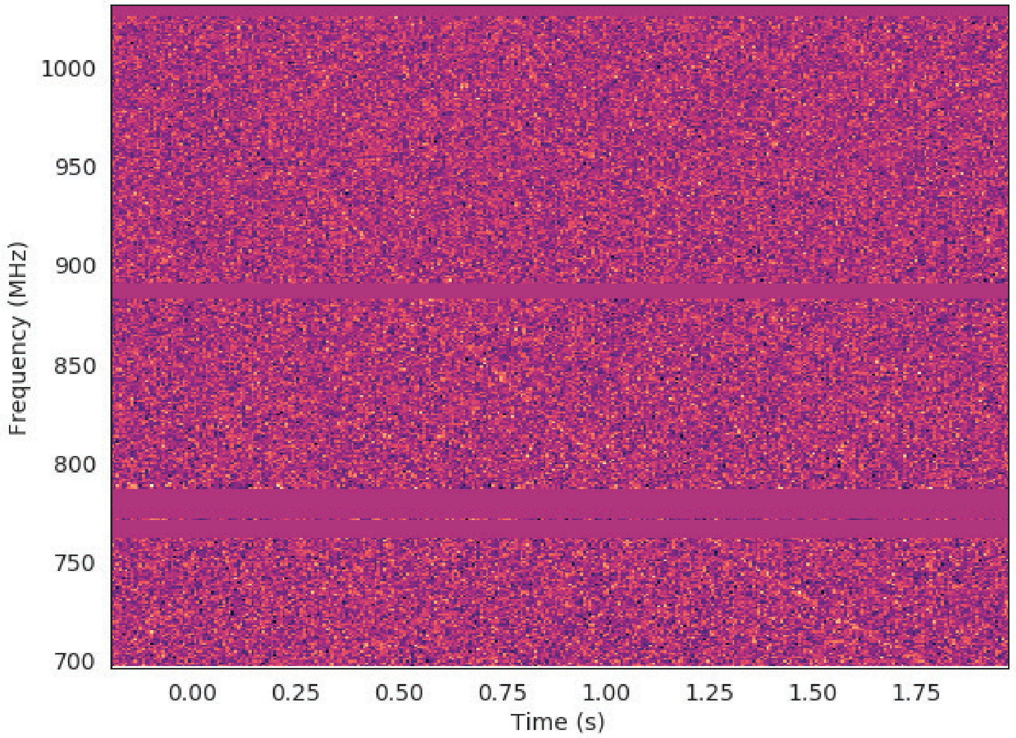
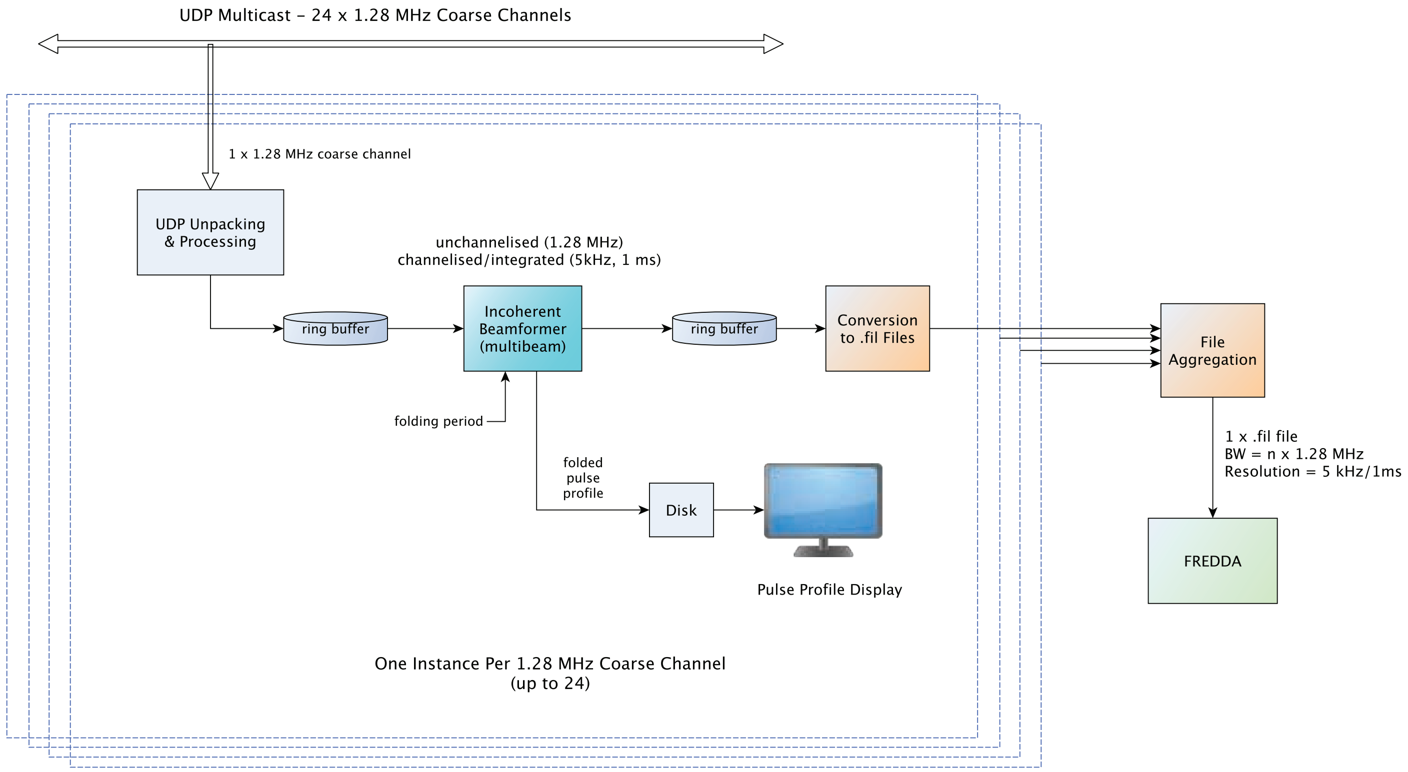


Right: FRB 200430 detected by ASKAP, showing the characteristic dispersion sweep in frequency as a function of time. The blanked regions are due to narrow-band RFI. Image courtesy P. Kumar.

Below: Block diagram of the MWA FRB search pipeline.



After beamforming we have single or dual-pol power or voltage signals, one signal-set per beam. Each beam's signal-set is stored in a special file format known as a "filterbank file". This format was chosen because we can then make use of an existing and highly optimised transient detection module, i.e. fast, real-time engine for de-dispersing amplitudes (FREDDA). FREDDA was originally developed and proven successful for FRB detection with ASKAP. It uses the fast dispersion measure transform (FDMT) to find dispersed pulses in the dynamic power spectra in the filterbank files and produces a list of FRB candidates, which can undergo additional filtering criteria (e.g. using machine learning) before visual inspection.

The same pipeline has also been adapted to support searches for technosignatures (also known as the Search for Extraterrestrial Intelligence (SETI)), by reducing the frequency resolution of the incoherent beamformer to 1 Hz. In this case the filterbank files are processed by our collaborators in the Breakthrough Listen team using their "turboSETI" software, which looks for emissions narrower than we would expect from known natural sources. While SETI searches have been done on MWA data before [5], we can reach far higher sensitivities (100 times more sensitive!) to narrowband signals with our system's exquisite 1 Hz frequency resolution.

Going forward we intend to begin a pilot commensal survey in incoherent beamformer mode, both for FRBs and technosignatures. Then later we plan to add a coherent beamformer mode option, to allow users to trade between FoV and sensitivity.

We are looking forward to using the MWA to discover the first non-repeating FRB below the current record of 320 MHz. Those working on SKA-Low will be watching with interest!

[1] K. W. Bannister et al, "A single fast radio burst localized to a massive galaxy at cosmological distance", Science Vol. 365, Issue 6453, pp. 565-570, August 2019.

[2] J. -P. Macquart et al, "A census of baryons in the Universe from localized fast radio bursts", Nature, Vol. 581, Issue 7809, pp. 391-395, May 2020.

[3] C. W. James et al, "Which bright fast radio bursts repeat?", MNRAS, Vol. 495, pp. 2416-2427 , June 2020.

[4] Z. Pleunis et al, "LOFAR Detection of 110-188 MHz Emission and Frequency-Dependent Activity from FRB 20180916B", arXiv:2012.08372, Dec. 2020.

[5] Tremblay et al, A SETI Survey of the Vela Region using the Murchison Widefield Array, PASA, Vol. 37, pp. 35, Sep. 2020.

The revised MWA antenna - a team effort

DAVID KENNEY
Project Engineer

The antenna is the first and perhaps the most important component in any radio telescope. It performs the conversion of radio waves from astronomical radio sources into electrical voltages.

The Murchison Widefield Array (MWA) is a low frequency radio telescope, located at the Murchison Radio-astronomy Observatory (MRO), which is maintained and operated by the Curtin Institute of Radio Astronomy (CIRA). Since commissioning in 2013, the MWA has used the same antenna, an active dual-polarised, bow-tie design. There are currently 4096 such antennas in the array.

Following many years of operation, some design limitations with the antenna have been identified and improvements desired. These mostly relate to mechanical problems experienced over years of use however improvements in manufacturability, reliability and maintainability were also desired.

Given the above requirements, CIRA staff worked together with consulting engineers from GENG to develop a revision of the antenna that achieves the design improvement while preserving the electromagnetic properties of the current design. With specialist knowledge and experience in manufacturing methods and materials, industry partner GENG have developed an innovative prototype design known as the Curtin Radio Astronomy Bow-tie or CRAB. Innovative ideas in the prototype include; tool-less assembly, pressure based dipole electrical connections, castable one-piece dipole arms, tight tolerance design, dustproof electronics housing and quick connect/release feet.

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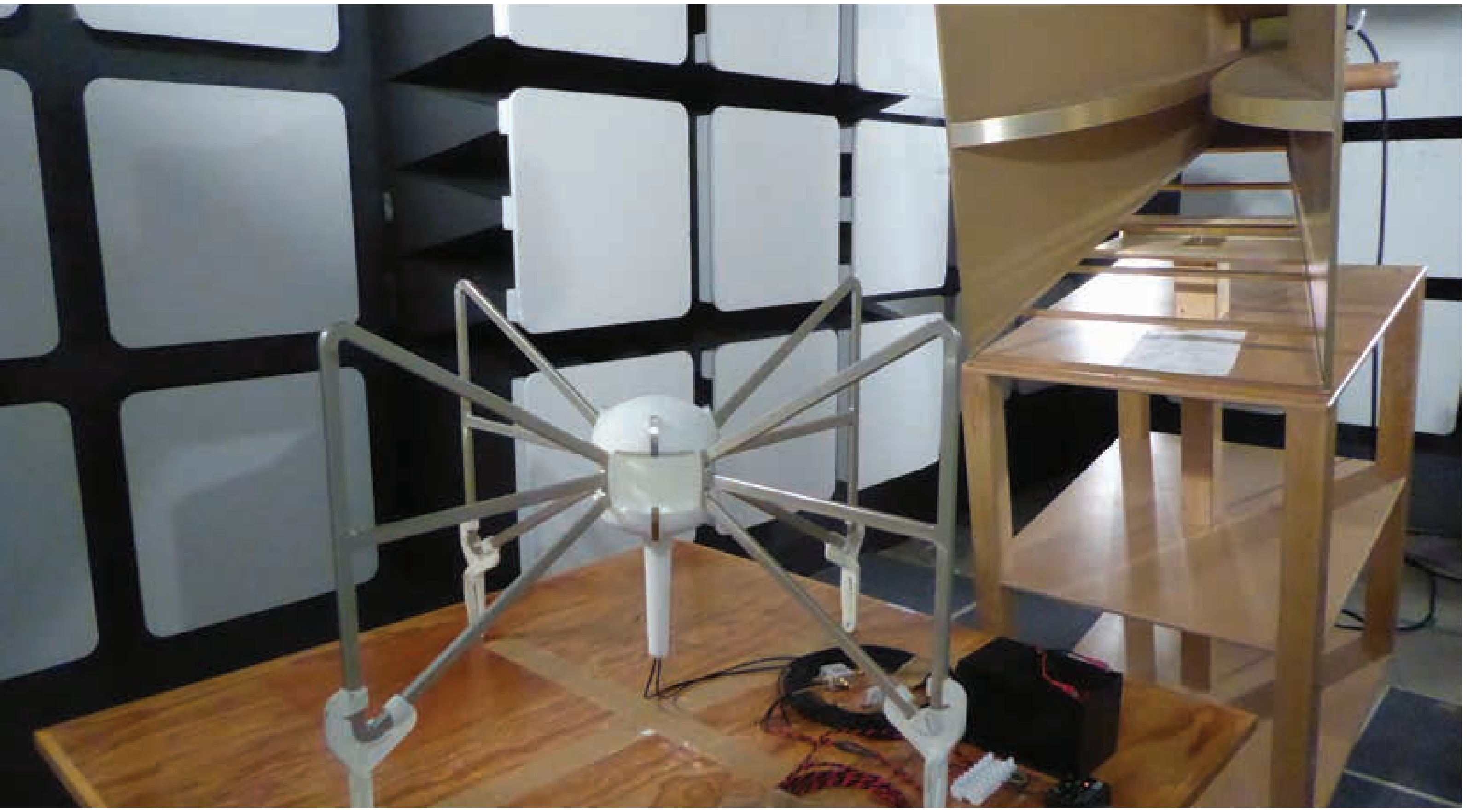
Below: Radiated emissions testing of the CRAB antenna prototype. Credit: Kenney



> **“The improvements offered cannot come at the expense of the performance of the antenna.”**

As mentioned, the improvements offered cannot come at the expense of the performance of the antenna. To evaluate this, a passive test PCB was produced to assist with characterising the dipole impedance. Using specialist equipment from the CIRA Engineering laboratory, an outdoor measurement was performed to confirm the change in the dipole design did not create a significant change in response of the antenna over the operating frequency.

Next was the development of the antenna electronics, the role of which is to amplify the voltages from the dipoles without significantly degrading the radio signal. This is commonly referred to as a Low Noise Amplifier (LNA). Local electronic designers from BrainSystems assisted in this task, providing Printed Circuit Board files for the electronics. Using these files, Linktek, an Australian company specialising in high frequency PCBs, was able to fabricate the circuit board. Assembly and testing of the LNA was then performed in-house at CIRA.

While laboratory testing provides valuable information, the ultimate way to evaluate the CRAB antenna and verify the objectives of the design is to monitor its performance within a telescope in the field, in particular at the MRO. As with any active device deployed at the MRO, the CRAB design must comply with site radiated emissions requirements. These requirements are set by CSIRO who operate the MRO. This is to ensure that the telescopes at the MRO, a radio quite zone, can detect astronomical radio sources as opposed to detecting electromagnetic signals generated by the telescope hardware. Assessment for electromagnetic compliance was performed at the Curtin University EMC Laboratory.

The CRAB antenna prototype is now approved for deployment at the MRO, once proven in the field, this antenna will be used in future radio telescopes.

Above: Outdoor characterisation of the CRAB dipoles using a Vector Network Analyser (Clinton Ward and Maria Kovaleva). Credit: Kenney

Investigating how **High Power Microwaves (HPM)** affect electronic components

BUDI JUSWARDY, AARON SILVESTRI & ADRIAN SUTINJO

Radio frequency and microwave interference, when transmitted into a remote target with sufficiently high power, could potentially produce intense electromagnetic fields that can disable electronic circuitry at a distance.

We have been investigating the effect of high power microwaves (HPM) on semiconductor and electronic components, as part of research agreements with Defence through the Defence Science and Technology Group, funded by the Next Generation Technologies Fund (DSP ID9520 and ID10020) [1]-[3]. The aims of our study are to analyse the effects of HPM pulses on the circuit response, understand the failure mechanism and to validate the semiconductor modelling and simulation results.

During our initial investigation, we identified two major effects of HPM on semiconductor and electronic components:

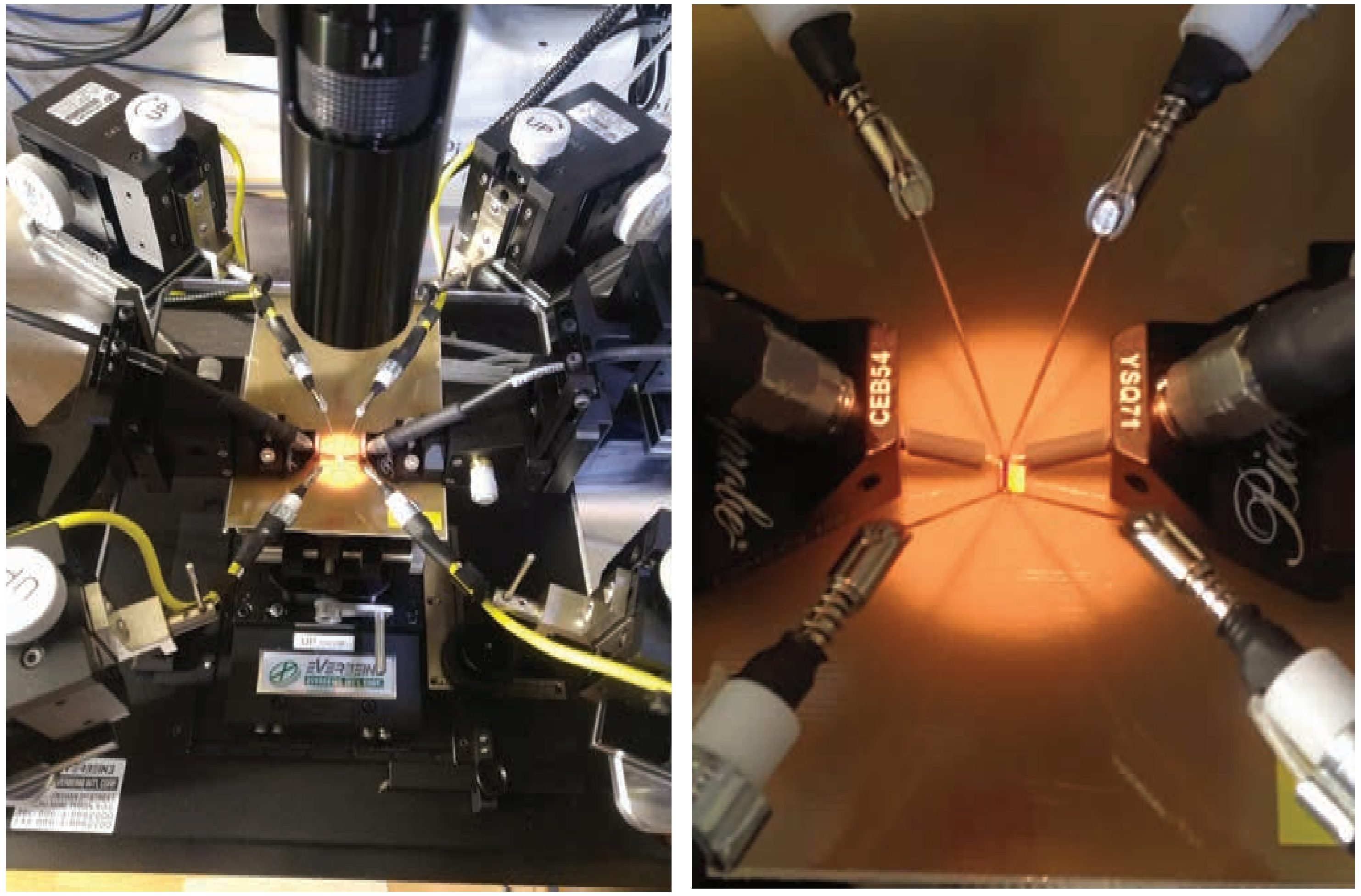
- **Upset event (soft failure):** temporary disturbance to the functionality of the device/system, which may lead to permanent damage over time if the event is sustained.
- **Catastrophic failure (hard failure):** Permanent damage immediately upon exposure to HPM.

As most of the electronic devices are implemented using the complementary metal oxide semiconductor (CMOS) process, we focussed our investigation on failure mechanisms in devices fabricated using this process. In CMOS devices, a failure mechanism called a 'latch-up event' could be triggered upon exposure to HPM, which disrupts the functionality of the device and leads to permanent damage due to overcurrents.

CONTINUED-

Right: The measurement set-up for HPM injection and semiconductor characterisation at the CIRA laboratory. Credit: Silvestri

Below: A semiconductor probe station in the measurement set-up, probing the manufactured CMOS prototype. Right photo is a zoomed-in shot of the middle of the left photo. Credit: Juswardy



To validate our model and simulation results, we designed a custom CMOS device, and sent the integrated circuit (IC) microchip for fabrication on a commercially available 0.35µm CMOS technology from a semiconductor foundry in Europe. We have also constructed an experimental set-up and semiconductor probe station at the CIRA lab, to characterise our prototype, as well as to inject HPM current directly into the microchip and analyse the response of the prototype.

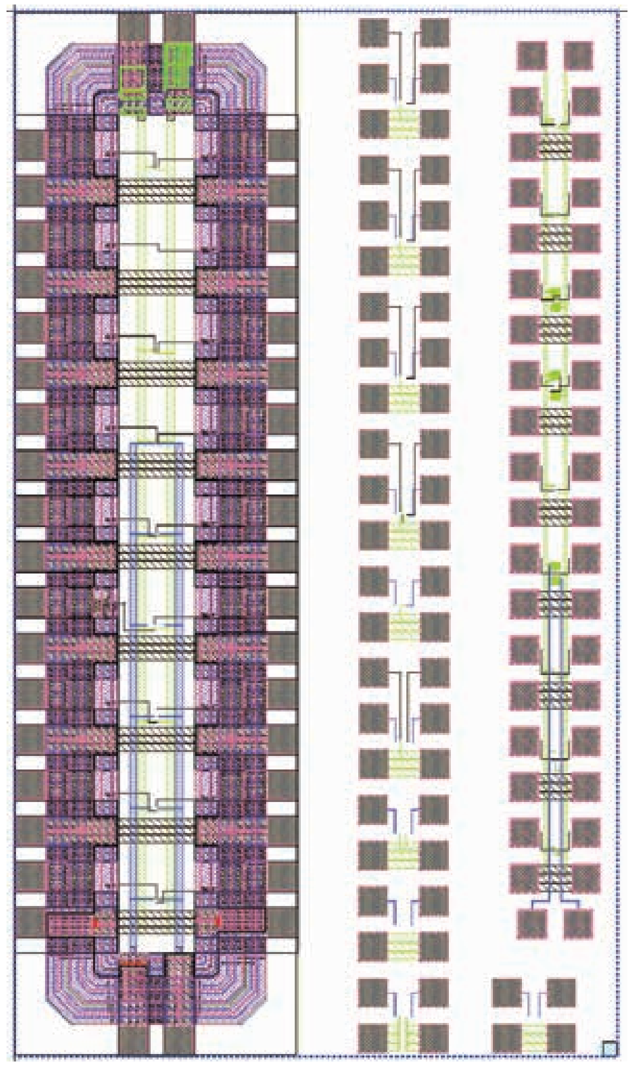
The results of these investigations will be used to further validate and refine our simulated models of electronic devices responding to HPM pulse injection, and could potentially provide further insight into how to design for HPM-hardened electronic systems in the future.

This work has been supported with Defence funding, through the Next Generation Technologies Fund.

[1] B. Juswardy, M. Kovaleva, D. Ung, A.T. Sutinjo, "A Case Study- HPM effect on a simple circuit with CMOS transistors", Work Package 2, DSP Research Agreement ID10020.

[2] "Research Agreement: Study of high power microwave effects on electronic components," Defence Science Technology Group, Edinburgh SA, Feb. 2020.

[3] A. Sutinjo and D. Ung, "Theoretical analysis of interaction between HPRF and electronic devices," Curtin University, Bentley WA, Apr. 2020.



Left: The layout of the manufactured CMOS prototype. Credit: Juswardy

Connecting **scientists** and **engineers**.

Tom Booler
CIRA Operations Director

It's impossible to reflect on 2020 without acknowledging the impacts of the COVID19 pandemic. In Western Australia we fared better than most, perhaps better than anywhere else. Nevertheless, in a local context, the pandemic disrupted business as usual and presented a variety of significant challenges.

In the early days of the pandemic the situation was still developing rapidly, and information was changing nearly as quickly as it could be passed on. The lack of certainty compounded people's natural anxiety about the crisis unfolding around the globe. CIRA responded quickly. Students and staff adroitly navigated the administration required to ensure a safe and efficient transition to remote working. Those unable to work from home pitched in to implement the procedures necessary to ensure a safe working environment was maintained at CIRA. There were, inevitably, friction points in process and personal edge cases to work through. Everyone at CIRA rose to the occasion, demonstrating remarkable patience and understanding considering the circumstances.

All CIRA staff and students, and the leadership group in particular, owe a debt of thanks to the CIRA Admin Team. As the primary interface to and for the group, they bore the brunt of the wave of questions triggered by every update in the pandemic situation, and every new piece of guidance issued by the University. They also shouldered the lion's share of the considerable load associated with ensuring that we knew where everyone was and, more importantly, how they were doing. Their efforts were critical to the efficiency and effectiveness—relatively speaking, and not minimising peoples' personal challenges—of CIRA's transition to the state of 'COVID-normal' that we settled into for much of 2020.

2020 saw the continued evolution of CIRA's 'Translation and Impact' (T&I) initiative. A number of the articles in this report attest to the diversity of the non-core activities CIRA researchers are becoming engaged in. In 2020 CIRA provided a secure data sharing platform in support of sensor testing activity conducted by the Air Force; investigated the effects of directed energy on electronics for the Defence Science and Technology Group; wrote a white paper on small form factor, multi-function communication systems for submarines for Lockheed Martin Australia; operated and maintained Square Kilometre Array prototypes on the Murchison Radio-Astronomy Observatory; led the international Murchison Widefield Array (MWA) Collaboration; et cetera, et cetera, et cetera. CIRA's T&I success has been largely facilitated by Mr Andrew Burton. Andrew has rapidly assimilated CIRA's T&I philosophy and established himself, and CIRA, as an exemplar of effective industry engagement.

Throughout 2020 I was on hiatus from my role as Program Manager of the Murchison Widefield Array (MWA). I am very grateful for the efforts of Ms Mia Walker who, more than ably, supported the MWA Director in my stead. Mia's patience and agility were critical enablers of the MWA Team's ability to maintain MWA operations, and continue to support the international collaboration in the face of the numerous obstacles presented by the pandemic.

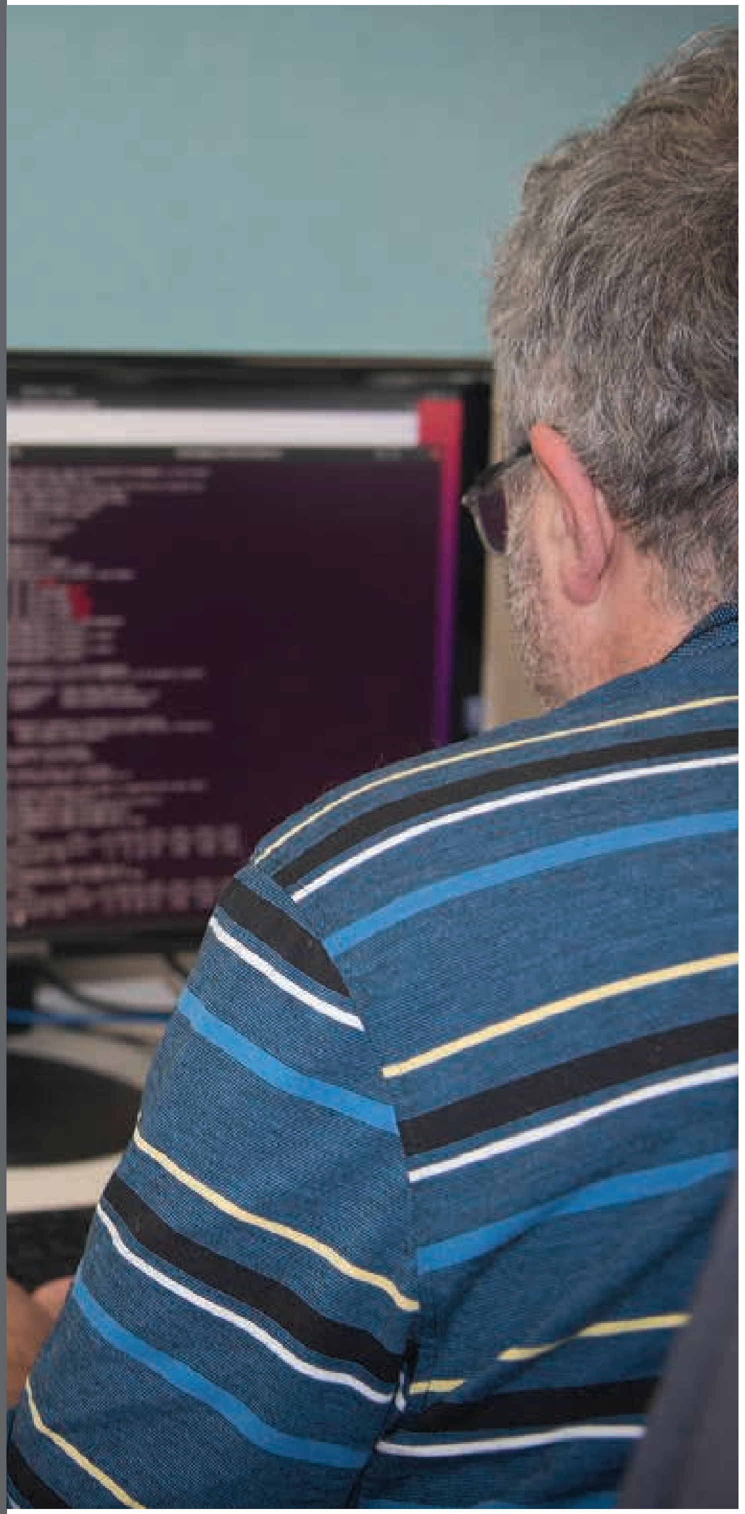
2020 was also the final year of Professor Melanie Johnston-Hollitt's term as Director of the MWA. Professor Johnston-Hollitt's contribution to the MWA—including service in a number of senior leadership roles spanning more than a decade—has been enormous. As Director, Professor Johnston-Hollitt built strongly on the foundations laid by her predecessors, and passed on a thriving operation and team to her successor.

2020 also saw the commencement of the refurbishment of CIRA's home, 'Building 610'. The refurbishment had been a long held ambition—a remodelling and revitalisation of the facility to, among other things, reflect CIRA's status as one of the Universality's premier capabilities. The timing, however, turned out to be less than ideal. Commencing in mid-September, the construction activity required the decant of the building. Staff and students that had already been displaced and dislocated by COVID19 saw the disruption extended. Again, notwithstanding entirely understandable grumbles and groans, everyone responded with understanding and patience. With the refurbishment now behind us and the benefits clear for all to see, I hope that people agree that that the inconvenience was worth it.

This document chronicles CIRA's achievements in 2020. In spite of the challenges presented by COVID, this year's report is as compelling as any of its predecessors. This is testament to the character and calibre of the individuals within the institute. Looking ahead, the lessons we take from our experience in 2020, the resilience we've shown, and the outcomes we've delivered, all lend great promise to the future of CIRA.

Monitoring and controlling a **telescope's new brain**

ANDREW WILLIAMS
Instrument Engineer



Above: Dr Andrew Williams at work. Credit: Curtin

At the time of writing, the MWA group is preparing to deploy and test MWAX, a new correlator, or 'brains', for the MWA telescope. The new correlator opens up observing modes that have never been possible before, and runs with entirely new software, on mostly new hardware. This has required a number of changes to the MWA 'Monitor and Control' code, both in the scheduling system (allowing the user to select new observing modes), and in the runtime system that passes the desired configuration for each observation to the new MWAX code, running on 32 servers at the Murchison Radioastronomy Observatory (MRO).

The existing correlator does not apply any delays to phase up visibilities to the target of interest – it doesn't even correct for the varying cable lengths to each tile. Instead, the cable delays, and geometric delays depending on the position of the source in the sky, as well as other calibration factors, are corrected in the final processing stage on a supercomputer.

The new correlator will be able to apply some or all of these delay corrections in real time, so a 'delaymode' option has been added to the scheduling tool, allowing the user to specify whether they want to emulate the old correlator with no delay correction, apply only the cable length corrections, or phase up to a moving source (including tracking Earth-orbiting satellites, using their orbital elements).

As observations progress, a new control daemon sends a message over the network to the new MWAX M&C daemon, exactly four seconds before the start of each observation. That message contains a complete description of the desired MWA configuration for the upcoming observation. The content includes the coarse channel numbers included in the observation, the desired delay mode and the time/frequency averaging settings.

The MWAX M&C daemon then creates a 'metafits' file describing that observation, and writes it to a shared directory that all MWAX hosts can access via NFS. This file is similar to the existing metafits files used to describe MWA observations to the processing pipelines, but adds the latest calibration fit data from the calibration database tables. It also adds a table in a new HDU that contains the Alt/Az of the target coordinates, calculated every 4 seconds for the duration of the observation.

The MWAX software uses the GPS timestamps in the incoming data to read the correct metafits file for each new observation, and uses it to set the correct delay mode, frequency/time averaging, etc. The MWAX delay engine also interpolates the 4-second Alt/Az coordinate table to calculate geometric delays for each time step during the observation (if applicable). It then applies the requested delay and gain calibration corrections.

Once MWAX is installed and running, new observing modes will open up, and with the new real-time delay calculation and calibration correction, less supercomputer time will be needed to reduce MWA visibilities to turn them into images.

Above: Opening up the test jig for a low-noise amplifier. Credit: Curtin

Building telescope **test jigs**

DAVID EMRICH
Engineer

PHILLIP GIERSCH
Technician

Diagnosing signal path faults is made easier when a known, well behaved and repeatable signal can be injected at some point in the chain, and the actual system response compared with what should be expected given the test signal input. Any difference in responses helps point to the location and type of fault that is causing the problem.

The pandemic-related working from home months during this year shifted some of the priorities for those of us still working in the CIRA Labs, and this allowed us to develop two such test jigs that simulate various points within the MWA antenna signal chain. This process is made easier still if the jig is small and portable and powers itself from the same source as the device it is simulating, as well as having a consistent behaviour with time and temperature.

The first jig replaces/simulates an MWA Dipole and low-noise amplifier (LNA) combination exposed to a typical daytime radio sky. It can be connected in place of the LNA at the antenna end of the 7m LNA cable, or directly to the input of the corresponding beam-former. The jig powers itself from the 5V bias present on the beam-former port and hence LNA cable, then injects a characteristic band-shape signal which is similar in overall total power level to that which is provided by “the sky”. While generally similar, band shape from the jig is less complex and not affected by such things as RFI, satellite emissions or dynamic radio sources in the sky. An LED on the jig indicates the presence of the 5V, and the “burst-live” system plots are used to confirm the proper frequency response. When connected first at the antenna, then at the beam-former, the differences in response can be used to confirm the performance of the 7m LNA cable.

Lastly, when connected directly at the face of the beam-former any inconsistencies in the burst-live plots indicate a problem further up the signal chain, which includes the beam-former itself, the coaxial DoC cable that connects it to the receiver, or the contents of the receiver.

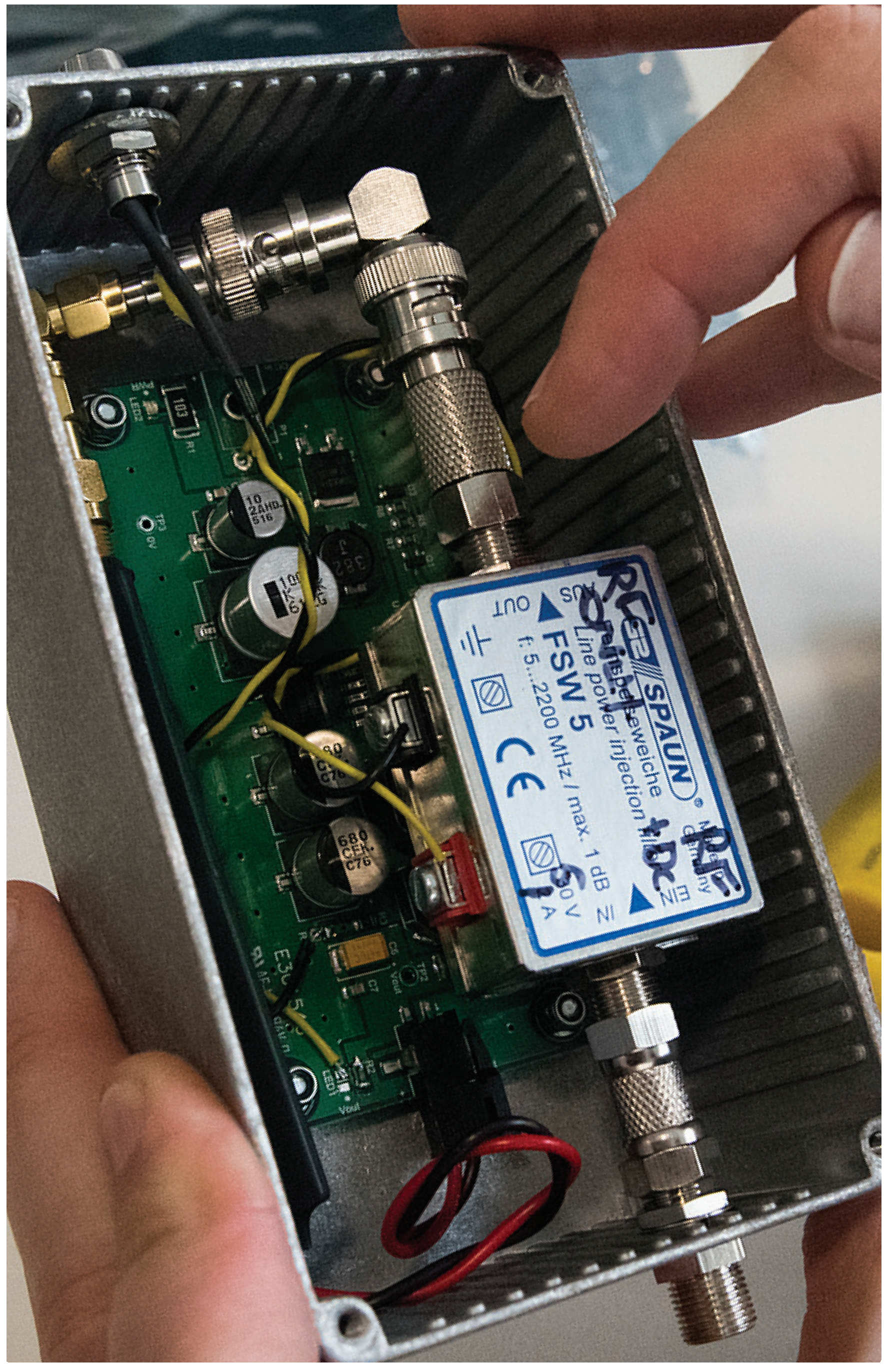
To help in further isolating problems, a second jig can be separately used in place of the beam-former. Similarly to the LNA jig, this beamformer jig powers itself from the 48V bias present on the beam-former data-over-coax (DoC) cable, has an LED that indicates the 48V supply is working, and injects a sky-similar signal in place of the entire tile under test. It can also be connected at either end of the DoC cable although the channel gain would have to be adjusted if the jig is connected at the receiver in order to avoid overloading the Analog Signal Conditioner inside the receiver.

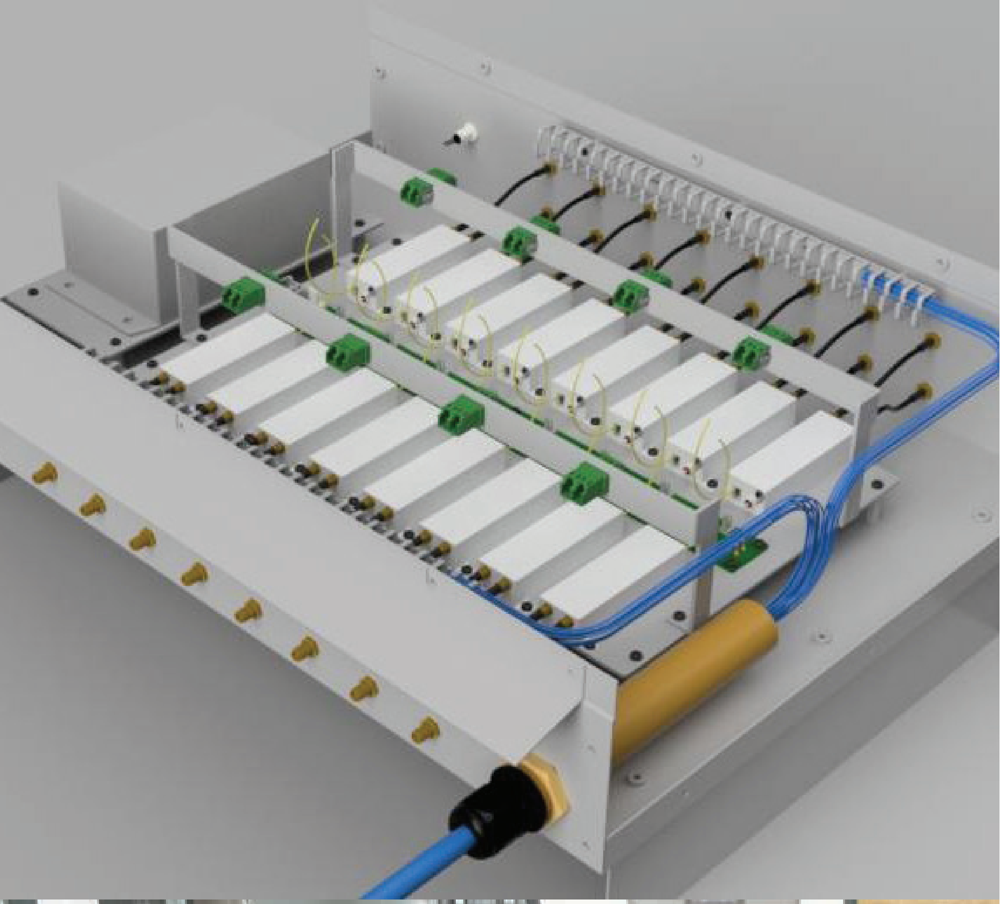
Both jigs have been tested in the laboratory to confirm that their outputs are stable over time, and the resulting reference spectra have been captured at 25 degrees Celcius. Measurements still need to be undertaken to quantify any slight changes in either power level or band-shape that might result from changes in the ambient temperature around the jigs, since the temperatures in the field can vary by more than 40 degrees over the entire year.

Once any temperature effects are understood the jigs will be taken to the field and trialled on a known good signal chain to obtain comparison spectra for future diagnostics.

> **“Measurements still need to be undertaken to quantify any slight changes...that might result from changes in the ambient temperature around the jigs, since the temperatures in the field can vary by more than 40 degrees over the entire year.”**

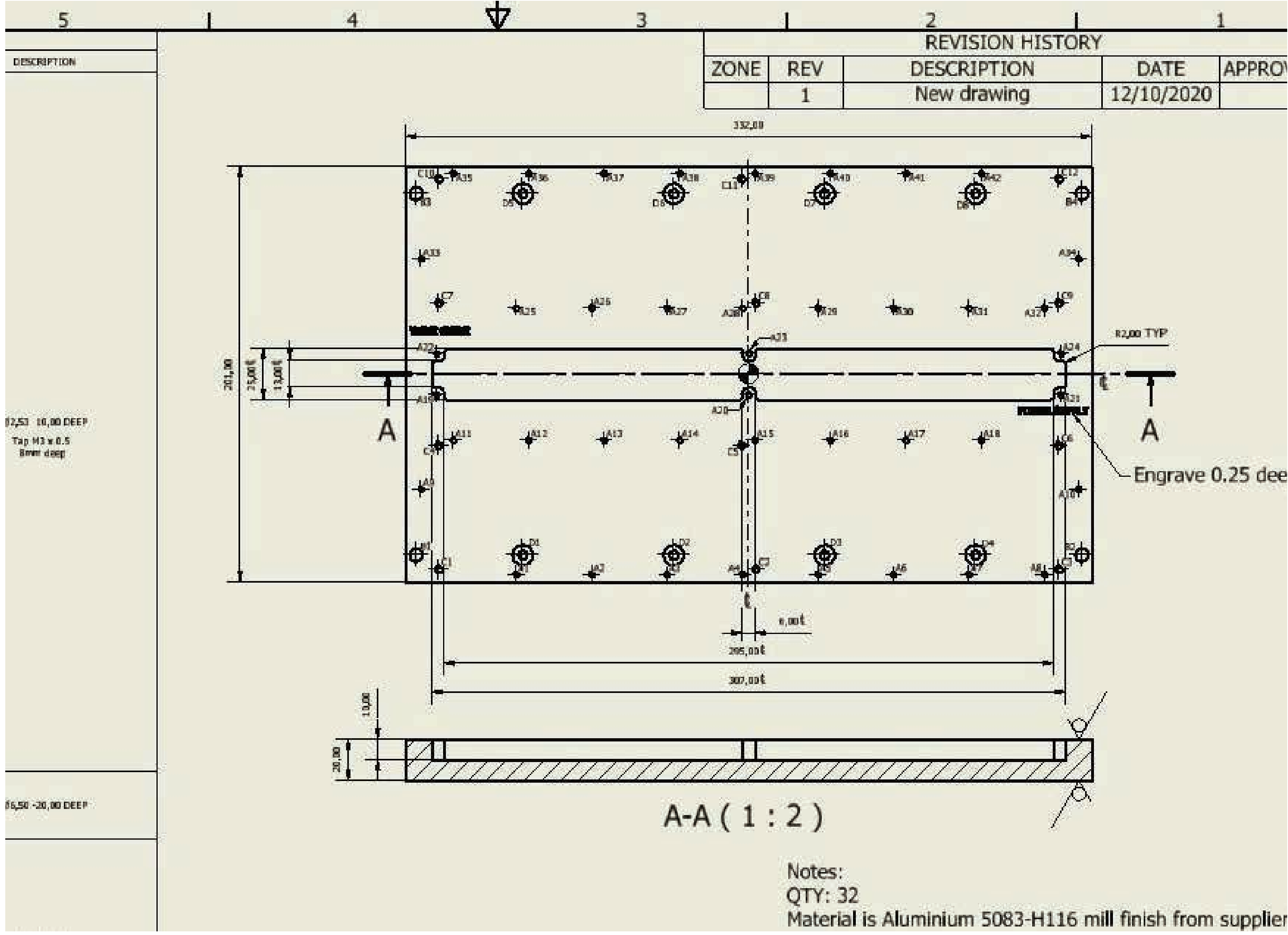
Below: Opening up the test jig for a beamformer. Credit: Curtin





From **design** to **prototype** to **production**

LUKE VERDUYN
Technical Specialist:
Mechanical Design



In 2020 we set out to launch the thermal upgrade to the SMART boxes (SB) on site at the MRO, to do this effectively, the use of CAD (Computer Aided Design) and the campus prototype lab was pivotal.

Using the CAD models sent to us from the guys over at INAF (Istituto Nazionale di Astrofisica) we were able to create iterations of the design so that decisions could be made on which designs would be taken to the prototype phase.

The original FEM mounting plate was a thin sheet (2mm to be exact) of Mild Steel. This did not help with thermal dissipation; we needed a material with enough thermal mass that it would transfer the heat from inside the box to the outside, and then through a Heatsink that we were mounting underneath the SB. Using the two final iterations of the design, we decided to move into the prototype stage by using the University prototype Lab.

The designs were one long plate to accommodate the power supply, power distribution PCB and all 16 FEM's and one short plate which holds all but the power supply. Once tested, we found that while the difference in size of plate was significant, the 0.35°C drop in temperature did not justify the cost implications of using a larger plate.

The next task was to figure out how to effectively deploy the upgrade in the field with as little parts as possible. The solution, a Drill template that had the four location holes and eight drill holes needed to fix the heatsink below the SB. The location holes used the existing standoffs to help align the drill fixture to ensure the holes were drilled in the correct place.

A shade cover for the SB was designed and the shadow that was cast on the box was simulated using CAD software, this was done to find the optimum size needed to ensure coverage throughout the day in the hottest months. This was only for shade and not heat simulation and although the SB was covered in shade, it had no cooling effect on site and the two prototypes were removed.

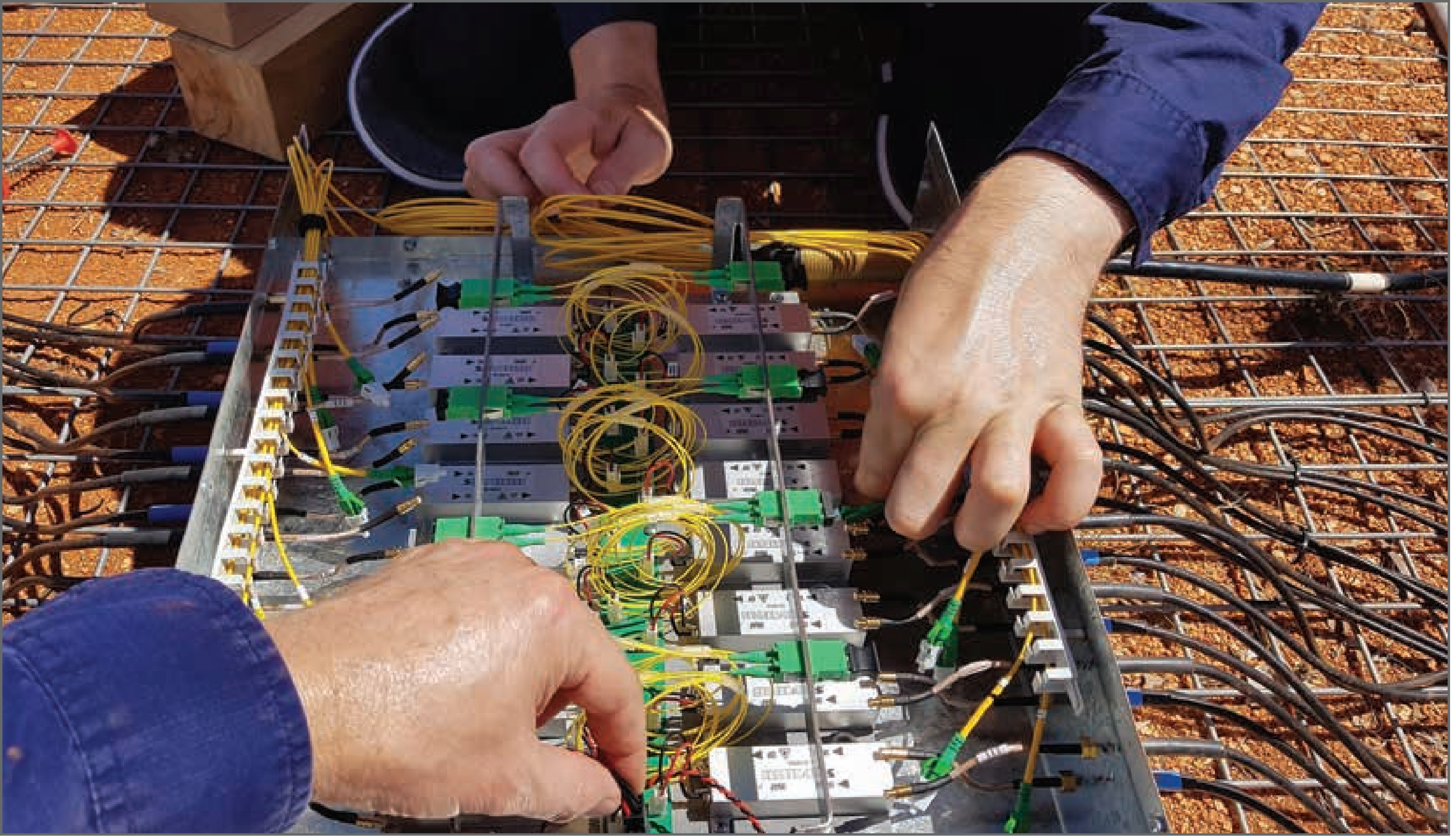
Once all the data was collected and the decisions made on which design to use, we contacted a local machining company and supplied them with 2D Drawings and 3D CAD models in a format that they could read using their own CAM (Computer Aided Manufacturing) software. The completed parts were then delivered to us by the company, and we got them ready to take up to site.

Being able to complete tasks like this in our own facilities save a great deal of time and money which can be shifted to other phases of the project. This also helps us improve on future iterations as all updates are captured on the CAD system as they happen leaving no room for error and no waiting times for services.

Far left, above: Render of the SB sent from INAF before the thermal upgrade. Credit: INAF

Far left, below: An aluminium plate set on a milling machine in the prototype lab. Credit: Verduyn

Above: A drawing of the small 'Cold Plate' that was used for production. Credit: Verduyn



Above: Re-assembling a SMART box on-site at the Murchison. Credit: Minchin

The ‘quick and dirty’ **thermal upgrade**

DAVE MINCHIN
Senior Technical Officer

In the summer of 2019, while the SKA prototype instruments were being commissioned, the team realised exactly how hot it can get in the Murchison. Indications were that the equipment was operating at temperatures which pushed the upper design limits. This sparked a whole new project, which would ensure the longevity of the SKA even in the extremes of the West Australian outback.

Inside each SMART Box there are 16 Front End Modules (FEM’s) that are only designed to operate in temperatures up to 50°C. The site often experiences daytime temperatures close to this in the shade. The SMART Boxes sit in the Sun and, they house heat generating electronics. It was now obvious to everyone that we had a new challenge. A flurry of activity commenced as we tried to quantify the problem and come up with solutions. A fortnightly conference call was set up to facilitate discussion amongst the relevant organisations including SKAO, Istituto Nazionale di Astrofisica (INAF), CIRA, et al. The challenge was defined as follows: To redesign a SMART Box so that its internal temperature would not exceed 50°C, given that it sits in the summer Sun when ambient temperatures often reach 49°C, it has a heater inside, and you can’t resort to any form of active cooling. This project lasted 12 months. For Raunaq Bhushan and myself, it was our only focus for the last four months of that as we needed it finished before the summer time heat.

We began by placing four USB temperature data loggers into a few selected smart boxes in order to ascertain just how hot it really was getting. The results were startling at almost 70°C. There was a real concern that the life expectancy of the FEM’s would be greatly reduced. Also, it was highly likely that they would distort the RF signal from sky, reducing data quality. Something had to be done!

While the team in Perth diligently gathered temperature data from site, the Italian team from INAF were modelling novel solutions. Marco Schiaffino came up with an idea that involved ripping out the insides of each SMART box and rebuilding them one by one, in situ, on the desert floor. This is when the project became known as the “Quick and Dirty Thermal Upgrade!”

CONTINUED -

> “Marco came up with an idea that involved ripping out the insides of each SMART box and rebuilding them one by one, in situ, on the desert floor.”

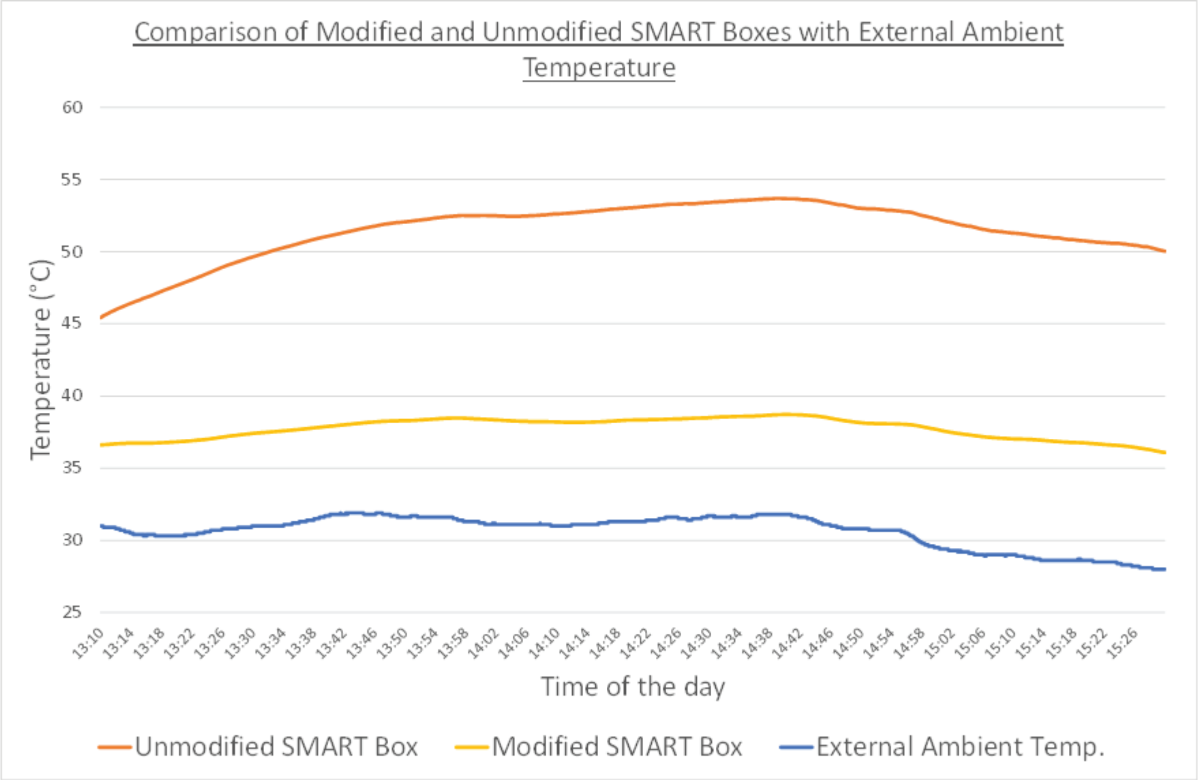
The skill set at CIRA was expanded with the timely arrival of Luke Verduyn, a mechanical engineer and machinist. He set about designing three versions of the proposed solution and made some prototypes. In October we modified a SMART box with the first iteration and trialled it in the back yard at CIRA. We then altered the implementation and trialled it twice more to determine which method achieved the best results for the least effort and cost. It turned out that the simplest and cheapest method was as good as the others, so it was the chosen one.

This implementation meant that for each of the 32 SMART Boxes in the field we had to remove all the FEM’s from the existing 1.6mm steel FEM mounting plate and screw them to a new 20mm thick solid aluminium “cold plate.” Then we had to install a large aluminium heat sink under each SMART Box and put the whole lot back together without damaging anything, including the optical fibres on each FEM.

All parts and materials were bought. Machining was done by local company West Coast Machining Services. Special tools were purchased, jigs were made and trialled. A complete procedure was developed, rehearsed and further refined at CIRA. All parts and tools were shipped to the MRO.

At the end of November Andy McPhail, Dave Emrich, Phillip Giersch, and I went to site where we spent the following two weeks retrofitting all 32 SMART Boxes. By the end of the exercise we had doubled the weight of each SMART Box, increasing their combined mass by more than 250 kg.

The final result was very rewarding. Marco had predicted a 16°C reduction in internal temperatures and that is exactly what was achieved.



Right: Graph comparing the external ambient temperature with pre and post modification SMART Box internal temperatures. Credit: Minchin

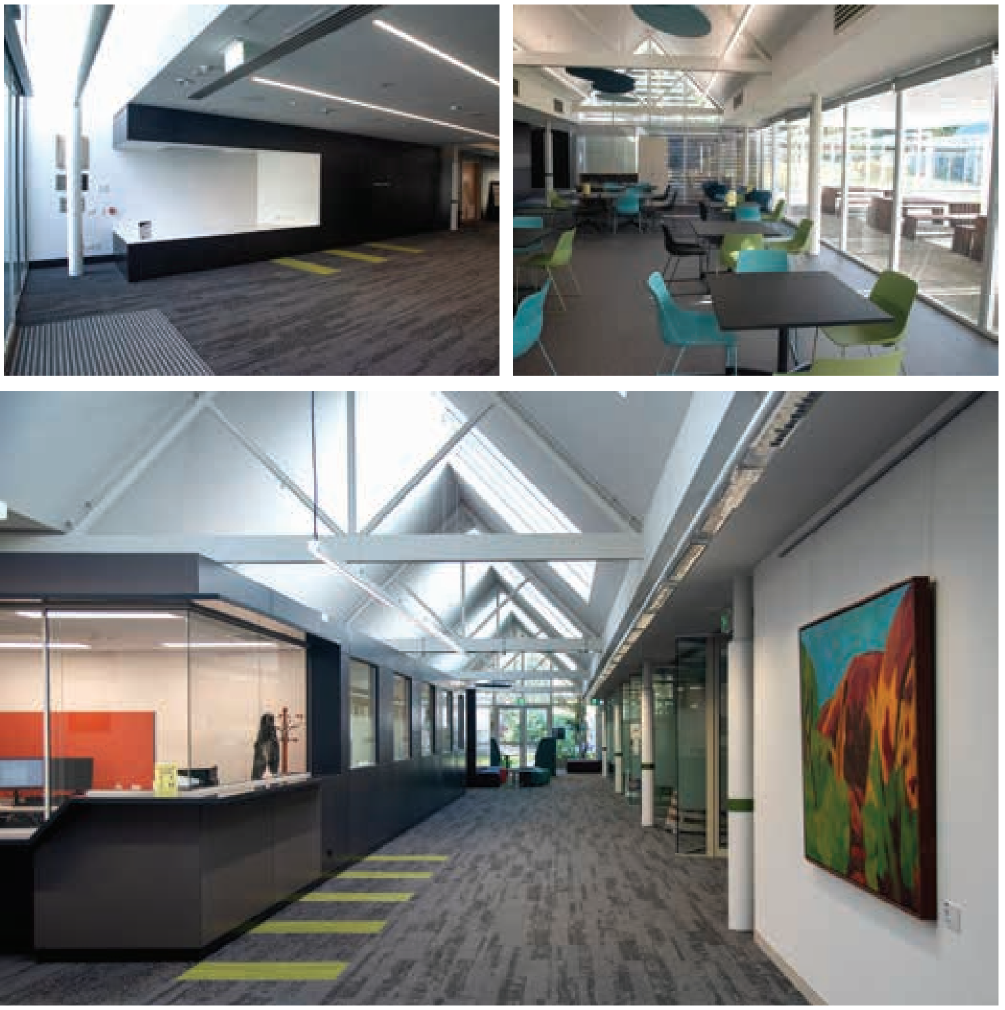
A fresh **new look** for CIRA

CHAMILA THRUM
Administrative Officer

Amidst the COVID-19 pandemic in 2020 came the opportunity to finally progress the refurbishment of CIRA itself, Building 610.

This project was 2 years in the making, and to ensure minimal impact on occupants the refurbishment was carried out in 2 stages. In addition, staff were given the option of working from home, or being temporarily relocated to Building 603, also in Technology Park. A small team continued to work within Building 610 to maintain operational capacity.


Right: The entrance/ foyer area (top photo), and the eastern walkway (bottom photo) of Building 610 prior to reburishment. Credits: Curtin



Stage 1 was completed in 10 weeks and saw many areas throughout the building repurposed. The FETI laboratories were cleared and have now been created into amazing open-plan office space. A number of offices were demolished, allowing a more expansive lunch room space to be created, as well as modern end-of-journey facilities for staff and students with new bathrooms and lockers.

Stage 2 took six weeks and saw changes in the main walkway towards the Video Conference room. Offices that were within that space were removed, replaced with a comfortable and informal meeting place with more walk room and natural light.

The building also has state-of-the-art AV technology installed in all of the newly created meeting spaces, to increase accessibility of Curtin systems.

The refurbishment has been a major improvement to the aesthetics of Building 610. The fresh modern design reflects CIRA as a centre for excellence, as a resesarch epicentre for scientists and engineers pioneering the way for radio astronomy within Australia.

Left: The entrance/foyer area (top far left photo), the lunch space (top right photo), and the walkway (bottom photo) of Building 610 after reburishment. Credits: Curtin

FEATURED

Scientist of the Year


Above, from left to right: Professor Ryan Lister, Minister Dave Kelly, and Professor Steven Tingay. Credit: MCB Photographics

John Curtin Distinguished Professor Steven Tingay was named joint Scientist of the Year at the 2020 Western Australian Premier's Science Awards.

Professor Steven Tingay from Curtin's Institute of Radio Astronomy (CIRA) and the International Centre for Radio Astronomy Research (ICRAR), won the top award in partnership with Professor Ryan Lister from the Harry Perkins Institute of Medical Research, Australian Research Council Centre of Excellence in Plant Energy Biology, and The University of Western Australia.

Professor Tingay is a former (and now current) Director of the Murchison Widefield Array project, the precursor telescope for the Square Kilometre Array (SKA) which will be one of the largest pieces of space infrastructure ever built. He has been at the forefront of some of the fundamental advancements made possible by these projects, including the search for the first stars 13 billion years ago, the discovery of missing matter in the Universe and the search for extraterrestrial life.

Curtin University Vice-Chancellor Professor John Cordery congratulated Professor Tingay for being recognised as leaders within WA's science community. "Professor Tingay has made a significant contribution to the field of astronomy and astrophysics throughout his distinguished career and has become an inspiring mentor for both his peers and students. Being recognised as the joint Scientist of the Year is testament to his high-quality research and outstanding leadership," Professor Cordery said.

The Premier's Science Awards recognise and celebrate the outstanding scientific research and engagement taking place in the State. The Awards cover all fields of science, including natural, medical, applied and technological science, engineering and mathematics.

IN THE MEDIA

A Very Big Bang

The MWA telescope (led by Curtin Univserity and operated from CIRA) was used to identify the biggest eruption ever known, from a supermassive black hole at the centre of the Ophiuchus galaxy cluster, 390 million light-years from Earth.

The story of this result was also truly explosive, having the largest coverage to date out of all ICRAR's press releases. The release was picked up and expanded on by 1500 major media outlets globally, with a total potential reach of over 2.6 billion people.

MWA Director Melanie Johnston-Hollitt was a co-author on the paper and conducted a multitude of interviews on the result and the MWA's involvement.

DISCOVERY OF A GIANT RADIO FOSSIL IN THE OPHIUCHUS GALAXY CLUSTER

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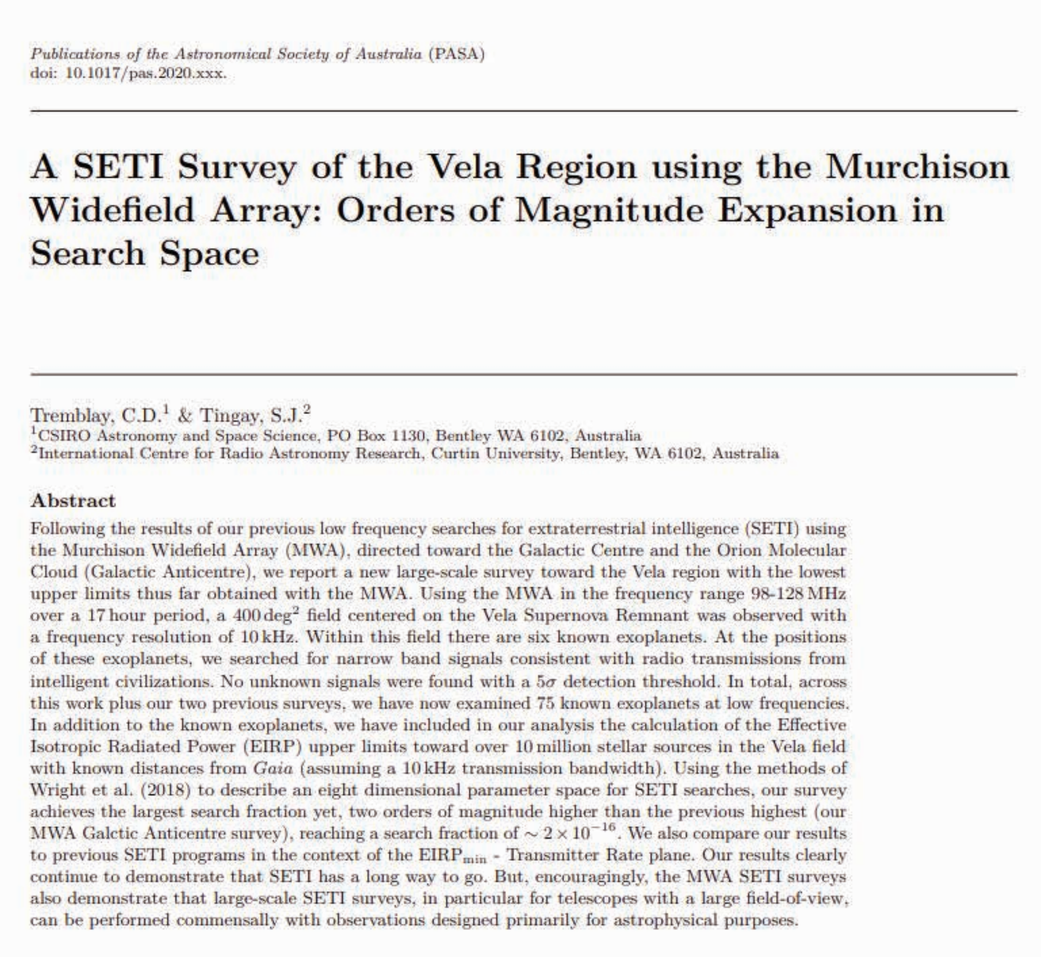
ABSTRACT

The Ophiuchus galaxy cluster exhibits a curious concave gas density discontinuity at the edge of its cool core. It was discovered in the *Chandra* X-ray image by Werner and collaborators, who considered a possibility of it being a boundary of an AGN-inflated bubble located outside the core, but discounted this possibility because it required much too powerful an AGN outburst. Using low-frequency (72–240 MHz) radio data from MWA/GLEAM and GMRT, we found that the X-ray structure is, in fact, a giant cavity in the X-ray gas filled with diffuse radio emission with an extraordinarily steep radio spectrum. It thus appears to be a very aged fossil of the most powerful AGN outburst seen in any galaxy cluster ($pV \sim 5 \times 10^{61}$ erg for this cavity). There is no apparent diametrically opposite counterpart either in X-ray or in the radio. It may have aged out of the observable radio band because of the cluster asymmetry. At present, the central AGN exhibits only a weak radio source, so it should have been much more powerful in the past to have produced such a bubble. The AGN is currently starved of accreting cool gas because the gas density peak is displaced by core sloshing. The sloshing itself could have been set off by this extraordinary explosion if it had occurred in an asymmetric gas core. This *dinosaur* may be an early example of a new class of sources to be uncovered by low-frequency surveys of galaxy clusters.



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A SETI Survey of the Vela Region using the Murchison Widefield Array: Orders of Magnitude Expansion in Search Space

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Abstract

Following the results of our previous low frequency searches for extraterrestrial intelligence (SETI) using the Murchison Widefield Array (MWA), directed toward the Galactic Centre and the Orion Molecular Cloud (Galactic Anticentre), we report a new large-scale survey toward the Vela region with the lowest upper limits thus far obtained with the MWA. Using the MWA in the frequency range 98-128 MHz over a 17 hour period, a 400 deg^2 field centered on the Vela Supernova Remnant was observed with a frequency resolution of 10 kHz. Within this field there are six known exoplanets. At the positions of these exoplanets, we searched for narrow band signals consistent with radio transmissions from intelligent civilizations. No unknown signals were found with a 5σ detection threshold. In total, across this work plus our two previous surveys, we have now examined 75 known exoplanets at low frequencies. In addition to the known exoplanets, we have included in our analysis the calculation of the Effective Isotropic Radiated Power (EIRP) upper limits toward over 10 million stellar sources in the Vela field with known distances from *Gaia* (assuming a 10 kHz transmission bandwidth). Using the methods of Wright et al. (2018) to describe an eight dimensional parameter space for SETI searches, our survey achieves the largest search fraction yet, two orders of magnitude higher than the previous highest (our MWA Galctic Anticentre survey), reaching a search fraction of $\sim 2 \times 10^{-16}$. We also compare our results to previous SETI programs in the context of the $\mathrm{EIRP}_{\mathrm{min}}$ - Transmitter Rate plane. Our results clearly continue to demonstrate that SETI has a long way to go. But, encouragingly, the MWA SETI surveys also demonstrate that large-scale SETI surveys, in particular for telescopes with a large field-of-view, can be performed commensally with observations designed primarily for astrophysical purposes.

Looking for E.T.

Dr Chenoa Tremblay and CIRA's Executive Director Professor Steven Tingay used the MWA telescope to conduct the deepest and broadest search yet for extra-terrestrial signals, in an area covering over 10 million star systems around the Vela constellation. Their results were published in PASA, and offer another example of how the MWA continues to push the limits of observational science.

This paper was widely distributed in media and placed second on PASA's list of 'most downloaded papers published in 2020'.

National Science Week Win!

MWA Project Manager Mia Walker was awarded 'best emerging writer' for her entry in a creative non-fiction monologue competition. This event, held by Claire Bowen Management and ICRAR in partnership with National Science Week, invited participants to let their imaginations actively engage with any research outcome from ICRAR. Walker took a slightly unusual approach, inspired by her interactions with the researchers themselves. Her piece is published here. Image credit: ICRAR

Teaching Programs

CIRA also continued to contribute 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 and Thermodynamics, and Electromagnetism. Third/fourth year units include Relativistic Astrophysics and Cosmology, Exploring the Radio Universe, Nuclear and Particle Physics, Engineering Electromagnetics and Transmission Lines, Electronic Design, and Mobile Radio Communications, plus the honours unit Advanced Topics in Astrophysics.

An Astronomer Walks Into A Bar

By Mia Walker

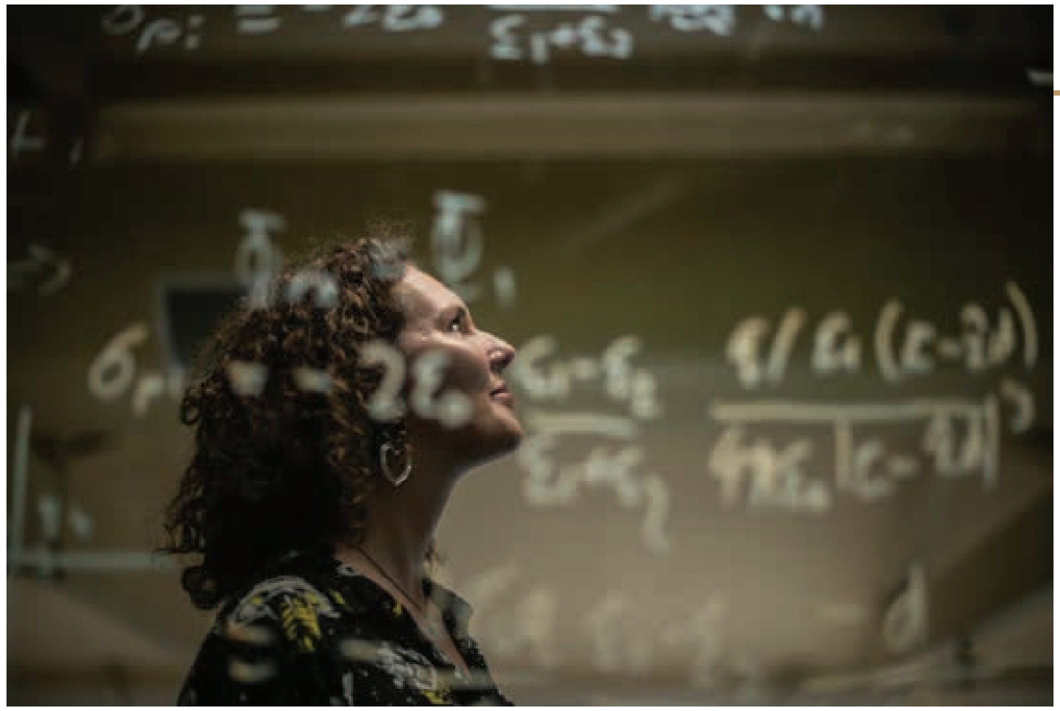
MONOLOGUE

An astronomer walks into a bar
This isn't a joke, just an observation
One made with my eyes, so we're talking optical wavelengths
Which aren't as popular on the spectrum these days
Why point your face at something when you can point antennas at it instead
And then use maths to convert it back into something that your eyes would see?
Astronomers make a living out of observing this way
They can while away hours talking about an object of fascination and study
And conclude by saying they know nothing about it, really
Do you know what a fast radio burst is?
It's ok, they don't know either
I think they are hoping that **we** can tell **them**
They tell us a lot about the Universe
And almost nothing about themselves
And even I don't know if I'm talking about the radio bursts or the astronomers now
They seem out of place in an office environment
Displaced in time
And in anything except jeans and t-shirts
The hours they work would make sense if they still only looked at the stars at night
They can dedicate their lives to the advancement of knowledge
Just a tiny advancement is fine, even astronomically small
Like a packet of light, travelling across the cosmos
Astronomers will detect single photons and the smallest molecules
And use them to explain the largest objects in the Universe
There's lots of hand-waving involved
Even when they're not Italian
They're a jack of all trades and master of one
Because you have to have mastered something to get an ungendered title
They claim their research is very obscure and you wouldn't understand
They are right
Everything they do is shrouded in mystery
And only others who speak their tongue dare to question them
By tongue I mean lingo, and by lingo I mean acronyms
Ask them to expand the ones they use, and even they get confused
BF? ASC? ADFB? ABCDEFG?
That's a bunch of BS if you ask me
To be fair I think those acronyms come from engineers
Who are just mad scientists with multimeters
They share a lot in common with astronomers,
But that's the subject of another monologue
Astronomy is considered to be the most inspiring of all fields
Not to the astronomers, of course
They create instruments that can track single stars orbiting black holes
And then just call it the 'very large telescope' (VLT)
Soon to be eclipsed by the 'extremely large telescope' (ELT)
Which, to their credit, is indeed larger
I await the announcement of the newest embiggened telescope (E.T.)
Not very creative, the ones studying creation
But they are the font of all our other-worldly knowledge
Bit worrying, really
I like to think they're aliens in disguise
Similar enough to let us trust them but weird enough to be suspicious
Waiting until we're less stupid and more accepting of others
They'll be waiting a while
In the meantime giving us small tidbits of what life out there is like
Paper by paper, talk by talk
With every incomprehensible lecture,
And foreign symbol scrawled on a whiteboard
Extraterrestrial language or just bad handwriting?
It's all Greek to me
I once heard an astronomer describe an asteroid as a 'craft'
Freudian slip for a mothership
I'm not sure where students come into the equation
Are they innocent, or also part of the alien invasion?
Indoctrination by PhD seems cruel
That's a hazing ritual if I ever saw one
A casual abduction and a probe is at least quick and to the point
And arguably more enjoyable
What's a fast radio burst, again?
They still don't know
But they're pretty adamant it's not aliens
(Which is something an alien would say)
The astronomer walks out of the bar
And mutters 'why does it always come back to aliens?'

IN THE MEDIA

#IncludeHer

CIRA PhD candidate Kat Ross has taken Australian curriculums by storm with the #IncludeHer campaign: advocating that aspiring women in Science, Technology, Engineering and Mathematics (STEM) fields need to be shown potential careers are achievable and given visible role models. Ross has also been published or featured in articles by Space Australia, Women's Agenda and the Sydney Morning Herald, and has been a guest speaker on multiple podcasts to talk about the forgotten women of science through history and the specific issues women in STEM face. Image credit: Wolter Peeters, SMH



Public Outreach

2020 was a difficult year for teaching and outreach programs, with the international pandemic necessitating social distancing, travel limitations, and lockdowns for many areas- none of which are very conducive to education! Despite this, CIRA's staff and researchers rose admirably to the challenge of science communication in a COVID world.

Talks were generally held in person either early or late in the year, with the rest conducted 'virtually' through web conference software, such as a CSIRO webinar on the SKA and its precursors, a Q&A session with remote Year 3 students in Dalwallinu, and a presentation on black holes for the Abrams planetarium. Our astronomers and staff gave talks at community centres, the WA Foundation for Deaf Children at a 'Meet the Scientists' event, the Science Café for Year 10 students, the Scitech Gifted and Talented program, the First Lego League WA state finals, the Pawsey Future of Supercomputers national meeting, a guest interview for the Haileybury Colleges in Melbourne, and the keynote address for 'It Takes a Spark!'.

Curtin still managed to put on a great show at Perth's annual astronomy festival, Astrofest! CIRA staff and researchers helped at stalls, gave talks, showcased science and technology and volunteered with telescopes over the course of the night, which attracted over 4000 members of the public.

'Astronomer at Large'

The MWA team welcomed Dr Fred Watson to CIRA, for discussions about the future in astronomy (and our role in it!).

Watson (second from the right in the accompanying photo) is Australia's first Astronomer-at-Large and the bestselling author of Cosmic Chronicles. In 2010, Watson was made a member of the Order of Australia for service to astronomy, particularly the promotion and popularisation of space science through public outreach. Image credit: Curtin

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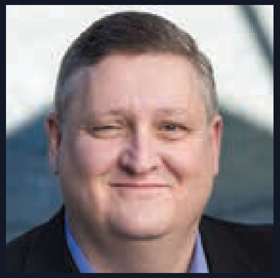

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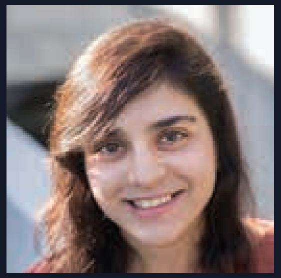

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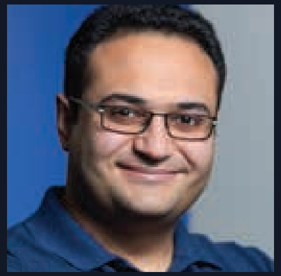

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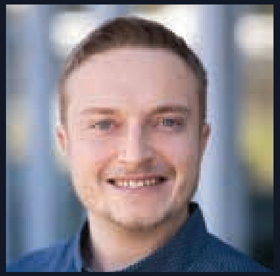

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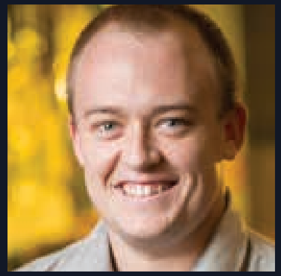

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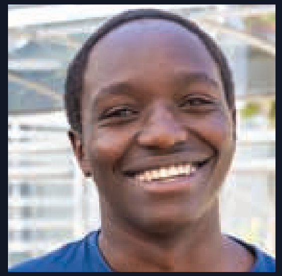

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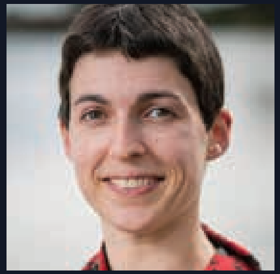
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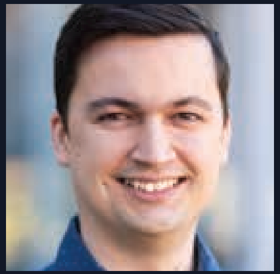
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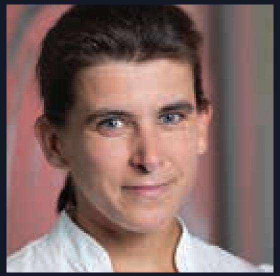
DR ADELA KAWKA
Senior Research Fellow

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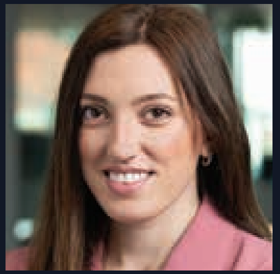
DAVID KENNEY
Project Engineer


DO WON KIM
PhD Candidate


DR MARIA KOVALEVA
Associate Lecturer


MIKE KRIELE
PhD Candidate


DR ESHA KUNDU
Research Associate


FERRY LANTER
PhD Candidate


DR JACK LINE
Research Associate


DR CHRISTENE LYNCH
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ASSOC/PROF JEAN-PIERRE MACQUART
Associate Professor


DR BEN MCKINLEY
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ULRIKE MCLERNON
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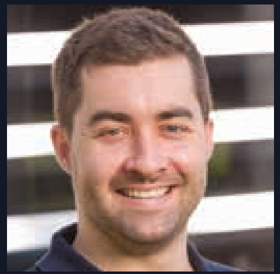
ANDREW MCPHAIL
Program Manager


DR SAMUEL MCSWEENEY
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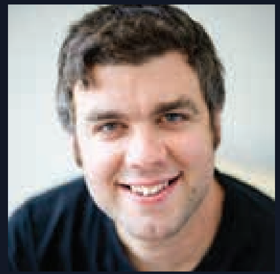
PROF JAMES MILLER-JONES
Director, Science


DAVID MINCHIN
Senior Technical Officer


DR JOHN MORGAN
Research Fellow


DR IAN MORRISON
Research Fellow


AINULNABILAH NASIRUDIN
PhD Candidate


BACH NGUYEN
PhD Candidate


FREYA NORTH-HICKEY
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ALESSANDRO PADUANO
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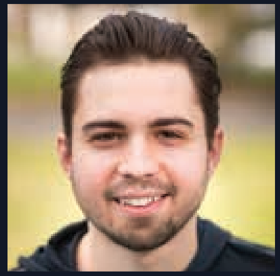
DR NIPANJANA PATRA
Research Fellow

STEVE PRABU
PhD Candidate

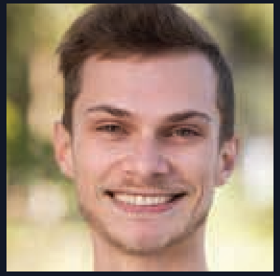
DR DANNY PRICE
Senior Research Fellow



BENJAMIN QUICI
PhD Candidate

KATHRYN ROSS
PhD Candidate

TINA SALISBURY
Business Manager



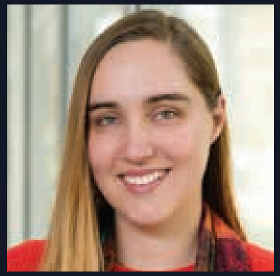
MAWSON SAMMONS
PhD Candidate

DANICA SCOTT
PhD Candidate

SUSMITA SETT
PhD Candidate

DR NICK SEYMOUR
Senior Lecturer

DR MAHAVIR SHARMA
Research Associate



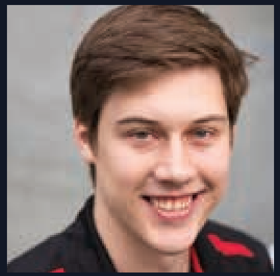
TERESA SLAVEN-BLAIR
Outreach Support Officer

GREG SLEAP
MWA Data Manager

KEEGAN SMITH
Masters Student

DR MARCIN SOKOLOWSKI
Research Fellow

DR ARIAN SUTINJO
Senior Lecturer



NICHOLAS SWAINSTON
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JISHNU THEKKEPPATTU
PhD Candidate

CHAMILA THRUM
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JUN TIAN
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Support Engineer,
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MIA WALKER
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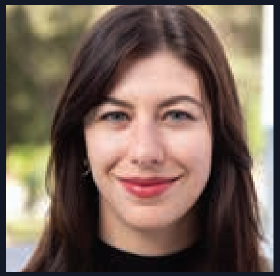
CLINTON WARD
Senior Technical Officer

ASSOC/PROF RANDALL WAYTH
Associate Professor

MALCOLM WHINFIELD
MWA Electronics Technician



DR AMANDA WILBER
Associate Lecturer

DR ANDREW WILLIAMS
Instrument Engineer, M&C

ALEXANDER WILLIAMSON
PhD Candidate

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In the spirit of reconciliation, CIRA acknowledges the Traditional Custodians of country throughout Australia and their connections to land, sea and community. We pay our respect to their elders past and present and extend that respect to all Aboriginal and Torres Strait Islander peoples today.

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