CIRA

CURTIN INSTITUTE OF RADIO ASTRONOMY

Annual Report 2016

Curtin University

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CRICOS Provider Code 00301J

This annual report covers the calendar year 2016

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ICRAR

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Annual Report 2016

Curtin Institute of Radio Astronomy

CIRA

Governance

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

Director’s Report

Science and Operations

Professor Carole Jackson

2016 was an excellent year for the Institute across all areas of our science, MWA operations, and engineering endeavours. The highlights of the year include basic research attracting significant peer and media interest, the award of new Australian Government ARC funding for the MWA Phase 2 upgrade including new collaborators joining the MWA consortium, and CIRA successfully teaming with five other University partners, led by the Australian National University, to secure a new ARC Centre of Excellence for all-sky Astrophysics-3D (CAASTRO-3D) commencing in mid-2017.

CIRA’s tenured faculty increased by one in 2016 with the appointment of Dr Jean-Pierre Macquart as a Senior Lecturer, bringing the total to five. In the current climate of University enrolments and funding strictures, CIRA’s impact through our own endeavours, plus with those allied with our Joint Venture partners ICRAR-UWA, have ensured that we continue to enjoy significant ongoing University support. It was particularly notable that a number of CIRA personnel were invited to contribute to a series of key Square Kilometre Array (SKA) design decisions and budget readjustments through 2016. This recognition of core expertise at CIRA is important through the international community, and this recognition continues to develop with our direct access to the SKA LOW precursor telescope, the Murchison Widefield Array (MWA).

With the MWA Phase 2 upgrade build commencing during 2016 we are now looking forward to new modes of observing whilst we also start planning for Phase 3. During 2017 new observations will be aimed at detecting the global signature from the Epoch of Reionization with the new hexagonal close-packed MWA tiles of phase 2, as well as the MWA-AAVS hybrid, and a wealth of other new MWA data.

A highlight from our MWA astronomy focus in 2016 was the publication of a catalogue of 300,000 sources detected by the GaLactic and Extragalactic All-sky MWA Survey (GLEAM). This multi-frequency catalogue not only provides astronomers with data from 72 to 231 MHz and showcases the MWA’s strength in mapping compact and highly extended sources, it also attracted a wealth of media interest thanks to its eye-catching imagery revealing a view of the Universe through ‘radio eyes’.

In addition to GLEAM, data from the MWA formed the centrepiece of many other high-impact publications in 2016, spanning astronomical topics from the Epoch of Reionisation, to pulsars, to fast radio bursts and other transient searches, to Solar science, several of which are highlighted in this report. CIRA's close access to the MWA has also contributed to the description of a great set of new PhD projects, including some with linkages with the Curtin Institute of Computation, all of which underpin our commitment to grow our higher degree student base.

Director's Report

Engineering & Industry

Professor Peter Hall

In this last report before my retirement at the end of 2016 I am delighted to once again record an excellent year for CIRA. The productivity of the Institute, and the pace of its journey to maturity as a world-class radio astronomy research centre, have exceeded even my optimistic expectations. Since its founding in late 2008, the CIRA family – past and present – has worked hard to ensure our success. CIRA is an indispensable partner in new-generation radio astronomy science and engineering, most particularly in the international SKA Project. CIRA is also an exemplar for collaboration, with many of our advances being achieved with partners in ventures such as ICRAR, CAASTRO and the MWA.

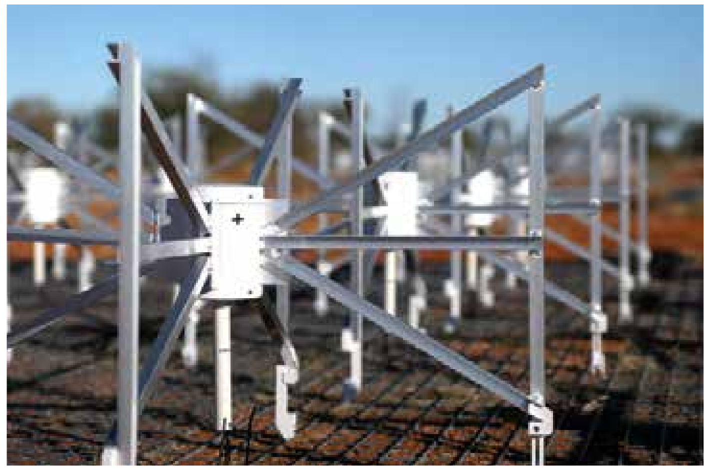
This 2016 Annual Report contains updates and results for a number of important activities, including the MWA extension and AAVS1 deployment and, for good measure, a royal visit. Less obvious, but just as important, the CIRA push into the wider University continues to grow, with many staff now having shared roles in mainstream science, engineering and computing streams. The success of CIRA as a research institute has been clear for years and it is exciting to see the second phase of our growth – returns to the wider University – now a reality. With the coming growth in SKA activity in Western Australia, CIRA has helped position Curtin very favourably in terms of returns to the University and the State.

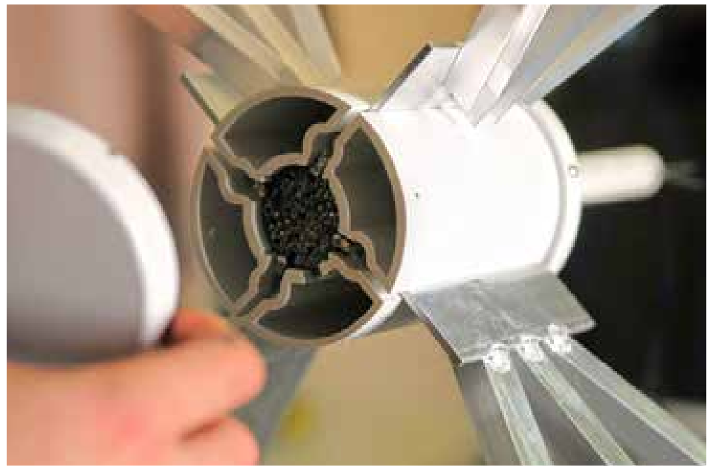
I want to conclude by noting two important senior staff changes, beginning with congratulations to Professor Carole Jackson on her appointment as the General and Scientific Director of the Netherlands Institute for Radio Astronomy (ASTRON). Carole has been a long-time friend and colleague and, on behalf of all at CIRA, I wish her every success in the Netherlands. I am confident that the new CIRA Science leadership arrangements will provide an opportunity for our talented mid-career staff to shine.

On the Engineering side I am delighted that my long-time international colleague, Professor David Davidson, will be my successor. With his very distinguished career in electromagnetics engineering, David will be a great asset to Curtin. I look forward to working with him, with Assistant Director Tom Booler, and the entire Engineering team in my capacity as Emeritus Professor.

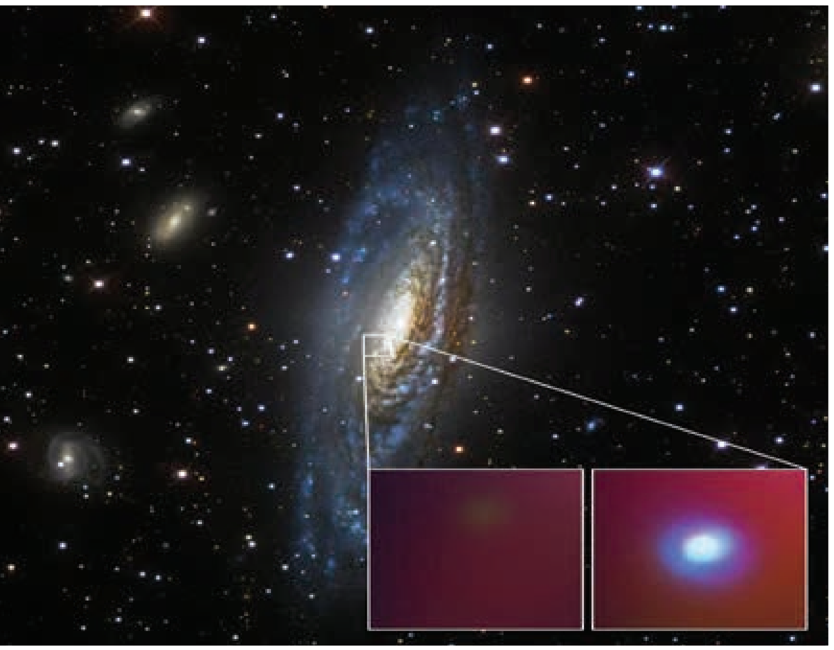
My thanks to all of CIRA, Curtin, and other colleagues for your hard work and support, and my best wishes for your continuing success.

Science Highlights





Images credit: ICRAR



X-rays from SN 2014C in "nearby" galaxy NGC 7331 (50 million light years away). The inset shows images taken with the Chandra X-ray Observatory, marking the position of SN 2014C before and after the supernova explosion, overlaid on an optical image of NGC 7331. Image credit: X-ray images – NASA/CXC/CIERA/R. Magutti et al; Optical image – SDSS

Science Highlights

A peculiar supernova with an explosive past

Gemma Anderson

New radio observations suggest that the massive stellar progenitor of supernova SN 2014C in NGC 7331 experienced two very different mass-loss episodes before it finally exploded.

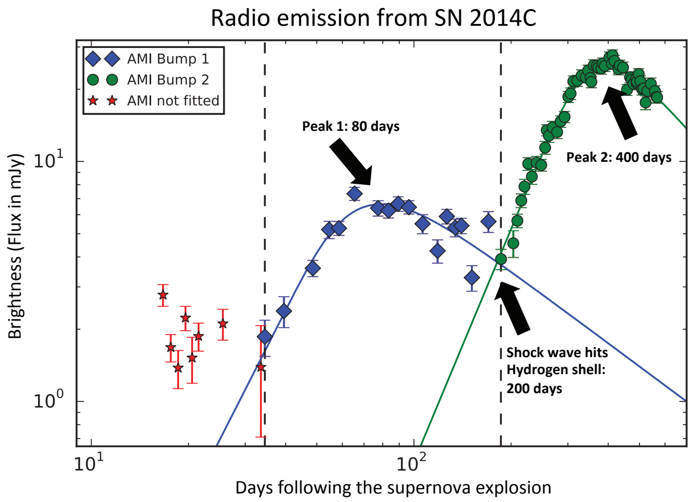
Massive stars end their lives through violent explosions known as supernovae, if their masses are roughly at least eight times more massive than our Sun. During the typical 107-108 year lifetime of a very massive star, the star can lose a fraction of the material in their outer layers through stellar winds with speeds between 10s to 1000s km/s. The amount of mass lost through these winds not only plays a crucial role in determining the evolution of the supernova progenitor star, but, as described below, it also dictates many of the observed properties after a supernova explosion.

A supernova produces an expanding shock-wave that likely travels at ~10% of the speed of light, which then impacts the surrounding gas that was lost from the progenitor star. This interaction produces radio emission, and the denser the surrounding environment, the brighter the radio emission will appear. Radio observations of a supernova can therefore directly track the mass-loss history of the progenitor, illuminating past eras of strong stellar winds or eruptive events just prior to explosion.

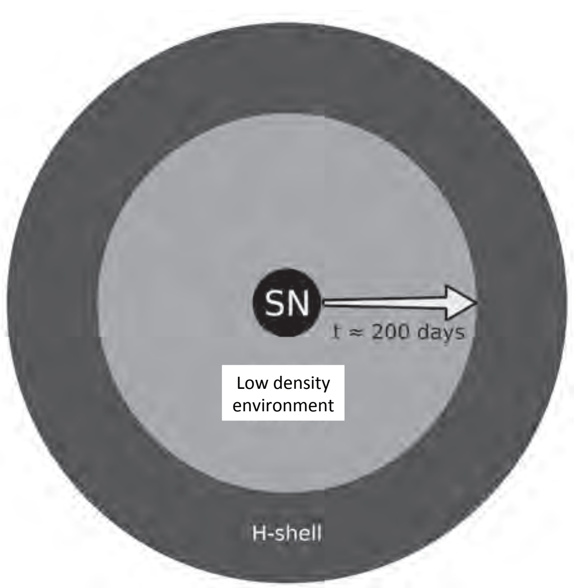
A steady brightening and fading in the radio emission over time demonstrates that most supernovae are surrounding by environments with densities that drop off steadily with distance, thus illustrating that the progenitor had an uneventful past. However, this was not the case for the supernova SN 2014C, discovered on 5 January 2014 in the nearby galaxy NGC 7331, which lies nearly 50 million light years away. Shortly following its discovery, the Arcminute Microkelvin Imager (AMI), a radio telescope based in Cambridge, UK, detected the radio emission from SN 2014C. AMI monitored its radio emission, watching it brighten to a peak at 80 days post-burst, before it began to fade. However, around 200 days post-explosion the radio emission unexpectedly began to re-brighten, peaking a second time at 400 days with a luminosity 4 times brighter than the first peak. This double bump morphology is shown in the figure on the next page. Such behaviour is extremely unusual and has only been seen from a small number of supernovae.

The radio re-brightening that AMI detected 200 days post-explosion was produced by the supernova shock-wave encountering a dense shell of hydrogen gas (see the figure to the right), which was shed by the massive progenitor star during its pre-supernova evolution. This hydrogen shell was likely lost during an extreme eruptive event, or through interaction with a binary stellar companion. The progenitor of SN 2014C therefore experienced at least two very different episodes of mass-loss during its lifetime, which was illuminated through radio observations.

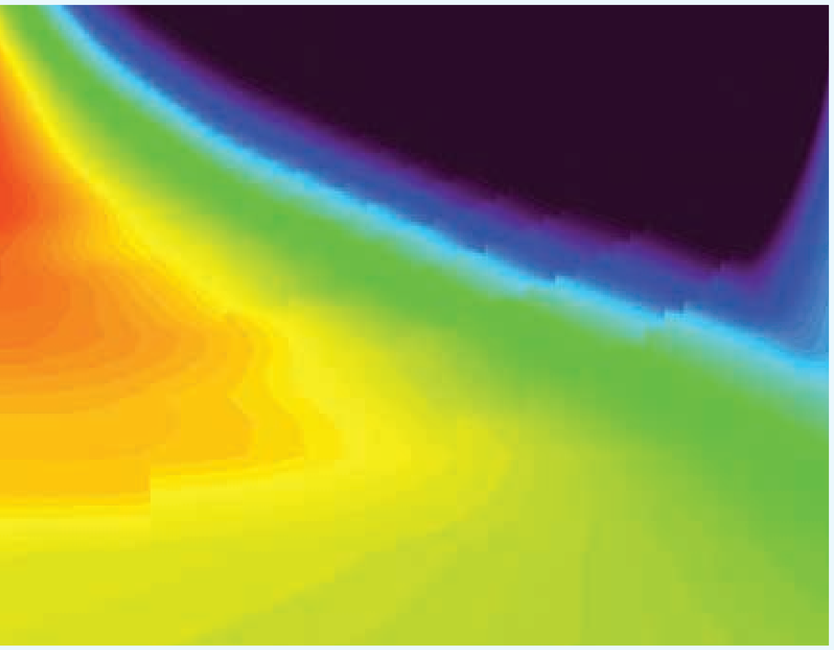
Reference: Anderson, G. E. et al. 2017, MNRAS, 466, 3648



The radio emission from SN 2014C as observed with the Arcminute Microkelvin Imager (AMI), showing changes in its radio brightness over 600 days. The two bumps suggest that the massive stellar progenitor experienced two distinct episodes of mass-loss before exploding.



A schematic of the environment surrounding the supernova likely produced by the massive stellar progenitor before it exploded. The darker areas indicate regions of higher gas density surrounding the supernova site.



Probing the Epoch of Reionisation with wavelets

Cathryn Trott

One of the primary scientific goals of current low-frequency radio telescopes, such as the Murchison Widefield Array (MWA) in Western Australia and the future Square Kilometre Array (SKA), is to detect, estimate, and explore the evolution of structure through the 21cm emission line from neutral hydrogen.

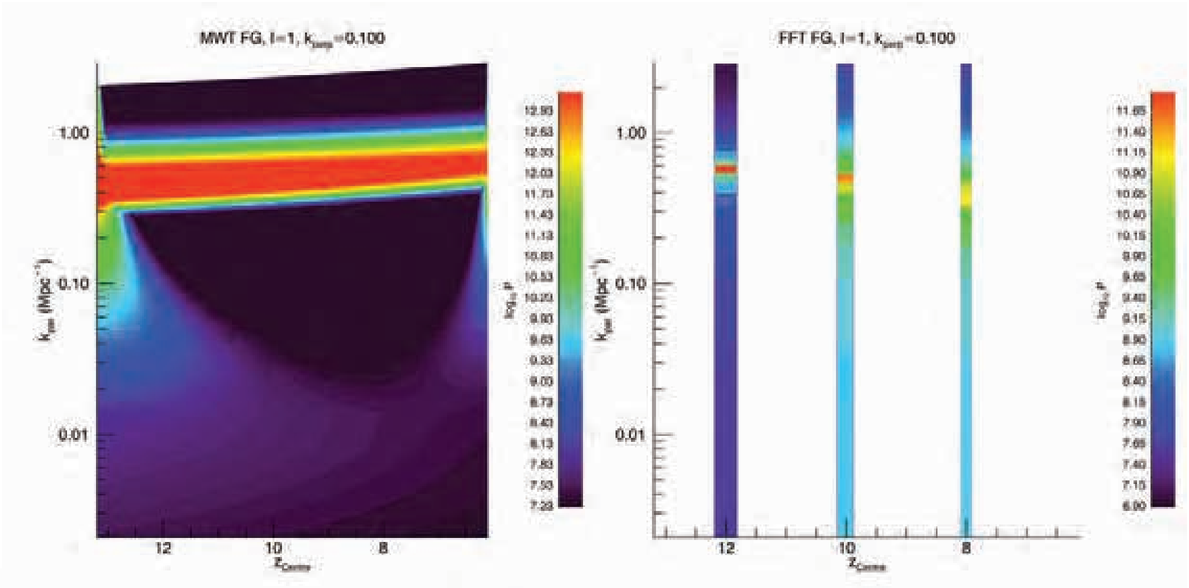
This Epoch of Reionisation (EoR) marks the end of the Cosmic Dark Ages, during which the first stars and galaxies formed, and probes the era when they first produce ionising radiation, illuminating the cosmos and destroying the ubiquitous atomic hydrogen lying between galaxies. This epoch is preceded by the observation of tiny temperature fluctuations in the otherwise uniform Cosmic Microwave Background (300,000 years after the Big Bang), and ends with the observation of the most distant quasars (1 billion years after the Big Bang).

This period marks the final, major unexplored phase transition in the state of the cosmos, but its observation requires a careful unpicking of many hundreds of hours of data to extract the weak cosmological signal from all other radio sources in the sky, and from effects of the instrument. Typically, to aid in this endeavour, we employ statistical methods to detect the signal, where large amounts of information are added together with the aim of increasing detectability. Such an approach has its limitations, however, because the very evolution of structure we are seeking can be lost in the addition.

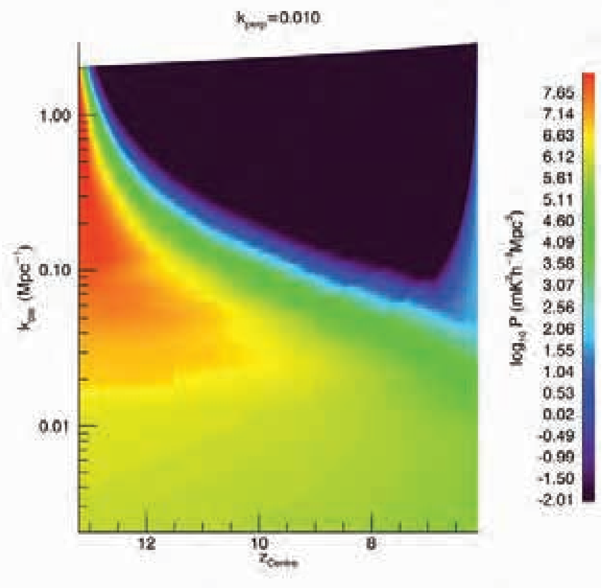
To alleviate this deficiency, Dr Cathryn Trott proposed an extension of the statistical analysis that would allow the best of both worlds; addition of data to maximise signal detectability, combined with spatial localization of the signal to accurately measure the evolution. This approach utilized `wavelets', a way of representing information that balances sensitivity with localization. Wavelets are employed routinely in image processing, but have not yet been applied to EoR data. As well as demonstrating the improved precision of measuring cosmological information using wavelets, Dr Trott was able to show the potential benefits of wavelets for more easily disentangling the contaminating signal from all other radio galaxies in the sky, and the effects of our own Galaxy's magnetic field, from the weak cosmological signal. This contamination, and its treatment, is one of the largest challenges facing current experiments, and a wavelet approach has the potential to provide the additional information we need to address this challenge.

In this work, Trott explored the improvement offered by wavelets using a mathematical model for the signal, foregrounds, and instrument, and a single type of wavelet. However, wavelets represent a broad suite of representations of the data, and future work will try to identify the best wavelets for undertaking this science. After this exploration, Dr Trott aims to apply the approaches to data from the MWA EoR experiment.

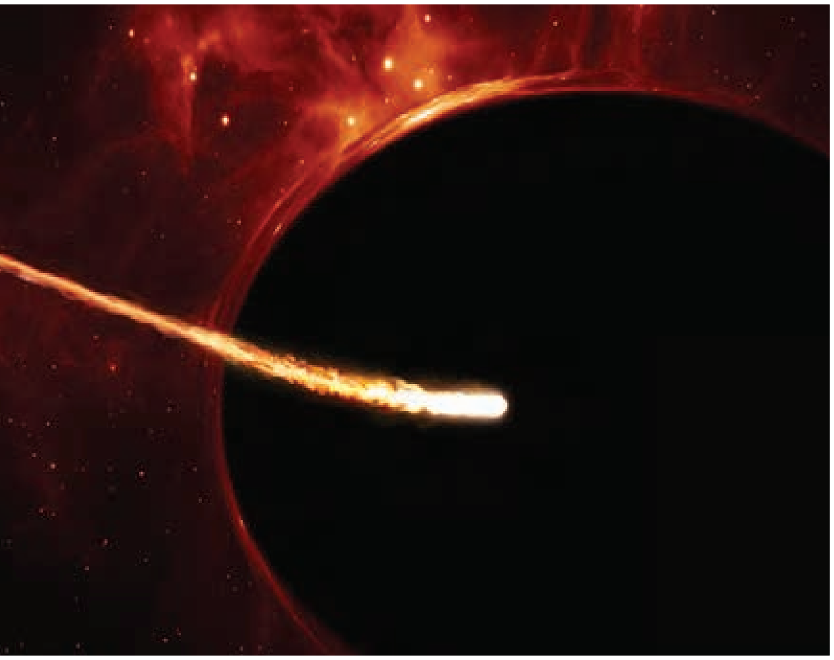
Reference: Trott, C. M. 2016, MNRAS, 461, 126



Above: the wavelet transform power of a single radio galaxy located near the horizon. The horizontal and vertical axes localize redshift and spatial scale, respectively. Right: same, but for the normal Fourier Transform.



Left: Wavelet representation of the signal from neutral hydrogen on scales of one degree on the sky, as a function of their redshift and their line-of-sight spatial scale. The different colours depict different signal powers, showing the evolution of the conditions in the gas between galaxies as a function of time.



Artist's impression of a spinning supermassive black hole tidally disrupting a passing sun-like star, pulling it apart into a stream of stellar debris. The rapid rotation of the black hole gives the event horizon an oblate shape. The large mass of the black hole bends light around it, so that stars and gas behind the black hole can be seen as the distorted light around the horizon. Image credit: ESO, ESA/Hubble, M. Kornmesser.

The superluminous transient ASASSN-15lh as a tidal disruption event from a Kerr black hole

James Miller-Jones

In June 2015, the All-Sky Automated Survey for Supernovae (ASAS-SN, pronounced "Assassin") discovered an extremely luminous optical transient located 3.8 billion light years away in the central regions of a relatively evolved, passive galaxy.

This powerful explosive event, which at its peak outshone the entire Milky Way galaxy by a factor of 20, was twice as luminous than the brightest supernova ever discovered, and was originally interpreted as the most exceptional of a rare class of events known as "superluminous supernovae." The optical radiation from this class of extremely luminous supernovae cannot be powered by the standard supernova mechanisms, namely the radioactive decay of nickel (for hydrogen-poor supernovae), or the recombination of electrons and protons following the ionisation of hydrogen gas by the supernova explosion (for hydrogen-rich environments). Their progenitors must be exceptionally large and massive, be embedded in a very dense environment, or be powered by an altogether different source of energy, such as the spin-down of a young, highly-magnetised and rapidly-spinning neutron star that is formed in the explosion.

The luminous optical transient that was discovered, known as ASASSN-15lh, radiated so much energy (at least 2 times 10^{52} erg; equivalent to one percent of the rest-mass energy of the Sun) that it stretched theoretical models for superluminous supernovae to their limits, and led our team to consider alternative explanations for this exceptional event. We monitored the optical and ultraviolet light curves of the event for ten months following the initial explosion, detecting a significant rebrighening in the ultraviolet part of the spectrum that has not been seen in any previously-studied supernova. This rebrightening implies an increase in temperature that cannot be easily accommodated in supernova models. We also made a very precise measurement of the location of the transient, which we found to be consistent with the centre of the host galaxy to within 450 light years.

The central location with respect to the host galaxy supported an alternative model for the event, as a tidal disruption event in which a passing star was torn apart and accreted by a massive black hole. The luminous optical emission could then have arisen from shocks created as streams of stellar debris collided, or from the energy released by the infall of material towards the black hole. Such an explanation would also be more consistent with what we know of the host galaxy, which is a relatively massive galaxy with an estimated mass of 100 billion solar masses, and which is forming stars at a very low rate of <0.02 solar masses per year. Such an old, massive, red galaxy is unlikely to still host the massive progenitor stars required to produce a superluminous supernova, which tend to occur in much lower-mass, blue, dwarf galaxies that are forming stars at a rate a thousand times higher than the host of ASASSN-15lh.

Detailed optical spectra of the evolving event showed the presence of highly-ionised gas (carbon, nitrogen and oxygen), similar to that seen in other confirmed tidal disruption events. As well as our optical and ultraviolet observations, we used the Australia Telescope Compact Array to put an upper limit on the radio emission from the event, and the XMM-Newton X-ray telescope to constrain its X-ray emission, although neither data set was sufficiently sensitive to provide a smoking gun that would confirm either scenario.

The main argument against ASASSN-15lh being a tidal disruption event is the high mass of the galaxy, which implies that the supermassive black hole at its centre should be very massive, with our best estimates ranging from 10 to 100 million times the mass of the Sun. Instead of tidalling disrupting a passing star, such massive black holes should swallow them whole, such that no luminous optical flash should be observable. However, if the black hole is spinning, stars can be tidally disrupted outside the event horizon up to a significantly higher black hole mass, due to the change in the size of the innermost stable circular orbit around the black hole, and the modification to the black hole's tidal field. In the case of ASASSN-15lh, we found that a sun-like star could be tidally disrupted outside the event horizon as long as the black hole was spinning at 68% of the maximum spin rate allowed by general relativity. Furthermore, a high black hole mass and spin could naturally explain both the high luminosity and timescale of this unusual transient event, with the original bright radiation arising from shocks between stellar debris streams, and the rebrightening being attributed to the release of gravitational potential energy as the material fell in towards the black hole.

While we believe the tidal disruption event to be the most natural explanation for the physical origin of ASASSN-15lh, the small samples of both superluminous supernovae and tidal disruption events detected to date mean that we have not yet sampled the full range of behaviour of either class of object. We are therefore making further observations to better discriminate between the two scenarios, including a deep radio observation with the Australia Telescope Compact Array to detect any jets launched by the accretion flow resulting from the tidal disruption, since model predictions for such an event place the expected radio emission only slightly below the current limits.

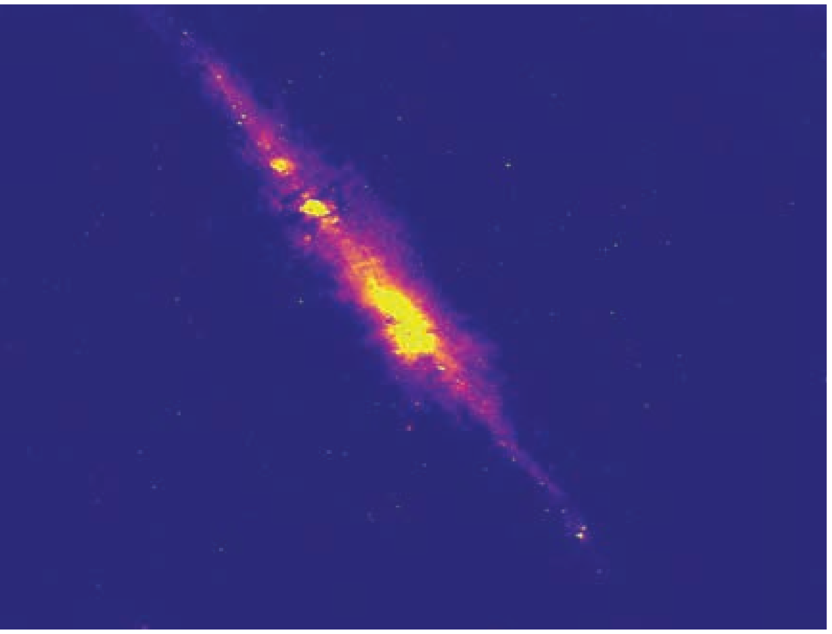
This result shows that tidal disruption events could be a new way of probing supermassive black hole spins, and it was published in the first edition of Nature Astronomy in December 2016 (Leloudas et al. 2016, Nature Astronomy, 1, 2).

Artist's impression of a thin disk of material from the disrupted star swirling around the spinning black hole. The release of gravitational potential energy causes the luminous optical outburst detected as ASASSSN-15lh. Image credit: ESO, ESA/Hubble, M. Kornmesser

Science Highlights

A search for molecules with the Murchison Widefield Array

Chenoa Tremblay



MWA image of the Milky Way Galactic Centre region comprising our survey area for molecular emission lines over the 70 –300 MHz frequency ragne.

The science focuses of the Murchison Widefield Array (MWA) include transient and pulsar science, the detection of the Epoch of Reionisation, and continuum survey science. However, the flexibility of the MWA's design allows for other new and exciting areas of science, such as the study of molecules at very low frequencies within our Galaxy.

Molecules are used as a probe to explore the chemical and physical environments of stars, dust and gas. Since the 1980s, the primary focus of molecular astrophysics has been at frequencies greater than 80 GHz, mainly due to the freedom from radio frequency interference (RFI) emitted by cell phones, televisions and satellites. However, the radio-quiet zone of the Murchison Radio Observatory (MRO) allows us to study the emission of molecular signatures from stars and star-forming regions at much lower frequencies, from 70 – 300 MHz.

A pilot spectral line survey was completed in 2014 with the MWA, with follow-up observations in 2016, to detect molecules located in cold gas regions within the circumstellar envelope surrounding evolved stars located near the centre of the Milky Way. Our MWA survey is the widest field of view molecular survey ever published, and no previous study to date has reported detections of molecules within the 70-300 MHz frequency range.

Our pilot survey yielded tentative discoveries of two molecules; the mercapto radical (SH) and nitric oxide (NO). Previous to our study, the chemical signature of SH itself had only two reported detections, and both were in the infrared portion of the electromagnetic spectrum. Our detected molecular transitions from both NO and SH are from slow variable stars near the end of their life cycles, which have unstable shocks that can boost the chemistry in the region surrounding them.

The tentative detection of these molecules validates that the MWA can detect molecular signatures, that molecules are indeed emitting photons that are detectable around 100MHz, and that the emission mechanisms appear to be non-thermal in nature, as predicted by theory. Our study opened the gateway to observe molecular line transitions that have never been seen before. The ultimate hope is that future work will detect complex molecules that are precursors to life.

Following on from our pilot survey, a survey of the Orion region is in progress with the MWA in the frequency range of 99 – 270MHz. The Orion nebula is a chemical-rich environment and one of the closest star-forming regions to Earth. It is the goal of this work to detect more chemical tracers in stars, compare these regions to the observations from the Galactic centre pilot region, and to better understand the emission mechanisms of these molecules.

In addition to the above science, the MWA molecular survey will constrain the requirements for the low-frequency component of the Square Kilometer Array (SKA) to further probe these chemical environments.

Reference: Tremblay C., Walsh A., Hurley-Walker N., et al.

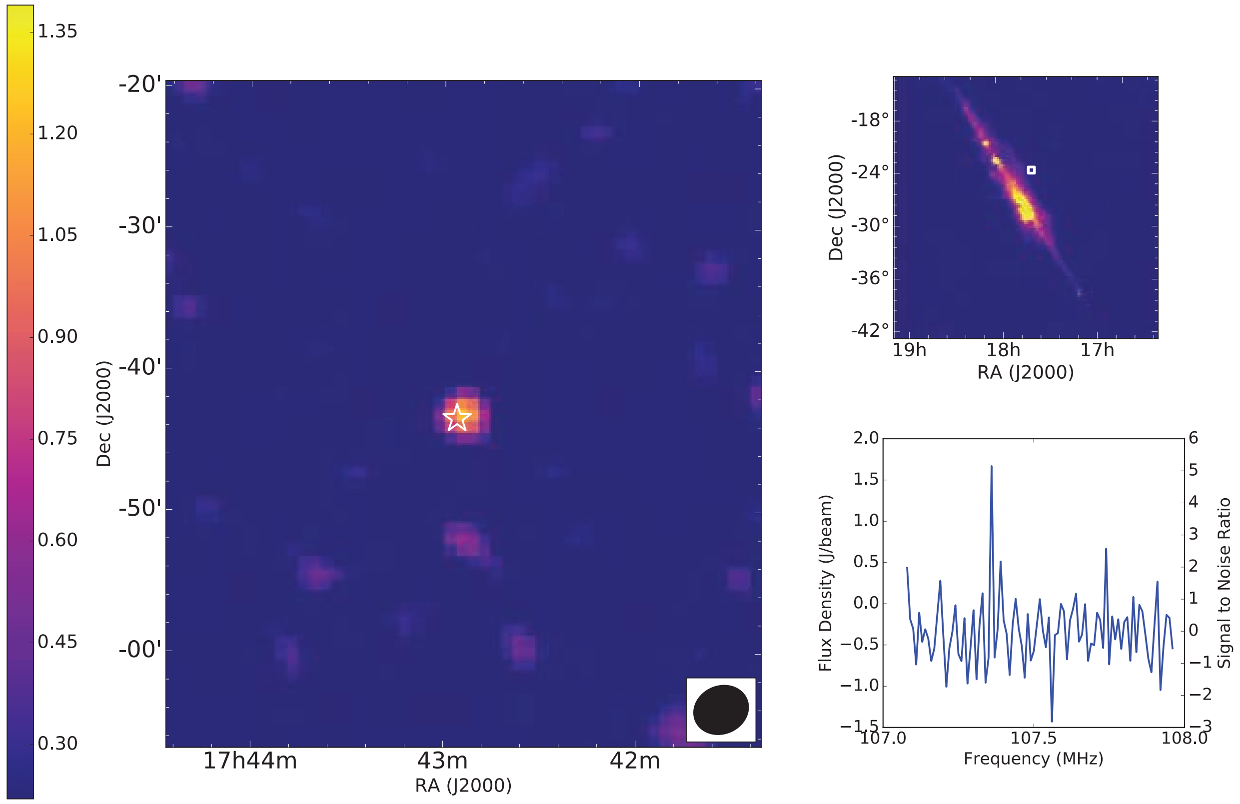
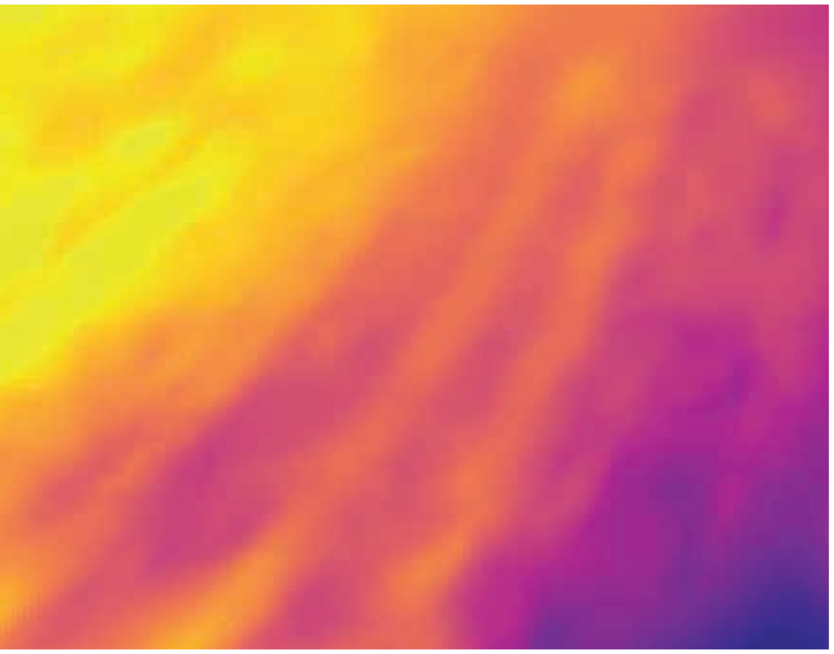


Image showing one of the tentative detections of nitric oxide. The top right-hand image is the full area of our survey with the Galactic Plane shown brightly through the middle. The white box represents the zoomed in region shown in the left-hand panel where the bright colors shows the molecular signature based on the intensity of the colour bar on the far left. The white star marks the optical position of a known variable star. The bottom right-hand image shows the MWA radio spectrum with the intense positive peak caused by emission from the molecule.



Ionospheric conditions above the Murchison Widefield Array

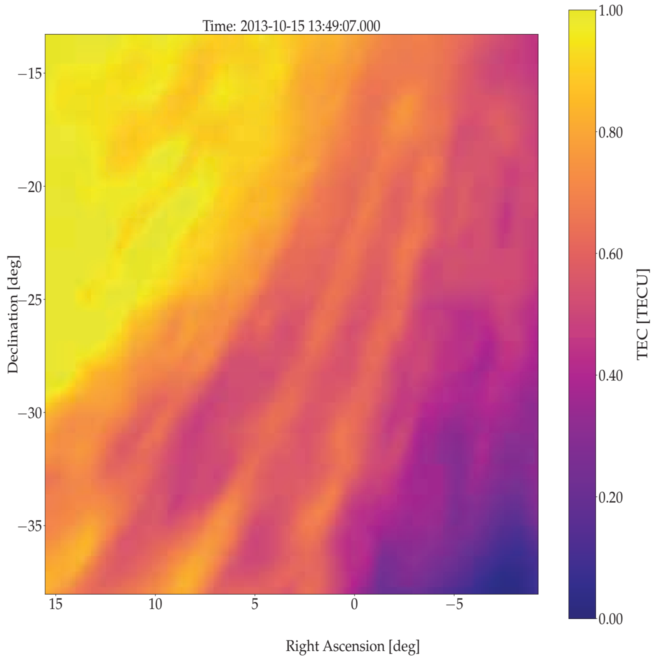
Christopher Jordan

The ionosphere is the outermost layer of the Earth's atmosphere, and it is poorly understood by scientists because it is difficult to see. Modern technologies, such as the global positioning system (GPS) and magnetic-field detectors, have been able to identify features of the ionosphe, but usually only on global scales that cover a large part of the Earth's surface.

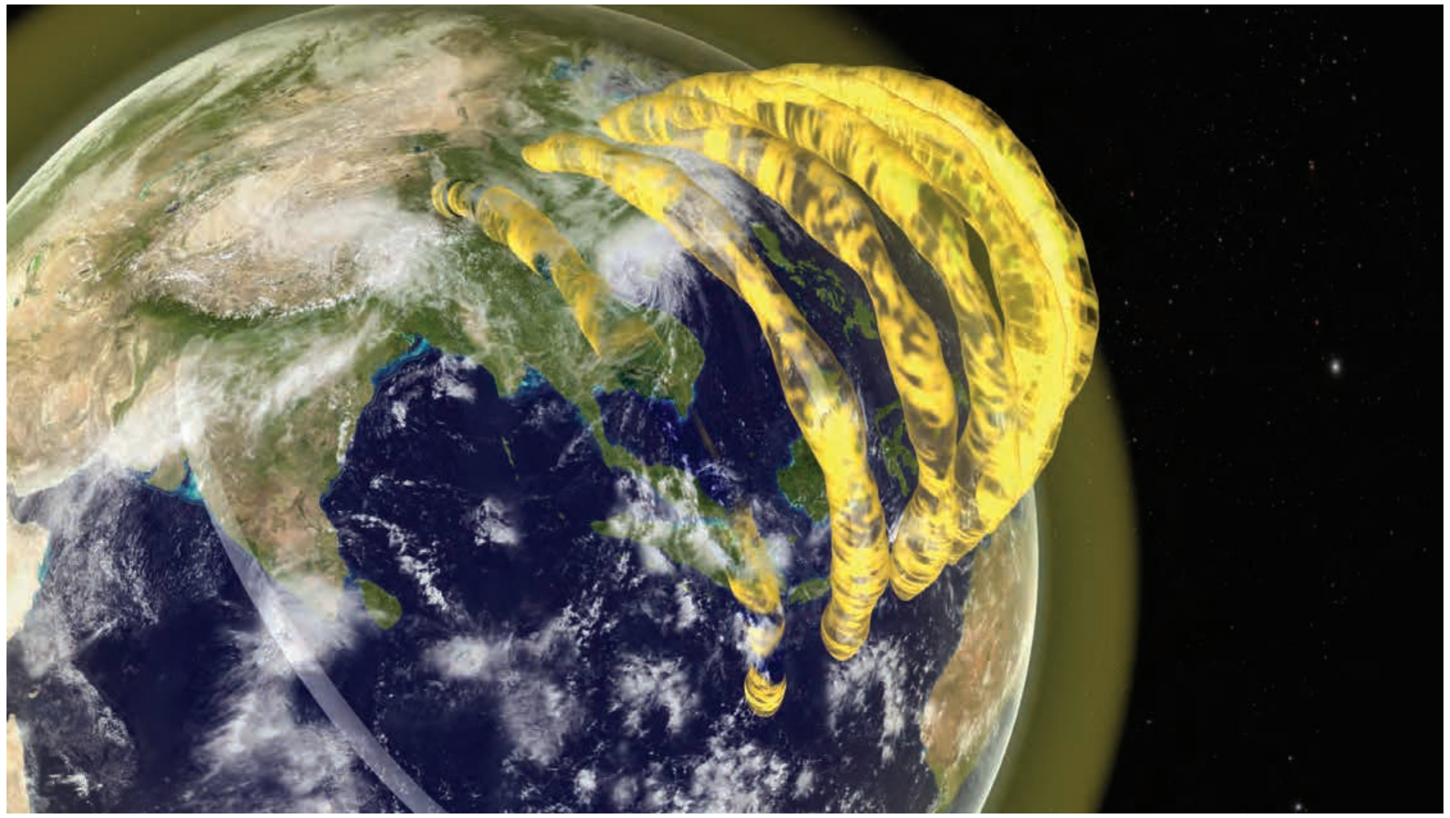
As technology has improved, so has our capability to peer out into the Universe with radio telescopes, including with the Murchison Widefield Array (MWA). Yet, the MWA is also a powerful machine for studying the Earth itself, because it sees so much of the sky that it is highly sensitive to ionospheric effects, at a level that has never before been seen in detail. This unique trait of the MWA led Cleo Loi to find huge "tubes" in the ionosphere, arching over the Earth's surface and aligned with the Earth's magnetic field, much like a compass.

Cleo's discovery represents what we think was a very active evening (an ionospheric "storm"). Having progressed on Cleo's work, we now know that the ionosphere is mostly inactive, but can sometimes show effects; these could be large or small, like waves in the ocean, except over the Earth.

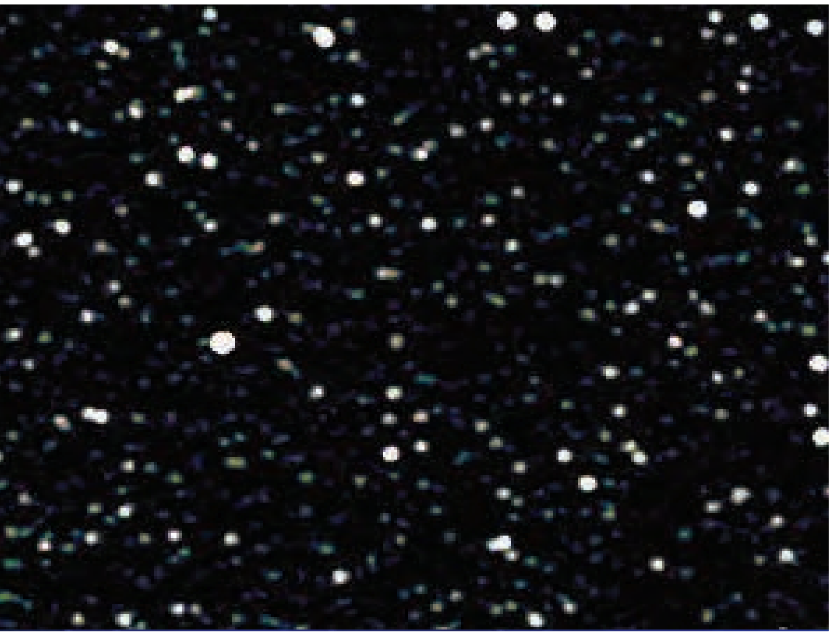
One area of research at CIRA is detection of the Epoch of Reionization (EoR) with teh MWA; this project seeks to detect a signal near the start of time at the edge of the Universe. To make a detection, we require a huge amount of telescope time staring into a relative blank patch of the sky. But, if ionospheric activity is present in any of the data which makes up the many hours required, then the EoR signal is masked in a sea of noise. For this reason, we are working toward a better understanding of the ionosphere to predict, model and "subtract" its behaviour, while simultaneously working together with other ionospheric science teams. Here, the MWA acts as an unprecedented tool for learning about a poorly understood phenomenon so close to home.



Left: An example of extreme ionospheric activity seen with the MWA. The colour bar is represents a measure of the the amount of gas in the ionosphere, encoding a parameter related to the electron column density. Credit: MWA EoR team



Artist's depiction of ionospheric tubes found by Cleo Loi.
Credit: CAASTRO



Science Highlights

The S-band Polarisation All-Sky Survey: over 20,000 sources at 2.3 GHz

Bradley Meyers • Natasha Hurley-Walker
Paul Hancock • Thomas Franzen

Radio source catalogues allow us to probe the physics determining how galaxies and their central supermassive black holes co-evolve over cosmic time.

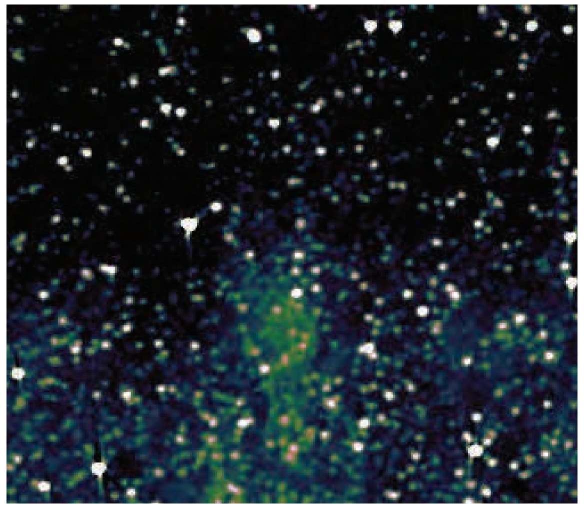
The S-band Polarisation All-Sky Survey (S-PASS) is a total intensity and polarisation survey conducted with the CSIRO 64-m Parkes radio telescope at 2.3 GHz. S-PASS was completed in January 2010, and its science goals include investigating Galactic and extragalactic magnetism, studying the diffuse polarised Galactic synchrotron emission, and characterising polarised foregrounds for Cosmic Microwave Background science. Polarisation and magnetism studies are ongoing, but they have already proved fruitful, providing evidence of giant magnetised outflows from the centre of our own Galaxy, and also allowing studies on disordered magnetic fields and Faraday effects in extragalactic sources.

One of the data products from S-PASS is a set of 107 total intensity (Stokes I) maps covering the entire southern sky with ~11 arcminute resolution. From these images, we produced a catalogue of nearly 24,000 radio sources in the Southern sky (we cover ~17,000 square degrees, or 40% of the **entire** sky).

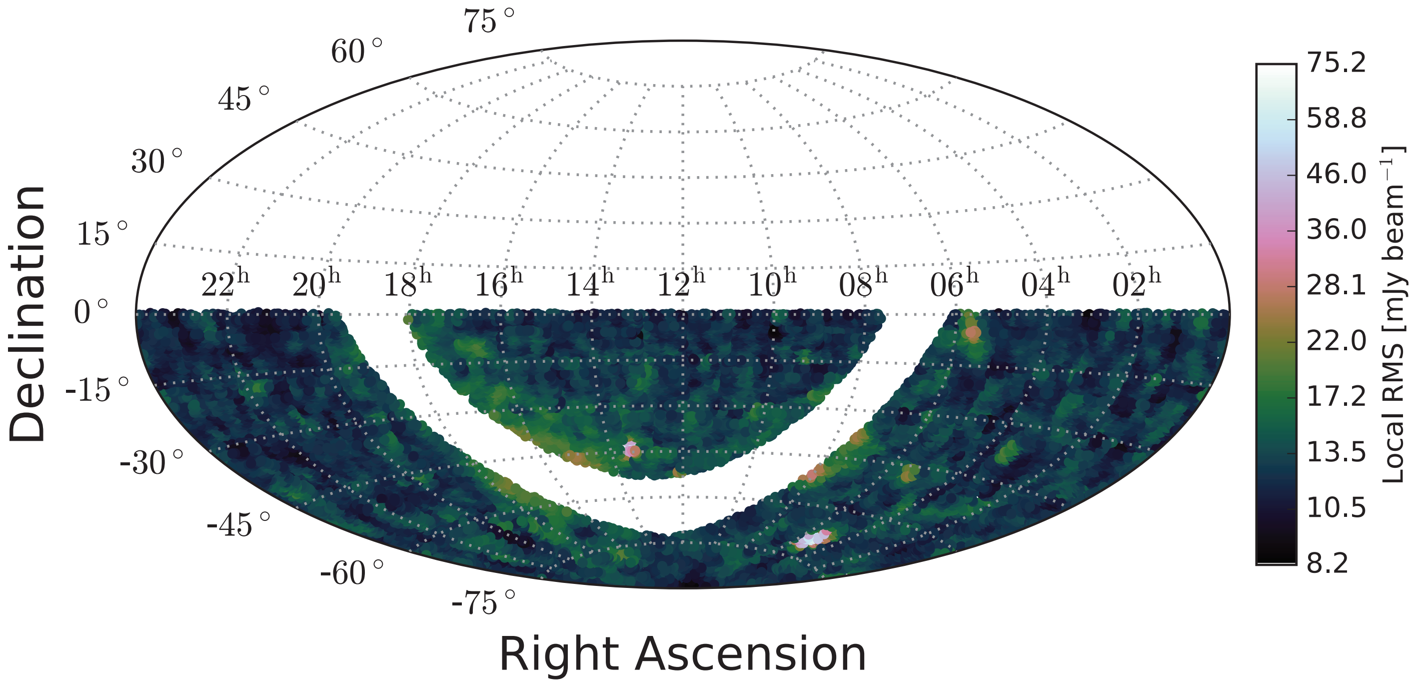
The S-PASS total intensity source catalogue is a high-quality scientific tool, with applications to several exciting areas of astrophysics. Most of the sources catalogued are radio galaxies with supermassive black holes at their hearts. Combining S-PASS with other radio surveys (for instance, the recently released GLEAM source catalogue at 72-231 MHz) provides us with spectral information for many thousands of sources. The 2.3 GHz central frequency is perfect for studying Gigahertz Peaked Spectrum sources – peculiar objects with a peak spectrum around 1 GHz thought to be the precursors to massive radio galaxies. Comparing S-PASS sources with other older southern-sky catalogues at similar frequencies could also provide interesting context into the nature of source variability and evolution over decade time scales.

The catalogue is now publicly available here: http://bit.ly/2nKr9KI

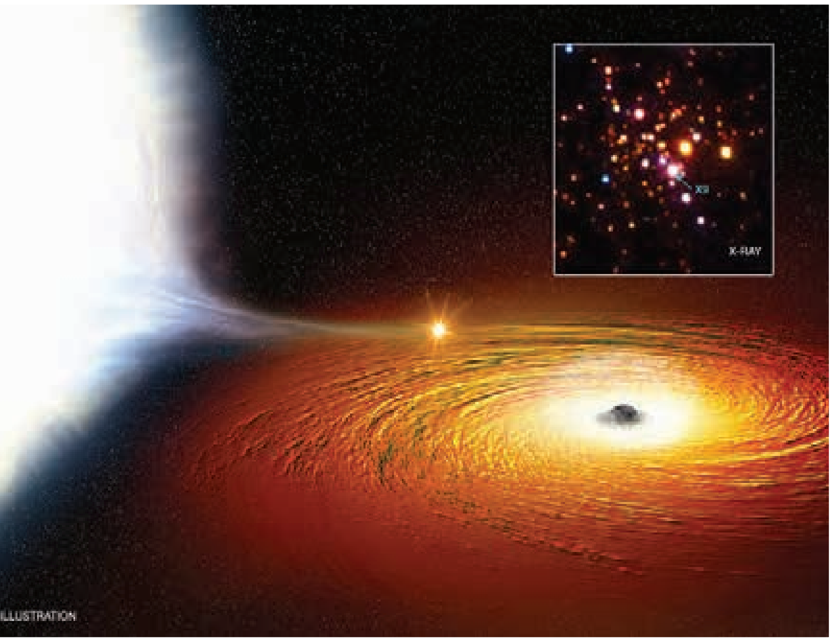
Reference: Meyers, Hurley-Walker, Hancock, Franzen et al., 2017, PASA, 34, 13



The footprint of the S-band Polarisation All Sky Survey (S-PASS)



Left: An example S-PASS field. On the top is an image with large scale structure filtered out, and on the bottom is an unfiltered image of the same field. The sources stand out significantly more in the top image, with fainter sources being much more clearly defined. The catalogue was produced using the filtered images in order to optimise point source detection.



The first binary black hole – white dwarf candidate in the Milky Way

Vlad Tudor

Globular clusters are very dense stellar congregations. Compared to the solar neighbourhood, where one would have to travel just over 4 light years to reach the nearsest star to the Sun, the core of the globular cluster 47 Tucanae is much richer, cotaining 100,000 stars in the same volume. At such high densities, frequent dynamical interactions between stars and their remnants (white dwarfs, neutron stars and black holes) are quite common.

While we have been observing white dwarfs and neutron stars in Milky Way globular clusters for decades, black holes have been much harder to find, with candidates emerging only in the last few years. Revealing why black holes appear to be so scarce in globular clusters requires knowledge of their properties in these environments, which can only be gathered by finding more of them.

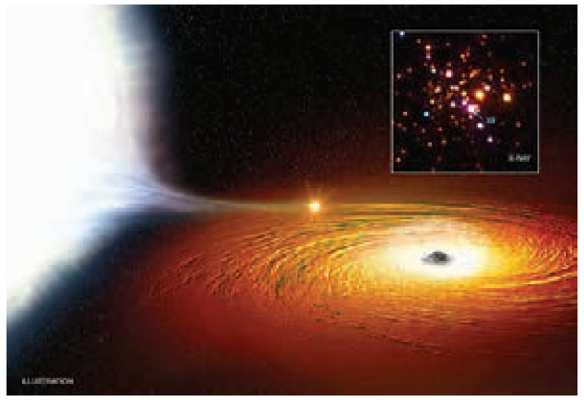
Black holes do not emit any light of their own, but they can be identified by various indirect methods. In a tight binary with another star, the black hole's strong gravity can pull material from its companion. The infall of gas towards the black hole releases huge amounts of energy, enough to produce X-ray radiation. Some of the gas falls into the black hole, but some of it is ejected from the system, which we often observe as jets launched away from the black hole at relativistic speeds that emit large amounts of radition in the radio waveband.

At low-accreiton rates, black holes that are not in globular clusters are known to display a correlation between their X-ray and radio emission, indicting a interplay between the inflowing accretion disk and the outflowing jet. From this radio/X-ray correlation, Miller-Jones et al. (2015, MNRAS, 453, 3918) suggested that the X-ray source X9 in the globular cluster 47 Tucanae could be a black hole with a white dwarf companion. To confirm this scenario, we carried out observations with the *Chandra* and *NuSTAR* X-ray space observatories simultaneously with radio observations with the Australia Telescope Compact Array. In archival Chandra data, we also found a periodic variation in the X-ray brightness of X9 every 28 minutes, which is likely due to the orbital motion of the binary system (see the figure on the next page). Such a short orbital period means that the distance between the white dwarf and the black hole is only around 2.5 times the distance between Earth and the Moon. Such a separation is too small to fit any system containing a black hole orbitted by a Sun-like star, and the only type of star that can fit into this small orbit with a black hole is a white dwarf. If most black hole systems in globular clusters are orbitted by stars with periods as short as X9, then their faintness is a natural explanation for why black holes in Milky Way globular clusters have remained so elusive.

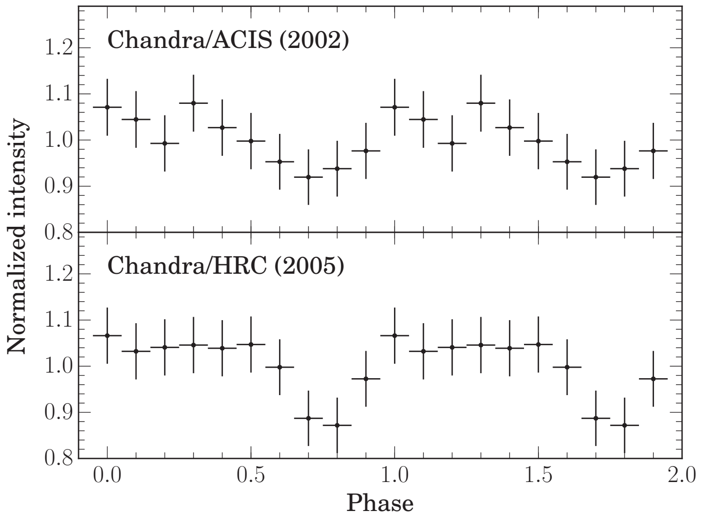
In our new Chandra data, we identified X-ray spectral lines produced by oxygen in this system. This is another strong piece of evidence for a white dwarf companion: normal stars are mostly made of hydrogen, but white dwarfs are the remnant cores of low mass stars and are made up of large amounts of helium, carbon or oxygen.

While we are confident that the companion star is a white dwarf, there is still a possibility that the object that it is orbiting is a neutron star instead of a black hole, and further observations are needed to determine the nature of the accreting object. If X9 indeed contains a black hole, then we predict that future gravitational wave observatories like the *Laser Interferometer Space Antenna (LISA)* might be able to detect it.

The work described here was published in Bahramian, Heinke, Tudor, Miller-Jones et al. 2017, MNRAS, 467, 2199.



An artist's impression of the source 47 Tuc X9, a candidate white dwarf in orbit with a black hole. The inset shows an X-ray image of the centre of the globular cluster 47 Tucanae acquired with the Chandra X-ray telescope, with the position of 47 Tuc X9 highlighted. Image credit: X-ray: NASA/CXC/University of Alberta/A.Bahramian et al.; Illustration: NASA/CXC/M.Weiss.



The folded X-ray light curve of 47 Tuc X9 from two observing epochs with the Chandra X-ray telescope in 2002 (top panel) and 2009 (bottom panel). The X-ray luminosity varies with a 28 minute period, likely indicating the orbital period of the system. The only type of star that can orbit a black hole or neutron star so rapidly is a white dwarf. Image credit: Bahramian et al., 2017, MNRAS, 467, 2199

Discovery of the first eclipsing rapidly accreting black holes

Ryan Urquhart

A three-colour optical image of the Whirlpool Galaxy, M51, taken with the Hubble Space Telescope. The white box indicates where ultraluminous X-ray sources are located. Although very bright in X-rays, the ultraluminous X-ray sources are difficult to distinguish from the surrounding stars at optical wavelengths.

Black holes are some of the most enigmatic objects in the Universe. Whether one considers supermassive black holes at the centres of galaxies, or the much smaller stellar mass variety that are created from the deaths of massive stars, black holes are important targets for astrophysics research.

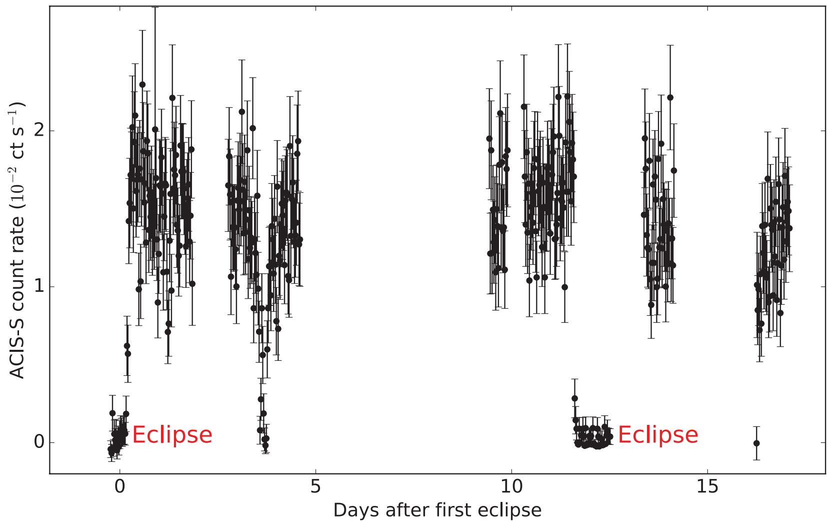
If close enough to a black hole, the gravitional pull is so strong that not even light can escape, meaning that black holes themselves do not emit any detectable radiation. In order to study black holes, astronomers must therefore use indirect methods. One option is to catch a black hole while it is feeding (usually from a nearby star), a process known as “accretion”. Thanks to their immense gravitational fields, black holes can convert the gravitational potential energy from infalling material into intense amounts of radiative energy. The faster a black hole feeds, the brighter it can shine. Some of the fastest feeding black holes are known as ultraluminous X-ray sources (ULXs).

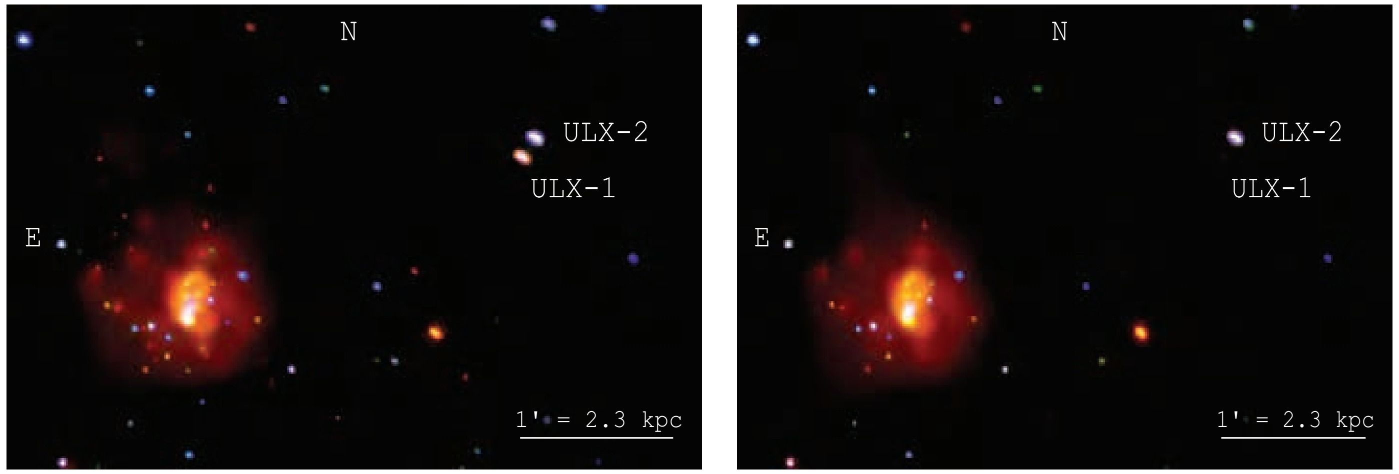
Recently, we discovered the first eclipsing ULX. It is located in the large spiral galaxy Messier 51, also known as the Whirlpool Galaxy (see the figure at the top of the page). We identified this object using data taken with the *Chandra* X-ray Observatory. By studying the X-ray emission coming from the ULX over a number of weeks, we discovered that the source would repeatedly, and abruptly, disappear (see the figure on the next page). The periodic nature of these disappearances led us to believe that the X-ray source was being eclipsed. Just like during a Solar eclipse, where the Moon passes between the Earth and the Sun, the rapidly accreting black hole was being obscured by the nearby star that it was feeding on, blocking out all of the X-ray emission.

Surprisingly, we discovered that the eclipsing ULX’s closest neighbour, another bright ULX, also showed evidence of eclipses. It turned out that we discovered not one but two separate ULXs. Of the hundreds of known ULXs spread throughout the Universe, we had found the first two eclipsing ULXs ever, practically on top of one another.

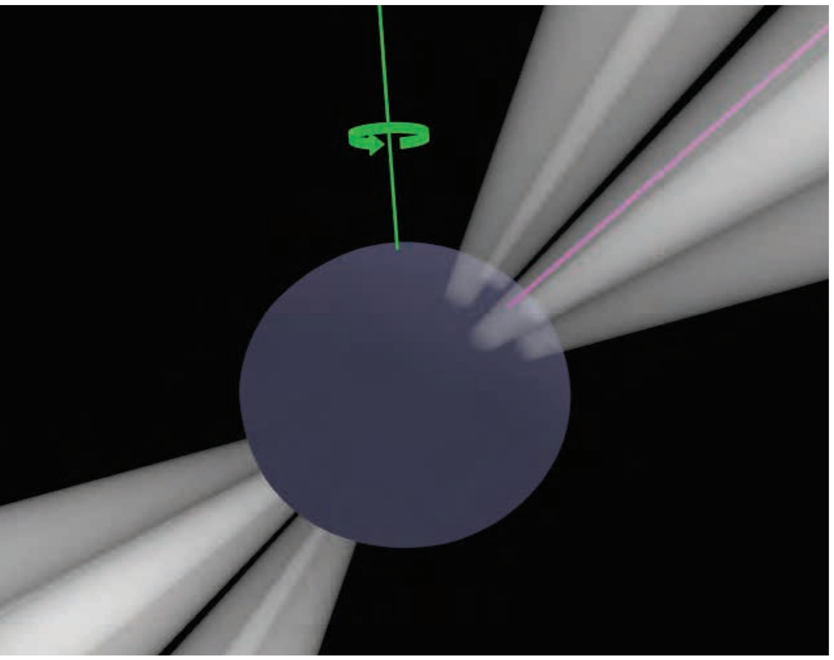
The presence of eclipses offers us a rare chance to accurately measure the mass of the black hole, something that has never been done for a ULX. Measuring the masses of either of these sources would be an important milestone, as the masses of black holes in ULXs are still heavily debated. Continued investigation is required, but these two exciting objects offer us a unique opportunity to further our understanding of black holes feeding at the fastest rates.

Reference: Urquhart et al. 2016, ApJ, 831, 56.





The top two panels at the bottom of the page show false three-colour X-ray images of the inner regions of M51, from the Chandra X-ray Observatory. The left image shows an epoch when neither ULX is in eclipse, and the right image shows an epoch when ULX-1 has gone into eclipse and is no longer observed at X-ray wavelengths. The figure to the left shows an X-ray light curve of the eclipses.



A schematic of a pulsar magnetosphere with an arrangement of a rotating carousel that can give rise to the phenomenon of subpulse drifting (see text for details) . The green line is the pulsar's rotation axis, and the purple line is the magnetic axis, about which the carousel rotates.

Science Highlights

Secrets from the subpulse drifter, PSR J0034-0721

Sam McSweeney

Pulsars are rapidly spinning neutron stars, the remnants of supernovae that mark the end of massive stars' lives, and are natural laboratories to probe extreme physics.

As pulsars spin they emit radio waves, beamed in the direction of their magnetic axes, which we detect as regular pulses of light. Some pulsars, such as PSR J0034–0721, are particularly interesting: their pulses are seen to march in time with each pulsar rotation – a phenomenon called "subpulse drifting." Subplus drifting pulsars like PSR J0034–0721 offer a unique window into the underlying physics governing the mehcanisms that produce radio emission from pulsars, an outstanding problem even after 50 years of research.

It is supposed that subpulse drifting is the direct result of an emission beam geometry that resembles a circular carousel of beamlets, centred on the pulsar's magnetic axis. The carousel rotates around the magnetic axis at some rate determined by the physical conditions within a relativistic plasma of charged particles that co-rotate with the pulsar, a structure called the magnetosphere (see the figure at the top of the page). The carousel rotation rate – if it can be accurately measured – provides a direct way to test theoretical models for pulsar radio emission.

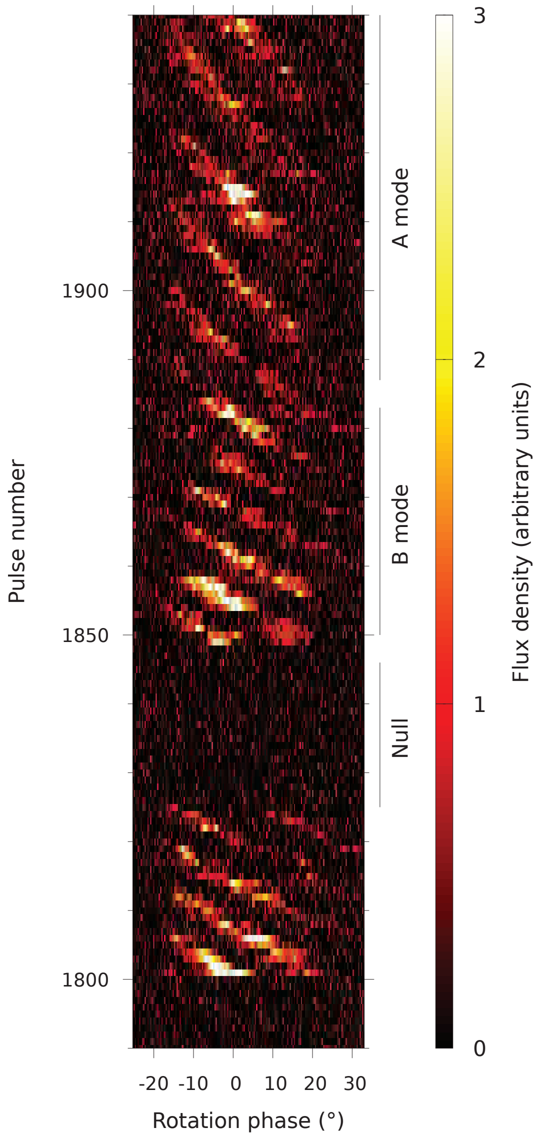
Crucial to the study of subpulse drifting is high time-resolution and high sensitivity observations of individual pulses. We made new observations of PSR J0034-0721 using the voltage-capture mode of the Murchison Widefield Array (MWA), yielding some of the most exquisite low-frequency (~185 MHz) observations of subpulse drifting ever seen. The figure on the next page shows a sample of 150 pulses from this pulsar. The subpulse drifting manifests as quasi-periodic diagonal "drift bands" stretching across the pulse window.

These pulses are grouped into sequences that can be classified into three distinct **drift modes,** depending on the average vertical spacing of the drift bands within each sequence. The rate at which a subpulse drifts across the pulse window relates directly to the carousel rotation rate. Different drift modes are observed to exhibit different drift rates, with the transitions between different modes occuring abruptly, which implies that the carousel is rotating at a rate that changes very suddenly with time. The existence of this pulsar's three drift modes with their distinct drift rates has remained unexplained since their discovery back in the early 1970's.

But the plot thickens. A subtle, hitherto unnoticed behaviour gleamed from our new MWA observations is a gradual, systematic change in the drift rate even **within** a single drift mode. In some sequences the rate increases, and in others it decreases; however, the implied torque of the carousel remains stable over the course of a single sequence. Because of this stability, the drift bands can be accurately modelled by simple quadratic curves. The results are pleasing, even near sequence boundaries where the drift rate usually changes most dramatically. These findings were published in the Astrophysical Journal (McSweeney et al., 2017, ApJ, 886, 224).

Varying drift rates immediately throw up a challenge to theorists. The traditional way to explain the carousel rotation (an explanation that harks back to the seminal work of Ruderman & Sutherland in the mid 1970's) is in terms of electric and magnetic forces that push charged particles around the magnetic axis. However, since both the electric and magnetic fields of pulsars are expected to be stable over short time scales, this model predicts a constant drift rate, in contrast to what we observe with the MWA. One possible explanation is that the surface temperature of the pulsar may fluctuate, in turn affecting the carousel rotation rate.

In order to investigate this further, and to reach our eventual goal of uncovering the underlying physics, we require longer data sets spanning multiple frequencies. We are undertaking such a study using the MWA, the Giant Metrewave Radio Telescope (India), and the Parkes radio telescope (NSW) to span a frequency range from ~150 to 1500 MHz. The emission at lower frequencies is thought to originate higher above the pulsar's surface than higher frequencies, and so the multifrequency nature of this campaign will allow us to probe the different physical conditions of the magnetosphere at different altitudes.



A sequence of 150 successive pulses from PSR J0034-0721, from our MWA observations made in the 170-200 MHz frequency band, zoomed in to show approximately 1/6th of the rotation window. The diagonal pattern is the manifestation of the phenomenon of subpulse drifting, thought to be evidence of a rotating carousel of emitting plasma blobs near the pulsar's surface.

The surprising complexity of the radio emission from star forming galaxies

Nick Seymour

Tim Galvin

Determining when, where, and how all the stars in the Universe formed is a fundamental question in astrophysics. Hence, measuring the ongoing star formation rate (SFR) of galaxies at a range of epochs, environments, and galaxy types is key to a deep understanding of galaxy formation.

Many tracers of star formation, for example in the ultraviolet (UV) and in the optical wavebands, are complicated by the presence of absorbing dust, which necessitates large, but uncertain, correction factors. Even direct observations of the absorbing dust at far-infrared frequencies can be complicated by dust geometry, the presence of a central active galactic nucleus (AGN), and the unknown amount of unabsorbed UV/optical light.

Radio emission, in the absence of a radio-loud AGN, is perhaps the cleanest measurement of star formation as radio photons are not absorbed by dust. Furthermore, the radio luminosity of a galaxy is directly proportional to its SFR. Two physical processes cause star formation to emit at radio wavelengths. In the ionized regions around young massive stars, free-free, or Bremsstrahlung, radiation is produced from the attraction between free electrons and protons. These same young, massive stars soon explode as supernovae, and the shocks from these supernovae accelerate electrons to relativistic speeds. The relativistic electrons then oscillate in the galactic-wide magnetic fields producing synchrotron radiation. Both the free-free and synchrotron emission are direct measures of the on-going SFR with the synchrotron emission arguably being a slightly delayed tracer by many tens of millions of years.

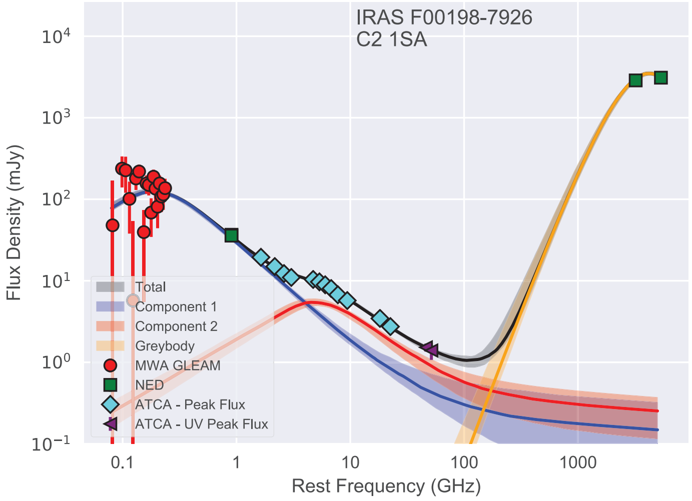
Typically, free-free emission has a fairly flat spectrum ($\alpha \sim -0.1$, where the flux density, $S_\nu \sim \nu^\alpha$) and synchrotron emission has a steep spectrum ($\alpha \sim -0.8$). Hence, synchrotron radiation tends to dominate the radio emission at lower frequencies. However, at high frequencies the more immediate tracer, free-free emission, will dominate. These high-frequencies get shifted to the lower observed frequencies for high redshift galaxies. Hence, free-free emission at high redshift may be our best tracer of star formation.

Upcoming radio telescopes in this new golden age of radio astronomy are going to find vast numbers of star forming galaxies. For example, the Evolutionary Map of the Universe (EMU) project on the Australian Square Kilometre Array Pathfinder will detect around 70 million radio sources, at least half of which will be star forming galaxies. Hence, when using EMU to measure the star formation history of certain groups or classes of galaxies, we will no longer be limited by small number statistics as before, but by our understanding of the astrophysics behind the radio emission. To this end we have conducted broadband radio observations of a sample of 19 low redshift ($0.067 < z < 0.227$) star forming galaxies. These galaxies are selected to be bright in the far-infrared and therefore have very high SFRs analogous to galaxies in the distant Universe. Our observations include photometric measurements across 70-230 MHz from the Galactic and Extragalactic All-sky MWA (GLEAM) survey as well as observations across 1-100 GHz from the Australian Telescope Compact Array (PI T. Galvin) in addition to some literature measurements (e.g. SUMSS.)

We present the spectral energy distributions (SEDs) of a star forming galaxy (IRAS F00198-7926) from our sample in the figure at the bottom of the page). This SEDs show the radio to far-infrared measured flux densities as a function of rest-frame frequency with a fitted model. The far-infrared emission is well modeled by a greybody (a modified black body with a varying emissivity). However, the radio emission, which has often been approximated as a power-law, shows considerable complexity with several kinks and a low frequency turnover. **Our results demonstrate a diversity and complexity in radio SEDs of galaxies with similar SFRs.** That is, radio SEDs are not simple powerlaws as has often been assumed. The radio emission is most often best fit in our sample with two components of a model combining (i) flat free-free emission, (ii) steep synchrotron emission, and (iii) a turn-over at low frequencies due to free-free absorption. Free-free absorption is the opposite process to free-free emission, where low energy radio photons get absorbed by free electrons as they interact with protons in a plasma.

While there had been some evidence of such complexity, including the low-frequency turn-overs, in star forming galaxies before, this is the first time this has been shown in such exquisite detail. Why such complexity though? The turnover frequencies of the free-free absorption relates to a property of the ionized regions called the Emission Measure. The Emission Measure is essentially the integration of the square of the electron density along the line of sight, hence we can assume it is related to the geometry of the star forming galaxy. In particular, if the synchrotron emission is being absorbed then it must be within, or behind, the ionised regions from our point of view. From our modeling we find two components with quite distinct turnover frequencies, ν_{turn}: one with $0.2 < \nu_{turn} < 0.6$ GHz, and one with $0.9 < \nu_{turn} < 12$ GHz. The high frequency turn-over component therefore likely corresponds to a component with a higher Emission Measure or a hgiher electron density.

To directly relate the radio SEDs to the optical properties



Radio through far-infared spectral energy distribution of the star-forming galaxy IRAS F00198-7926. Note the turnover at the lowest frequencies, caused by free-free absorption.

Continued overleaf

Science Highlights

The surprising complexity of the radio emission from star forming galaxies

Nick Seymour

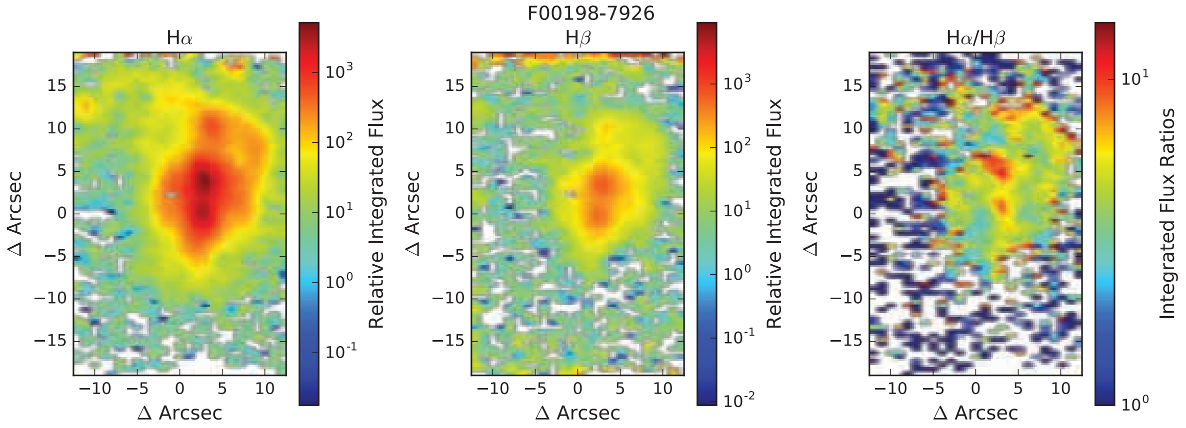
Tim Galvin

of these galaxies we undertook observations of all sources with the Widefield Spectrograph (WiFeS), a wide-field integral-field spectrograph (PI T. Galvin). These observations provided optical spectra from 330-900 nanometres across the full field-of-view of the galaxies. Such observations allow us to map out the intensity of the brightest permitted emission lines of the hydrogen Balmer series. Specifically we can trace Hα (656 nanometres) and Hβ (486 nanometres), two intense lines that can provide a measure of star formation, although both are heavily affected by dust. However, this absorption by dust is wavelength dependent, so that we can use the ratio between these two emission lines to measure the line of sight dust distribution and hence the dust corrected SFR across the galaxy. At the bottom of this page, we show the Hα and Hβ maps of IRAS F00198-7926 as well as their ratio, which is a measure of the dust distribution in this galaxy.

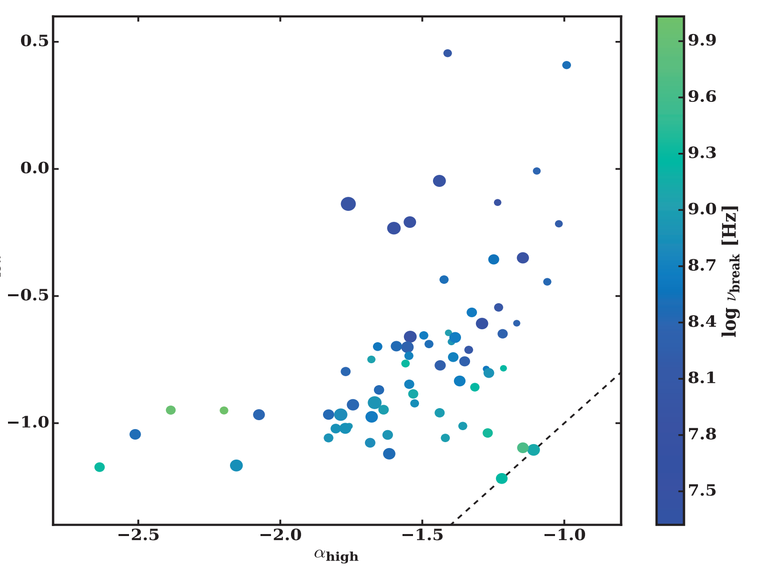
Two strong, but dusty, star forming regions can be seen in the figure at the bottom of the page, which we suggest are related to two components seen in the radio SED in the figure on the previous page. Our final interpretation is still pending, as another possibility is that the high frequency turnover in the radio SED (related to the denser ionised electrons) may correspond to the compact star formation, and the lower frequency turnover to the more extended star formation. Soon we hope to be able to directly infer the geometry of star formation from the radio SEDs alone.

An important implication of these results is that the radio SEDs of star forming galaxies are diverse and hence simple models used to dervie deep source counts may not be accurate. Such models assume, at best, a single component and a single turn-over frequency. Upcoming work will use well-constrained deep sources counts at 1.4 GHz to then predict deep source counts at lower radio frequencies using a more accurate and representative set of radio SEDs. This will be fundamentally important for determining the confusion limit of the next generation of low frequency radio surveys (e.g. the Square Kilometre Array) as well as providing a far more accurate foreground model for Epoch of Reionisation detection experiments.

The results described here are soon to be published in two papers (Galvin et al. 2017a, 2017b).



Maps of the intensity of emission from the Ha line (left panel), the Hb line (middle panel), and the ratio between the two (right panel) for the star forming galaxy F00198-7926. The right-most panel represents a description of how dust is distributed within the galaxy. These data were taken with the Widefield Spectrograph (WiFeS), an integral-field spectrograph on the Australian National University 2.3 metre optical telescope.



Two radio spectral indices at low (α_{low}) and high (α_{high}) frequencies, derived from spectra fits to a sample of 70 powerful radio galaxies that have raio spectra sampled from 70 MHz – 20 GHz.
The colour bar describes the frequency where the spectrum transitions from α_{low} to α_{high}. Larger circles correspond to higher redshifts (from z=1 to z=5.2).

Using multi-frequency radio observations to disentangle the accretion history of distant powerful radio galaxies

Guillaume Drouart

Understanding the connection between the formation and evolution of supermassive black holes and their host galaxies is one of the most exciting topics in extragalactic astronomy today.

At the moment, our most sensitive telescopes are capable of observing accreting black holes that are a few billion times more massive than our Sun, out to redshifts ~7 (Morlock et al. 2011) corresponding to when the Universe was about one billion years old. To grow so massive in such a short time, these supermassive black holes could not have grown by passively accreting matter at a steady rate. Rather, extreme accretion events would have been required (Volonteri 2016).

Powerful radio galaxies make wonderful laboratories to study how the most massive black holes grew, and how black holes co-evolved with their host galaxies (Seymour et al. 2007, De Breuck et al. 2010, Drouart et al. 2014, Drouart et al. 2016). Radio galaxies are powered by an accreting supermassive black hole, with outflowing relativistic jets eminating from the regions very close to the black hole. The relativistic jets eventually ram into the intergalactic medium at large distances from the black hole (up to nearly millions of light years in some cases). Locations where jets interact with the local environment are marked by diffuse lobes of radio emission, which represent a relic of recent accretion activity and provides clues about the recent past of the supermassive black hole.

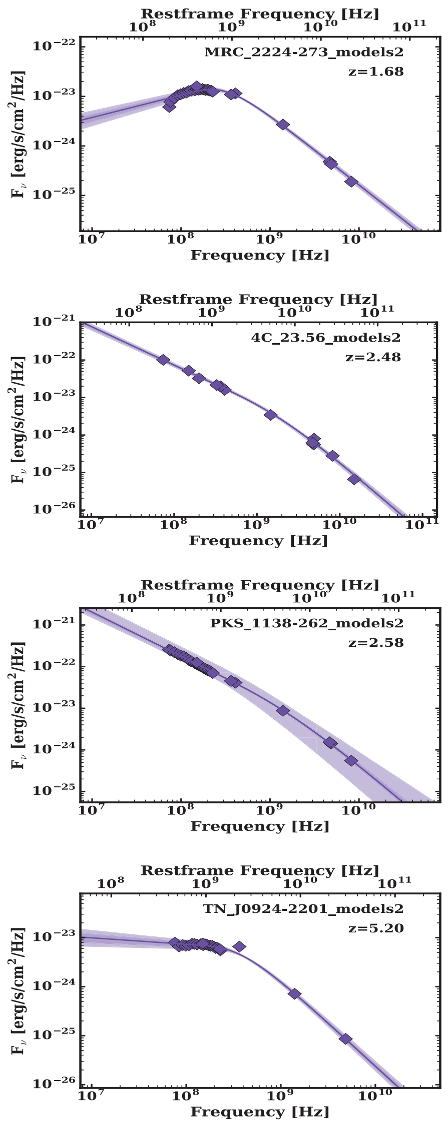
In this work, we focused on the radio emission from a sample of 70 powerful high-redshift radio galaxies to study the evolution of supermassive black holes. Our sample was derived from the newly released GaLactic and Extragalactic All-sky MWA Survey (GLEAM) catalogue (Hurley-Walker et al. 2017). GLEAM covers the low-frequency part of the radio spectrum (74-231 MHz), which we combined with higher frequency observations from other large surveys, and also individual observations from powerful radio telescopes like the Australia Telescope Compact Array and the Very Large Array. The result is a homogeneous collection of radio spectra containing 7-41 datapoints in the 70MHz-20GHz frequency range.

The radio spectra of radio galaxies can often be described as absorbed low frequency emission followed by a turnover at higher frequencies, with the turnover representing a transition into the optically-thin synchrotron regime. At even higher frequencies there is another break caused by dynamical energy losses from the highest energy synchrotron emitting particles. For each of our 70 spectra, we therefore fit a double broken power-law using a new Bayesian fitting code, MRMOOSE (Drouart & Falkendal, in prep). Key parameters of interest derived from our fitting include the shape of the radio spectrum above and below the break frequency (α_{low} and α_{high}, respectively, where $f_{\nu}=\nu^{-\alpha}$). The ensemble of best-fit spectral indices for all 70 radio galaxy spectra are shown in the figure at the top of the page.

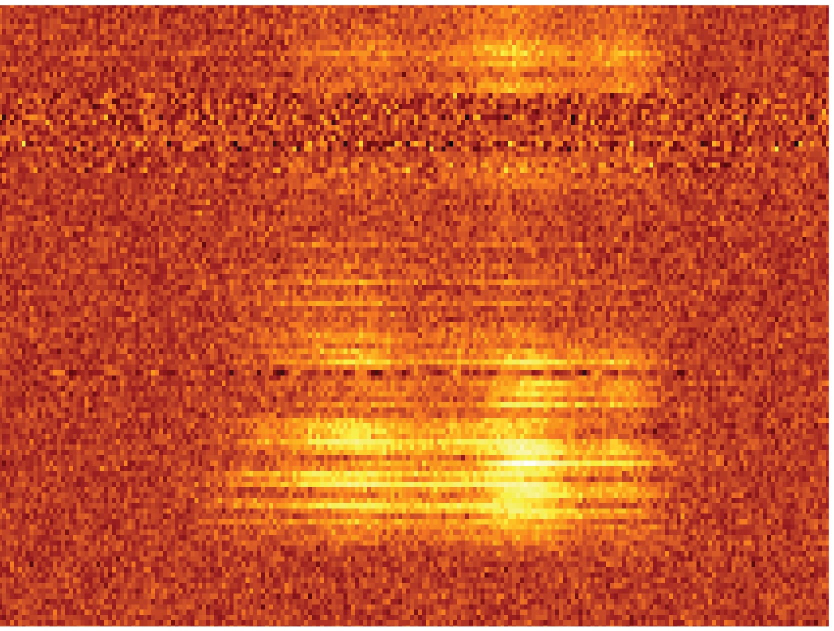
From the ensemble of 70 radio spectra we define four main populations, and we display examples of individual spectra from each population in the figure to the right. From top-down: (i): the spectrum is absorbed at low frequencies (α_{low} > 0); (ii) the high frequency spectrum is extremely steep; (iii) a steep spectrum with curvature (the majority of our objects fall in this popoulation); and (iv) a cluster of high-redshift sources with (α_{low} ~ −0.1 and (α_{high} ~ −1.4). The different populations very likely represent different stages of evolution and/or environment variations.

Finally, from the large frequency coverage of our sample, we can estimate the total radiative energy emitted in the radio waveband from 50MHz – 50GHz. We can then relate this radiative energy to the mechanical energy available, with the latter inferred from the energetics required for the jet to displace gas in the local environment (for which we have observaitonal contstraints from imaging data). We find that the total energy in the radio (which probes cumulative accretion powers over millions of years) is only a factor of a few lower than the power radiated in the infrared waveband (the infrared emission is emitted from regions much closer to the supermassive black hole and provides a nearly instananeous measure of the accretion power). Therefore, we conclude that both mechanical and radiative processes are important in shaping the galaxy host.

References: De Breuck, C. et al. 2010, ApJ, 725, 36 • Drouart G. et al. 2014, A&A, 566, A53 • Drouart G. et al. 2016, A&A, 593, 109 • Drouart G. & Falkendal T., in prep • Hurley-Walker, N. et al. 2017, MNRAS, 464, 1146 • Mortlock D. J. et al. 2011, Nature, 474, 616 • Seymour, N. et al. 2007, ApJS, 171, 353



Right: Examples of four broadband radio spectra fit with MRMOOSE, a new Bayesian spectral fitting method. The solid line represent the best fit, and the dark and light shaded areas represent the 25-75 and 10-90 confidence intervals, respecitvely.



Chasing pulsar emission across two octaves in frequency

Ramesh Bhat
Steven Tremblay
Marcin Sokolowski

2016 witnessed the ramping up of numerous scientific projects to exploit the newly developed pulsar science capabilities for the Murchison Widefield Array (MWA). Most notable among these was the ability to perform coherent addition of voltage signals recorded at the native 100 microsecond, 10-kHz resolutions from all 128 tiles within the MWA, in order to reach the maximum sensitivity for pulsar observations.

The investment in developing the MWA puslar capabilities is now beginning to yield exciting scientific dividends. Highlights from the past year include the discovery of parabolic scintillation arcs in observations of the millisecond pulsar J0437-4715, and the first detailed studies of individual pulses from PSR J0034-0721—a long-period pulsar that exhibits both intriguing sub-pulse drifting as well as long episodes of nulling. Such studies would not have been possible without achieving the MWA's full-array sensitivity at high spectral and temporal resolutions, and they demonstrate that the MWA has attained the maturity to undertake such high quality pulsar work.

Substantial efforts have also been made toward further augmenting pulsar scientific capabilities for the MWA, so as to fully exploit its large frequency coverage combined with the Murchison Radio astronomy Observatory's (MRO) superb radio-quiet environment. New capabilities include making observations simultaneously at multiple frequency bands across the 70 to 300 MHz frequency range. By carefully calibrating and beam-forming each frequency subband, it is possible to trace pulsar emission properties across nearly two octaves in frequency. This capability also enables systematic studies of various interstellar propagation effects on pulsar signals, including dispersion, scattering, and scintillation, all of which tend to be highly pronounced at the MWA's observing frequencies. Early science using this multi-frequency capability shows great promise. For example, observations of PSR J0437-4715 reveal a visibly rapid and substantial evolution of the temporal structure of the pulsar's radio emission with frequency. These newly revealed structures are in accord with the generally observed trend in millisecond pulsar radio emission, where large variations are typically seen in the shape of the radio spectrum as a function of the pulsar's rotation phase.

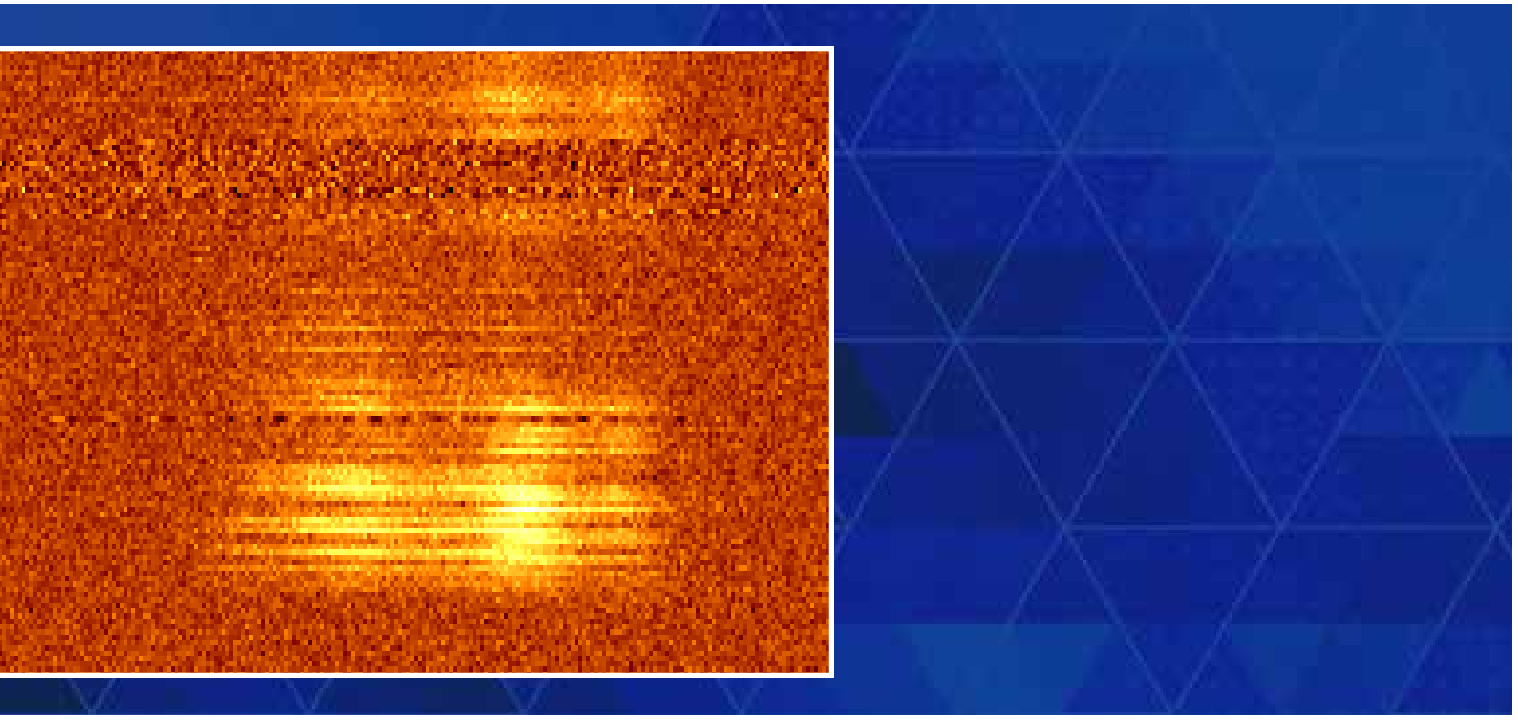
The coming year will see continued utilisation of the multi-frequency capability for a range new science, including the study of bright millisecond pulsars, which are important targets for pulsar timing array experiments. Pulsar timing arrays aim to detect gravitional waves that are produced by supermassive black-hole mergers, wich would have wavelengths on size scales of light-years (~10^{13} km). However, pulsar timing arrays require very careful calibrations of interstellar delays in timing measurements. The large frequency lever arm provided by the new simultaneous multi-frequency capability of the MWA will be used to obtain accurate dispersion measures, and for a detailed characterization of the interstellar medium along pulsar sight lines.

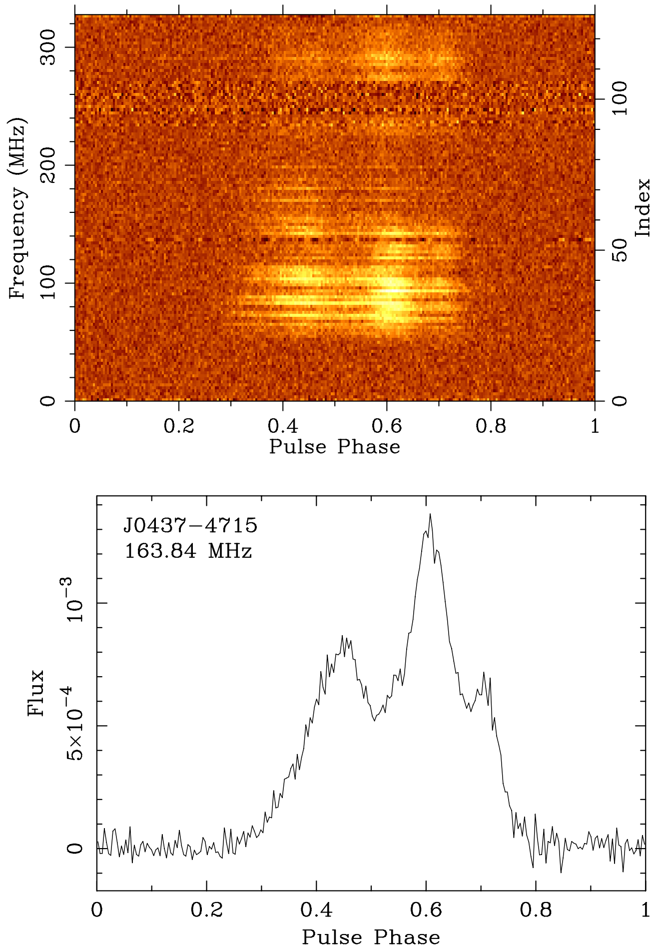
The final quarter of 2016 also saw the development of pulsar capability for the Engineering Development Array (EDA) – an SKA-Low prototyping station built from 256 MWA dipole elements. A timely visit by Dr Willem van Straten (Univeristy of Auckland), an expert in pulsar instrumentation and signal processing, helped accelerate the development. Data are sampled at a rate of 655.36 million samples per second, and thus require substantial computing in order to remove the signal distortion caused by frequency-dependent dispersion in the ISM. The large instantaneous bandwidth provided by the EDA – effectively restricted from ~50 to ~300 MHz by the response of MWA dipoles – brings in excellent avenues for undertaking wide-band pulsar studies. Even though the EDA's sensitivity will limit such studies to relatively bright pulsars, this is still an exciting development given the prospects of obtaining pulsar data that are minimally corrupted by temporal or spectral leakage. The first pulsar light from December 2016 was truly encouraging, with the detection of PSR J0437-4715 across a large part of the EDA band. The pulsar was detected down to a frequency of 52 MHz, which is significantly lower than the lowest frequency detection (~80 MHz) that was possible with the MWA.

The EDA capability also presents new avenues to gain useful insights into pulsar processing requirements relating to SKA-Low. Despite the very low dispersion measure of PSR J0437-4715, the processing of EDA data warranted performing Gigapoint fast Fourier transforms, even with a spectral resolution of 32,000 channels across the EDA's band. In the coming year we will explore the use of graphical processing units, with the goal of turning the EDA into a more efficient pulsar instrument. The study of millisecond pulsars will particularly benefit from this development.

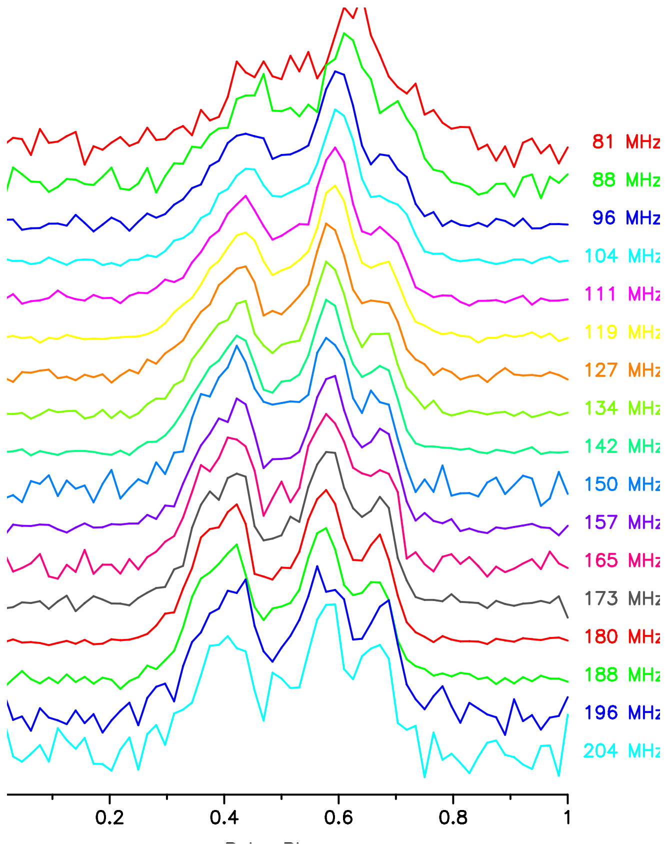
The commissioning of the multi-frequency and wide-band pulsar science capabilities and their successful integration with the suite of pulsar processing pipelines brings in new avenues for low-frequency pulsar science for the CIRA pulsar team. Besides allowing a range of new science in the areas of pulsars and interstellar medium physics, these developments will also yield much-valued wisdom as plans ramp up for the MWA's upgrade to Phase 3, and eventually for pulsar astronomy with SKA-Low.

Continues overleaf

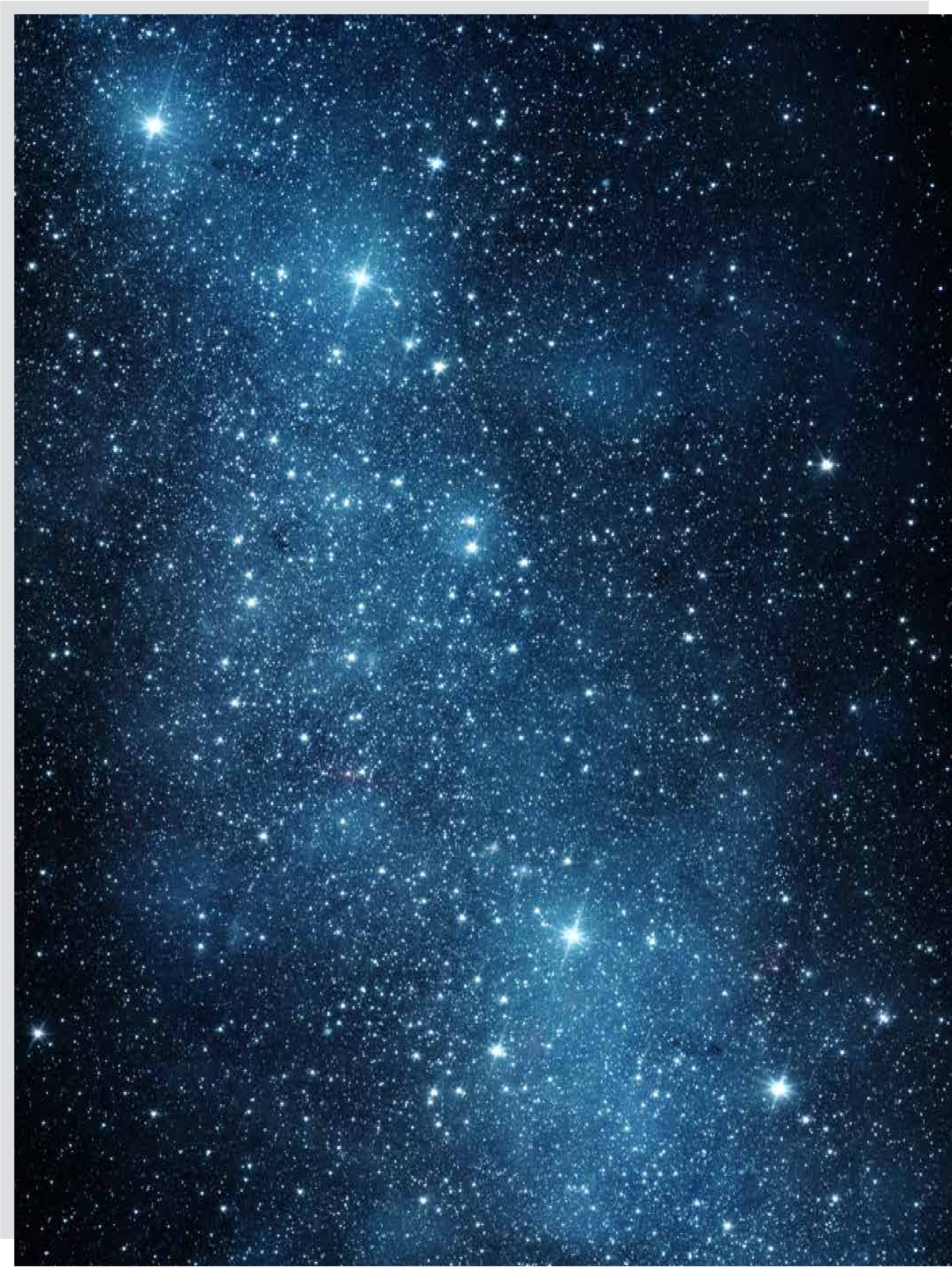




First pulsar light from the Engineering Development Array (EDA) – an SKA-low station equivalent made up of 256 MWA dipole elements, and thus effectively a "sister telescope" to the MWA. The millisecond pulsar J0437-4715 was detected over the frequency range from ~50 MHz to ~300 MHz. left: pulse strength vs. pulse phase and frequency; right: pulse profile after averaging in both time and frequency, displayed at an effective time resolution of approximately 90 microseconds.

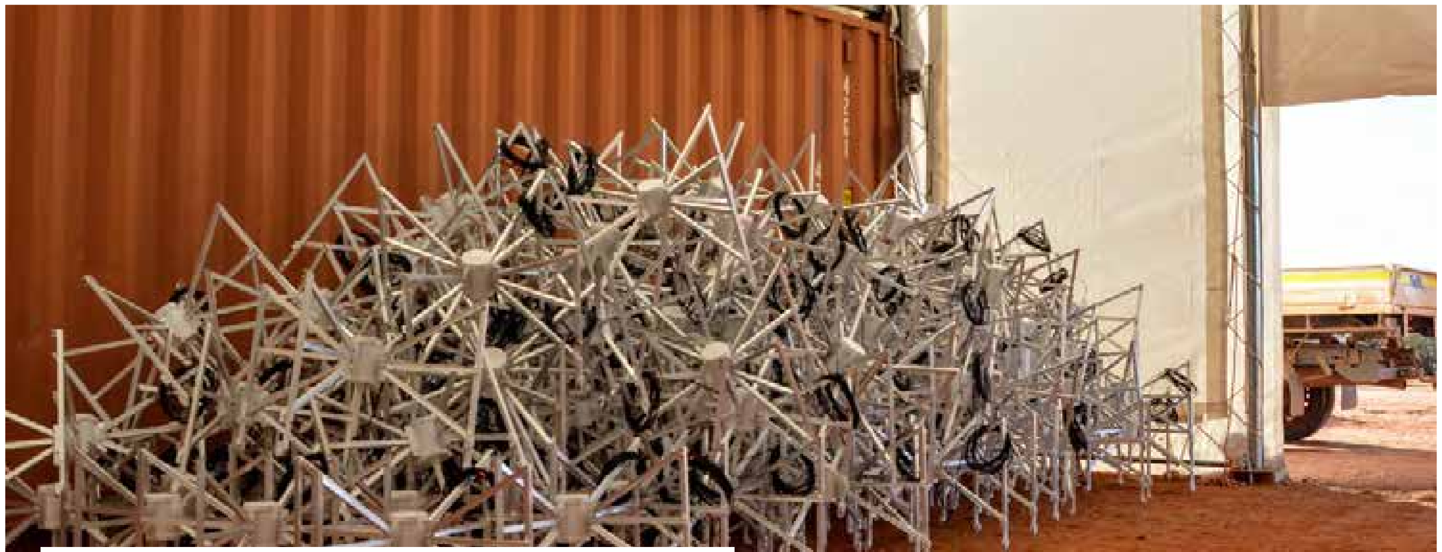


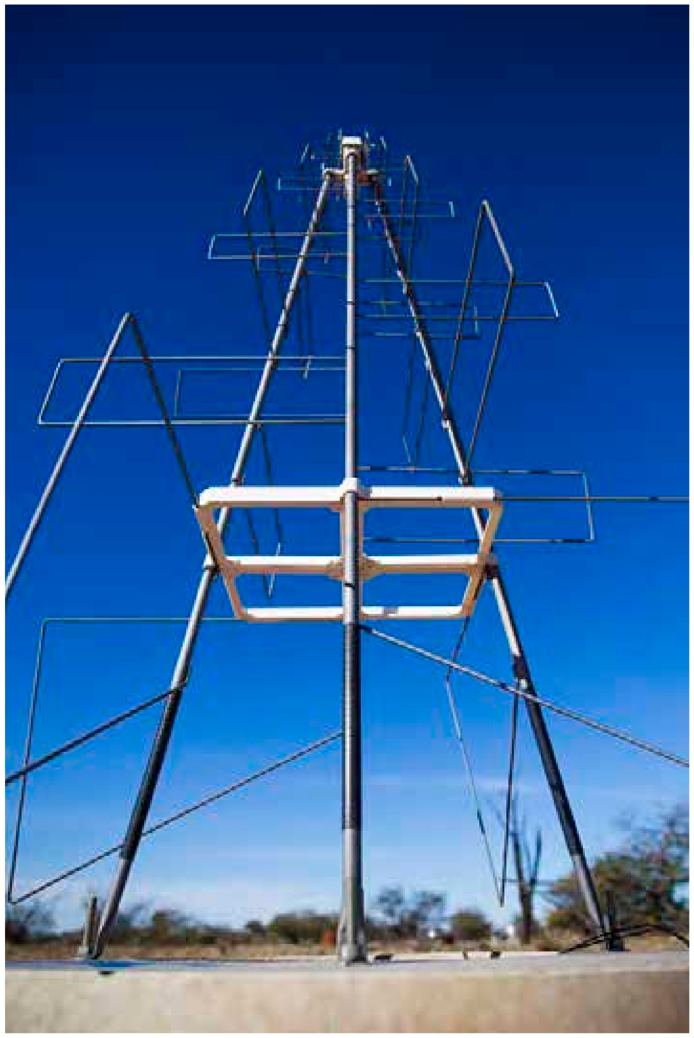
The integrated pulse profile of the millisecond pulsar J0437-4715 at multiple different frequency bands of the MWA extending from ~80 to ~200 MHz. The significant spectral evolution of the mean pulse profile seen at these low frequencies confirms our earlier results from the MWA, and the progressive outward shift of the component peaks suggests retardation and aberration effects in the pulsar's magnetosphere.



Engineering Highlights

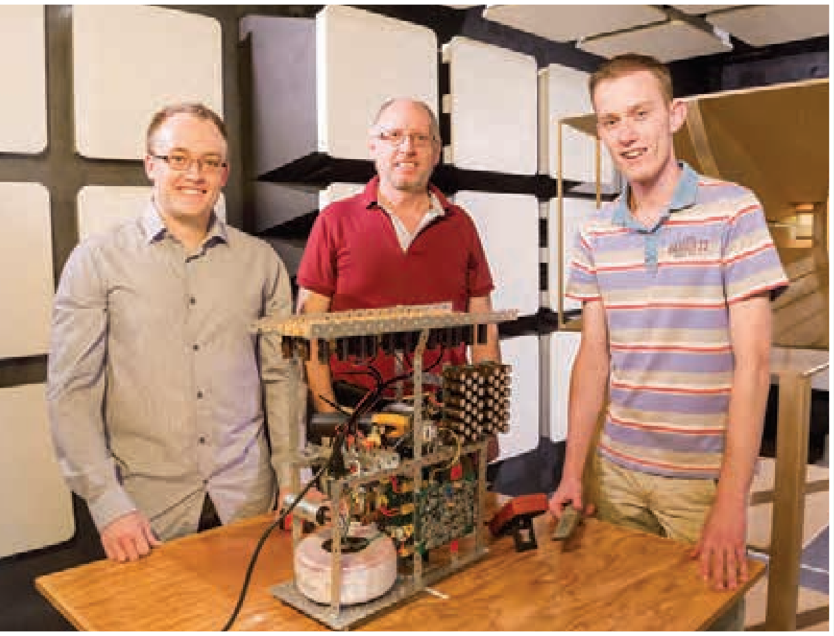
Image credit: ICRAR





CIRA Engineering: supporting local industry participation in SKA

Tom Booler



Curtin industry partner Balance Utility Solutions has done outstanding work in this area delivering a cost-effective, inherently RFI-quiet power distribution system for the AAVS1 program that complies with the MRO EMC requirement with no special shielding. Pictured are Balance engineer Lawrence Borle, Curtin engineering PhD student James Buchan, and visiting Dutch Intern Tom van Nunen

Curtin and industry partner GCo Electrical have learned valuable lessons through the deployment of the AAVS and its supporting infrastructure. These lessons have directly informed the development of the LFAA deployment plan and costing, which are considered among the most credible and robust planning documents in the SKA Project.

The CIRA Engineering Team is small and highly leveraged across a range of activities. Indeed, the activities conducted by the group are what have contributed to its unique preparedness to contribute to critical Square Kilometre Array (SKA) preconstruction activities, such as prototype commissioning and verification, and deployment planning.

The success of the CIRA Engineering Team is, by design, based substantially on deep and effective partnerships and collaborations with industry. Throughout SKA preconstruction, and with the MWA and a range of smaller projects before that, CIRA has worked hard to increase local industry awareness of radio astronomy and its unique considerations and demands. Equally, industry has helped CIRA to understand the myriad considerations and practicalities associated with construction projects, remote sites, and harsh environments. This approach has seen benefits accrue to both parties.

CIRA's industry partners have performed very strongly through SKA pre-construction. They have contributed in critical areas of the project, and had significant impact. This success has been enabled by intensive, ongoing collaboration. CIRA's role in this relationship is to provide its partners important project context, to help them develop an appreciation of the unique and critical considerations and requirements of radio astronomy, to keep them focussed, and to educate them about and insulate them from the imperfect and dynamic SKA project. In this way, CIRA is giving its industry partners the best possible opportunity to engage meaningfully in the procurement, construction, and operations phases of the project.

CIRA's SKA pre-construction industry partners have made particularly important contributions in two areas – the low-frequency aperture array (LFAA) power distribution, and deployment planning.

Perth based Balance Utility Solutions has been a CIRA industry partner since the beginning of SKA pre-construction and has made a considerable intellectual and in-kind investment in the project to date. Balance conducts the design and development of the LFAA intrastation power distribution system. They have done outstanding work, delivering an inherently radio frequency interference (RFI) quiet system for the Aperture Array Verification System 1 (AAVS1) program that complies with the demanding requirement for no special shielding at the Murchison Radio astronomy Observatory (MRO). This is a significant achievement and a key enabling step toward cost-effective realisation of SKA1_LOW.

Balance has also had a broader impact on the SKA. An SKA_LOW power options study completed by Balance in 2014 canvassed numerous technologies and models for the generation and distribution of power for SKA_LOW. This level of consideration was beyond the scope of responsibility of the AADC Consortium – which is limited to power distribution within LFAA stations – but considered, by Balance and CIRA, to be a necessary precursor to commencing the design of a system for delivering power to the antennas. The report was well received when it was submitted, receiving positive reviews for its comprehensive coverage and robust analysis and conclusions. At the time, however, the conclusions and recommendations of the report went largely ignored.

In 2016, with the project budget under significant pressure and a strong imperative to reduce capital cost, Balance's report was to the fore. The report's coverage and insights have allowed SKA to quickly identify options for reducing cost in the site power delivery model. The analysis and conclusions of the Balance report are being used to help validate the findings of a range of new and follow up investigations.

Another of CIRA's important responsibilities in SKA preconstruction is planning for the deployment of the LFAA. In phase-1 of preconstruction CIRA was charged with demonstrating that the deployment and installation of the LFAA was feasible within realistic cost and schedule constraints. The project information environment at the time meant that early investigations were, necessarily, based on a variety of assumptions across a range of project level issues. CIRA industry partner Raytheon Australia conducted an extensive investigation and developed a representative model of the LFAA deployment that achieved the objective of establishing its practical feasibility.

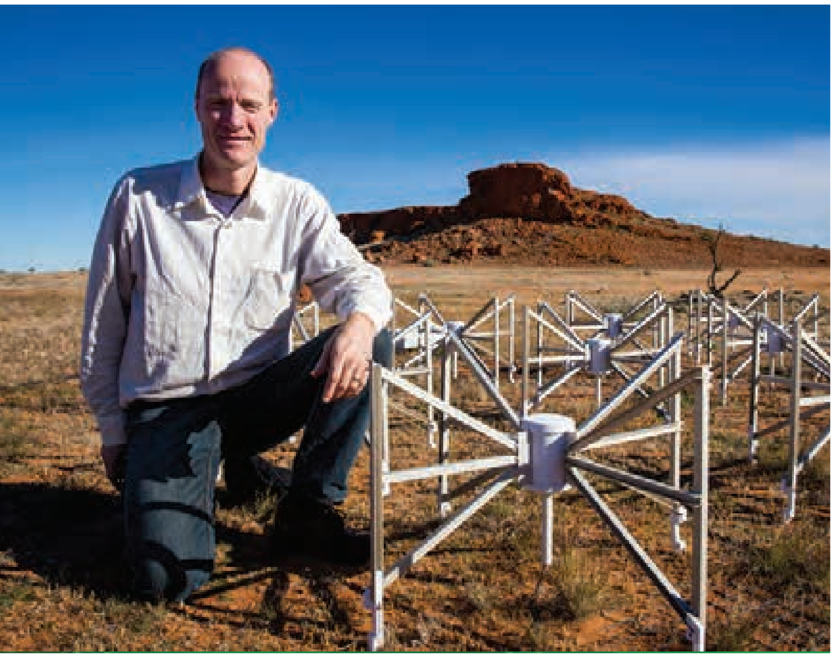
A limitation of the LFAA deployment plan developed by Raytheon was that it was developed in isolation rather than within the context of a holistic SKA1_LOW construction program. CIRA's focus in phase-2 of pre-construction has been on developing a realistic deployment and installation plan that supports an SKA1_LOW rollout strategy that has since been adopted by the SKA Project.

In order to transition deployment planning from the theoretical to the executable, CIRA engaged a local company, GCo Electrical, with the practical know-how to deliver the LFAA. Being Geraldton based, GCo were able to draw upon a robust local network of businesses across a variety of domains to ensure that the plans they developed were informed by the kinds of insight that only locals can provide.

In issuing the 'milestone acceptance certificate' associated with the delivery of the phase-2 LFAA deployment reports and cost model, the SKA Office noted the comprehensive consideration and coverage of the reports, and the robustness and substantiation of the cost and schedule estimates. There was also recognition of the wisdom of CIRA's approach in providing a report and support materials with ongoing utility, presented in such a way as to be useful in supporting subsequent planning and decision making.

This work, which draws on domain expertise across a range of engineering and logistics disciplines, is an exemplar for the collaboration and coordination that will be required to deliver the SKA in Australia. The impact achieved in this area by CIRA and its local industry partners underscores the capability and capacity of Australian organisations to play leading roles in the delivery of the SKA.

CIRA's leadership of on-site integration and verification, local infrastructure design, and deployment planning place it at the vanguard of efforts to transition the SKA Project from a participant oriented work breakdown to a 'product-based' structure that enables logical and efficient contracting in the procurement and construction phase. This transition is a necessary enabler of the kind of meaningful engagement of industry that will be required to cost-effectively realise SKA1_LOW. CIRA is highly visible as an advocate for collaboration – across the project and with industry – in the international SKA community.



MWA Director Randall Wayth next to an MWA tile. Credit: Ben Scandrett, Dept. of Industry

MWA completes third year of operations, Phase II begins

Randall Wayth

The Murchison Widefield Array (MWA) radio telescope, which is operated by Curtin University on behalf of an international consortium, completed its third year of operations in mid-2016. The milestone also marked a temporary halt to operations while the array was reconfigured into a new compact configuration, marking the beginning of the upgraded "Phase II" of the MWA.

Phase I of the MWA (2013-2016) saw over 10 PB (1 PB = 1000 Terra Bytes) of data collected for more than 30 individual science programs. Major science programs included:

- two years of observations of the "GaLactic and Extragalactic All-sky MWA (GLEAM)" sky survey, which surveyed the entire sky visible to the MWA between 70 and 230 MHz;
- the MWA Transients Survey (MWATS), which scanned a large fraction of the sky with a roughly monthly cadence, building a time-domain picture of the sky. MWATS allowed astronomers to study variable and transient radio sources;
- the Epoch of Reionisation (EoR) science program, which accrued many hundreds of hours during the observing season each year. The results and detailed analysis from the Epoch of Reionisation science teams have led directly to specifications for both an upgraded MWA and the SKA.

By the end of 2016, the MWA collaboration produced around 80 scientific publications spanning the broad range of MWA-enabled astrophysics.

In late 2015, a successful Australian Research Council (ARC) Linkage, Infrastructure Equipment and Facilities (LIEF) application, combined with contributions from MWA partner institutions, funded the expansion of the MWA. This upgrade become to be known as "Phase II" of the MWA.

MWA Phase II brings significant enhancements to the capabilities of the MWA by doubling the number of antenna "tiles" to 256 and doubling the diameter of the array to 5 km. The 128 new antenna tiles are comprised of 72 antennas in a closely spaced regular hexagonal layout and 56 antennas placed at long distances from the array centre (see the figures on the page immediately following this article). Phase II of the MWA keeps the same digital systems and correlator, which only support the processing of 128 antennas at a time. So the array will be regularly reconfigured between compact configuration, which consists of the core region of the Phase I MWA with the new hex configuration tiles, and the extended configuration, which uses the new long baseline antennas and existing Phase I antennas to create an instrument with twice the angular resolution as Phase I.

The compact configuration is used primarily to enhance the sensitivity of the MWA for EoR science, where the regularly spaced antennas combine to be much more sensitive when used in an EoR power spectrum detection experiment. The extended configuration, with its increased angular resolution and slightly increased sensitivity (compared to Phase I), supports many science cases within the MWA's Galactic and extragalactic science teams. The increased resolution from the Phase II extended array will help the MWA see radio sources in finer detail (by a factor of 2) and to greater depth (by a factor of approximately 10) than Phase I.

Infrastructure works for the Phase II expansion began shortly after the successful ARC LIEF announcement. The new antenna tiles for the compact configuration hexes were built and deployed in May and June 2016 by MWA operations staff and an amazing group of students from MWA partner institutions including Brown University, The University of Washington, Arizona State University and University of Wisconsin – Milwaukee.

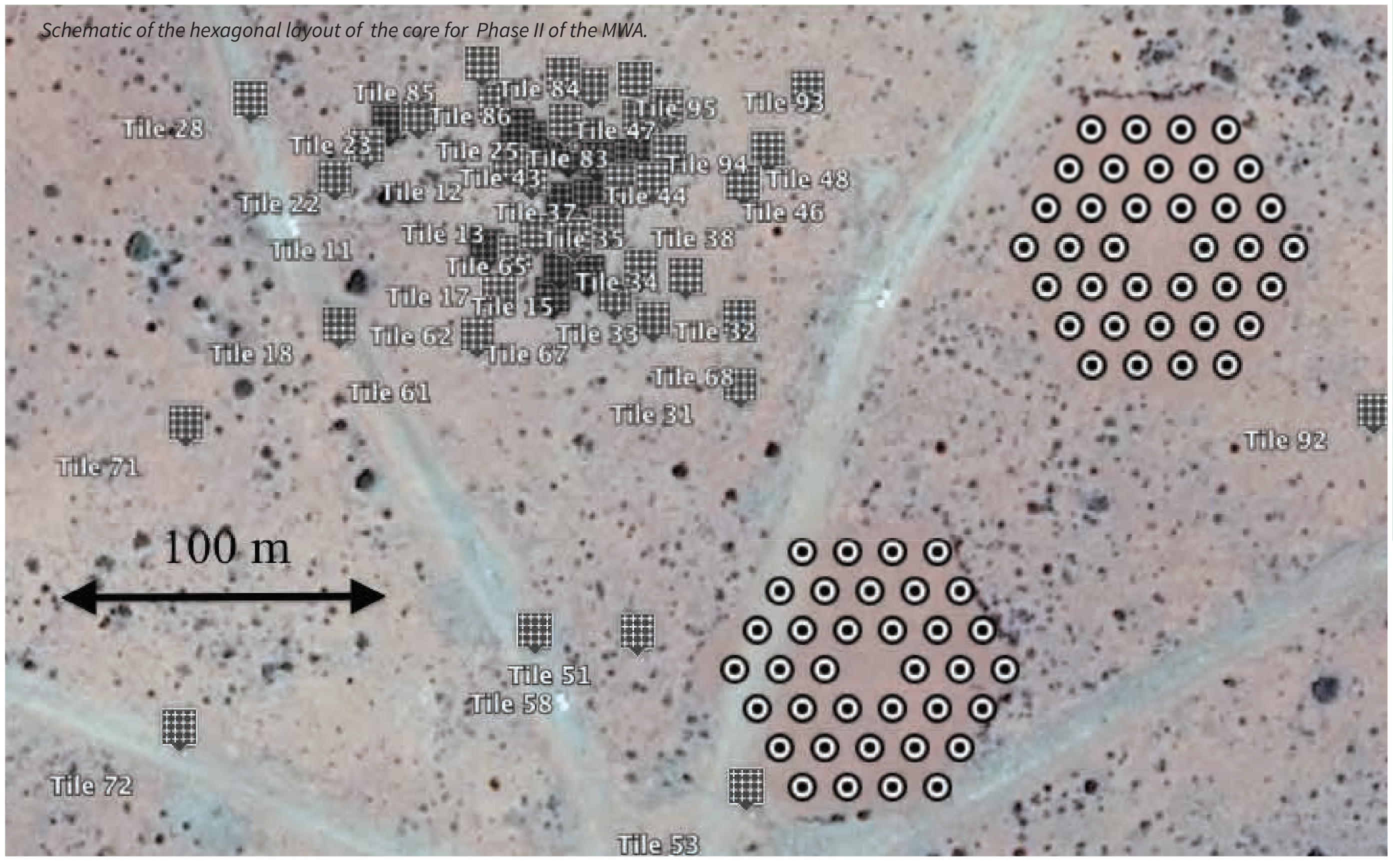
The new antenna tiles for the long baselines of the extended array will be deployed in mid-2017. These tiles will be far from the core infrastructure area of the MWA, and they hence require their own standalone solar power units. The astronomical signals captured by the tiles will be transmitted to the MWA core using "RF-over-fibre" technology, which converts radio waves into optical signals transmitted down optical fibres. Development work to support the power units and RF-over-fibre transmitters has been led by the Curtin University based MWA operations and support team.

Looking to the future of the MWA, the next major upgrade is envisioned to focus on the digital systems in the fielded receiver units, and on the digital correlator. With future receiver upgrades in mind, the MWA team has partnered with National Instruments to prototype a potential next generation of digital receivers using commercial-off-the-shelf (COTS) technology and NI's LabVIEW signal processing environment. These prototypes have many features that are desired for an upgraded MWA including increased processed bandwidth and the more accurate digital signal processing.

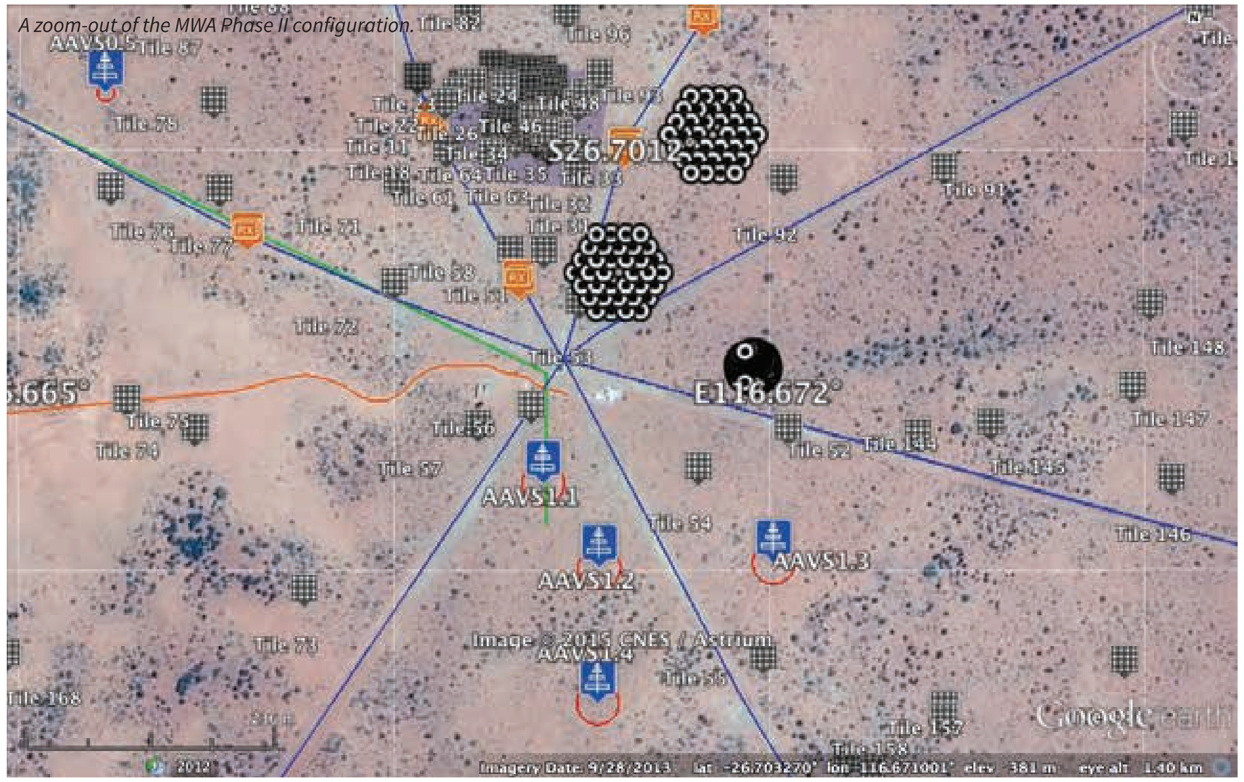
Also looking forward, the MWA has partnered with the Cisco Internet-of-everything Innovation Centre (CIIC), based at Curtin University, and MWA partner Swinburne University to develop a new digital correlator for an upgraded MWA. The correlator is the heart of the signal processing system in a radio telescope and traditionally one of the most complicated parts of the system. With a view to SKA-scale data processing, the MWA-CIIC-Swinburne partnership is working to build a correlator for the future MWA where all 256 antenna tiles are processed simultaneously with increased instantaneous bandwidth.

After an amazing and scientifically productive first three years of MWA operations, we look forward to the new and exciting capabilities of the MWA, Phase II.

Engineering



Schematic of the hexagonal layout of the core for Phase II of the MWA.



A zoom-out of the MWA Phase II configuration.

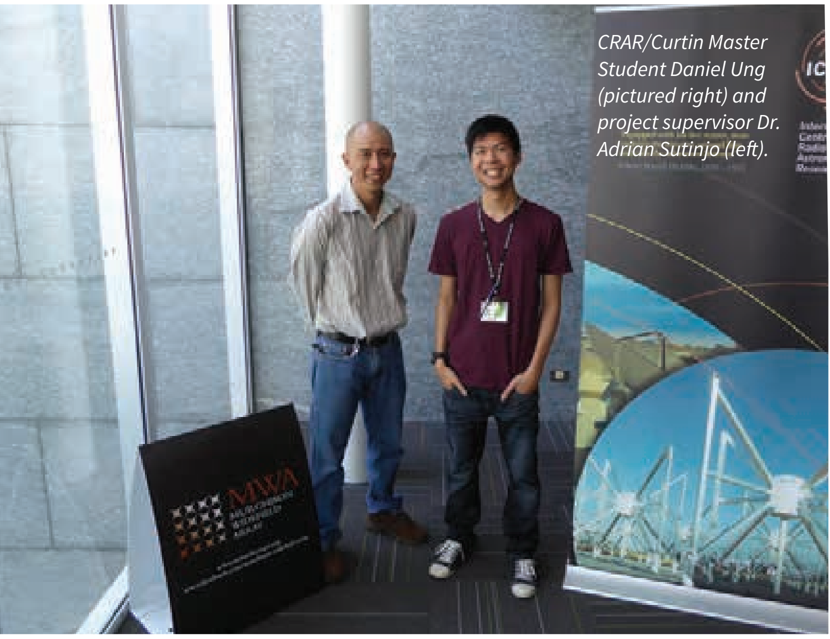
Assembly of MWA antennas at the MRO.

Engineering Highlights

An embedded element pattern beam model for the Murchison Widefield Array

Daniel Ung

Adrian Sutinjo



CRAR/Curtin Master Student Daniel Ung (pictured right) and project supervisor Dr. Adrian Sutinjo (left).

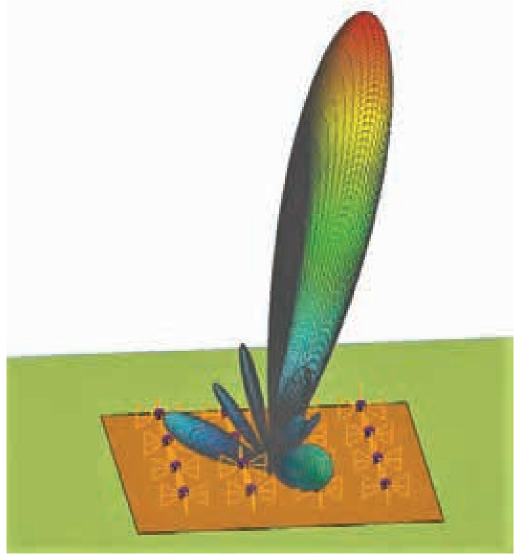
The work presented here was submitted as an entry to the 2016 FEKO student competition and claimed first prize. In conjunction with Altair Engineering, a webinar featuring the winning entry was presented on the 8th of March 2017. Pictured to the left is Daniel Ung (left) receiving his award from Mr. Mahan Rudd (right) from Altair Innovation Intelligence. Image credit: Mia Walker

The knowledge of the beam pattern of a radio telescope is vital for calibration and image correction. Recognising this led to the development of a rigorous beam pattern model for the Murchison Widefield Array (MWA) using FEKO simulation software.

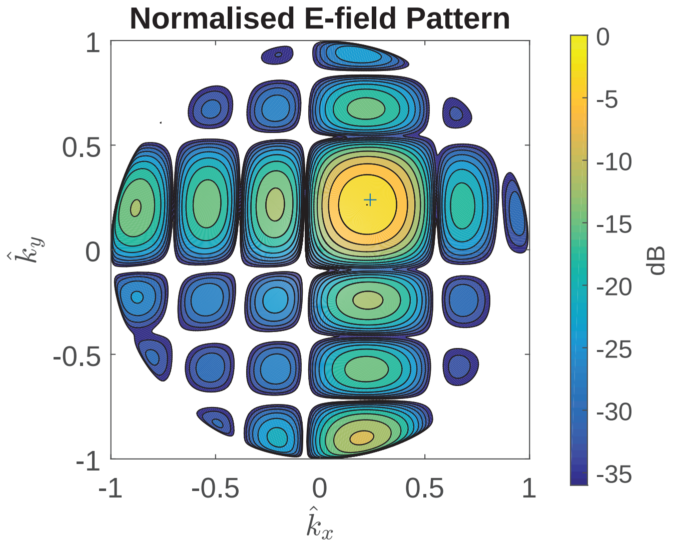
Radio telescopes in general require calibration prior to performing astronomical observations, and in order to do this, accurate knowledge of the beam pattern is required. For practical reasons, performing electromagnetic simulations of the MWA is the optimal method for determining the beam pattern. For this task, we use an electromagnetic simulator called FEKO released as part of Hyperworks.

Prior to this, primitive models have been used to estimate the MWA beam. In our new iteration of beam modelling, we recognise that each element pattern in the 4 x 4 configurations of each MWA tile are different. This led to the work of an embedded element pattern whereby each element pattern is simulated and stored individually. The element patterns are then later combined together to create the beam pattern of the MWA.

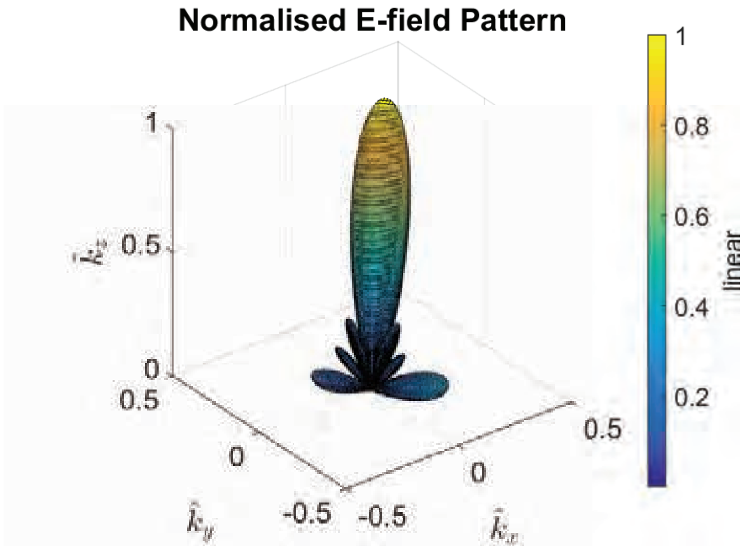
In addition to improved accuracy of the beam model, astronomers now have the ability to change the resolution of the beam without having to request for a new simulation to be performed or having to implement interpolation algorithms.



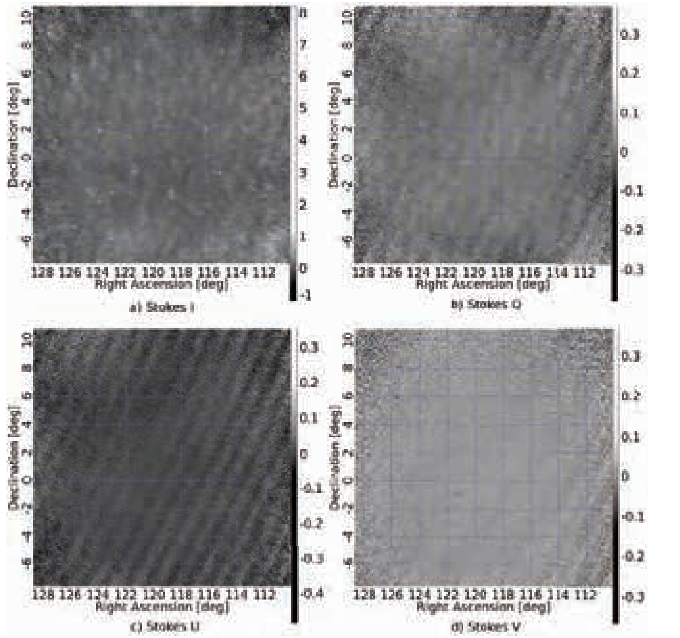
Simulated beam pattern of the MWA tile using FEKO simulation software. The beam pattern shown here is the result of direct simulation without the use of embedded element pattern whereby the resolution and pointing (location on the sky) is fixed. Another simulation would be required for a different resolution and pointing.



Contour plot of the normalised electric field pattern of the MWA operating at 216.32 MHz, when the MWA is pointed at the zenith. Contours shown are in steps of 3 dB.



A three-dimensional version of the contour plots shown in the above figure. This figure was produce via post-processing using the combined simulated element pattern.



Stokes I, Q, U and V images (a,b,c,d respectively) obtained from two-minute 200-230 MHz GLEAM observations started at 13:14:48 UTC on 2014 June 3. The images were calibrated with the FEE beam model. The black (images b and d) and white (image c) dots are the due to undesired false Q, V and U (respectively) polarisation cuased by relatively small inaccuracies in the FEE beam model.

Engineering Highlights

Calibration and Stokes imaging with the full embedded element primary beam model for the Murchison Widefield Array

Marcin Sokolowski • Daniel Ung • Tim Colegate
Randall Wayth • Adrian Sutinjo • Natasha Hurley-Walker
John Morgan

The Murchison Widefield Array (MWA) bow-tie antennas consist of two dipoles oriented in East-West (EW) and North-South (NS) directions, enabling measurements of radio signals polarised in each direction. The MWA is thus capable of obtaining measurements of polarisation in terms of four reference frame independent Stokes parameters, which include Stokes I – the total intensity of the incident wave; Stokes Q – linear (horizontal or vertical) polarisation; Stokes U – linear polarisation at +45 or -45 degrees; and Stokes V – the circular polarisation.

In many types of astronomical data analysis, measurement of the total flux density (Stokes I) of radio sources is sufficient. However, in several circumstances, improved physical understanding of astrophhysical phenomena can be obtained with measurements of the other Stokes parameters, Q, U and/or V. Accurate measurements of the Stokes parameters require application of a beam model of the radio telescope to the data. Hence, a good beam model is absolutely critical for polarisation studies.

Polarisation measurements of radio sources is the most sensitive way of testing beam models. The vast majority of radio sources are unpolarised, meaning that their Q, U and V polarisations are approximately zero. Inaccuracies of the beam model will manifest themselves as so called "false" Q, U or V polarisation, which is an observed polarisation signal resulting from instrumental effects, rather than from intrinsic properties of the radio sources.

The GaLactic and Extragalactic All-sky MWA (GLEAM) survey, which used the previous average embedded Element (AEE) MWA beam model, reported a noticeable (5-20%) false Q polarisation. Our tests have confirmed that a very similar false Q polarisation is expected if the inaccurate AEE beam model is used to calibrate data.

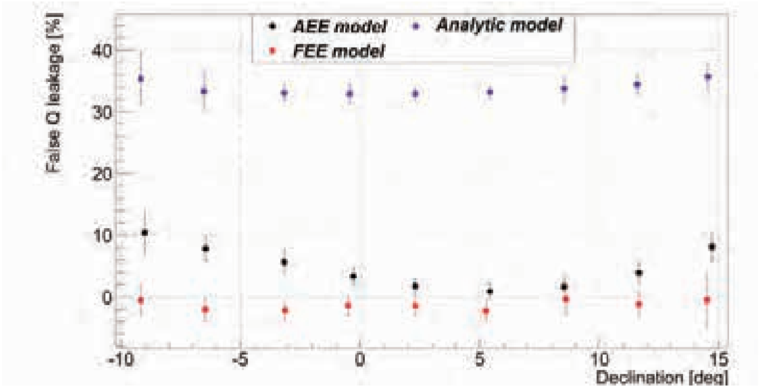
Following improvements to the MWA tile modelling, we have developed the newest Full Embedded Element (FEE) beam model, which represents a significant improvement, as described below.

We tested both the old AEE and the new FEE models together with the least precise Analytical model on 200-230 MHz (the higher end of MWA frequencies) observations from the GLEAM survey (we focus on high frequencies because that is when inaccuracies of the physical model become the most pronounced). The sky images in I, Q, U and V polarisations calibrated with the FEE model are shown in the figure at the top of the page. We also calibrated the same observation with the other two beam models (AEE and Analytical) and the measured Stokes Q polarisations resulting from all three models are compared in the figure at the bottom of the page. The new FEE model is indeed the most accurate.

The Stokes Q polarisation measured in the sky images calibrated with the Analytical model exceeds 30% (for reference, 0% is expected for unpolarised sources.) The AEE model performs much better than the Analytical model, but has some small residual false Q polarisation (reaching 10%). Finally, the FEE model is the best of the three models, as the Q polarisation of the radio sources in the sky images calibrated with this model is close to zero. We have also performed the same comparison for Stokes U and V polarisation, but in this case AEE and FEE models give similarly good results (both consistent with zero within measurement errors). In general, the amount of false Q (or U and V) polarisation depends on the pointing direction of the telescope.

Finally, we used the new FEE model to calibrate a large dataset (about 22,000 sources) from the GLEAM survey and the results further confirmed the superiority of the FEE model over the AEE model. Overall, the false Q polarisation was significantly reduced for most of the pointing directions, and for some of them it was even reduced to zero as desired for the ideal beam model.

The above tests indicate that the new FEE model is significantly more accurate than the previous AEE model, thereby improving our understanding of the MWA instrument, and enabling precise polarisation measurements of radio sources at low radio frequencies.



Comparison of false Stokes Q polarisation measured in the sky images in the frequency band 200-230 MHz, calibrated with the three different beam models. Both the AEE and FEE models perform much better than the simplest Analytical model (smaller false Q polarisation). They perform similarly well near the centre of the image (declination ~ 1.5 degree), but the FEE model shows less false-Q polarisation for sources away from the image centre.

Greg Sleap (left) and Mia Walker (right) with an NI FlexRIO and an IBM Power8 server.

A wide bandwidth and high frequency resolution receiver for the Murchison Widefield Array

Mia Walker • Greg Sleap

Brian Crosse• Andrew Williams

The expansion of the Murchison Widefield Array (MWA) radio telescope requires the development of a new receiver system that can accommodate a wider bandwidth, and provide higher frequency resolution and reduced aliasing. With the assistance and collaboration of National Instruments (NI) and IBM, we are jointly working towards this new front end system. In addition to solving the immediate needs of the MWA, development of this next generation receiver keeps ICRAR well within its core business of researching the future of radio astronomy engineering and developing precursor technologies for the telescopes of the future.

We are maximising the use of COTS components and standards-based interfaces to reduce development time, to ease interoperability, and to tap into the economies of scale that partners such as NI and IBM can provide to keep costs down. MWA Director and ICRAR Associate Professor Randall Wayth and MWA Support Engineer Mia Walker attended NIWeek in 2016, where A/Prof Wayth delivered one of the keynote presentations on this work.

National Instrument's 'FlexRIO' sampler and controller modules are initially being implemented in the Engineering Development Array (EDA) to evaluate their effectiveness as a replacement receiver.

The EDA is a low-frequency radio telescope, physically located within the MWA, comprising 256 dual-polarisation dipole antennas working as a phased-array. The EDA's dipoles are connected to a first-stage beamformer in groups of 16, and the resultant 16 beamformed signals are then sent to a second-stage beamformer and then passed onto the MWA correlator.

The scenario we are evaluating involves connecting 16 NI FlexRIOs to the 16 first-stage beamformers and replacing the current analog, second-stage beamformer with IBM Power8 servers. Each NI FlexRIO ingests the X and Y polarised streams of analog RF data from the first-stage beamformer, digitises at 800 MS/s, applies digital gains, and sends a selectable 24 coarse channels (37.5 MHz total bandwidth) of 8+8i bit interleaved data at 1.6 Gbps over UDP through a 40 Gbps switch to an IBM Power8 server. The IBM Power8 servers aggregate the channels and digitally beamform the 16 individual beams from each NI FlexRIO, sending 24 high-throughput data streams through to the MWA correlator.

The FlexRIO system consists of two NI modules, the NI 5772 Oscilloscope Adapter Module to perform 800 MS/s, 12-bit sampling, and the NI 7935 Controller to perform the coarse channel filter-bank operations, using a Xilinx Kintex-7 K410T FPGA. Monitor and control for the system is achieved by sending HTTP commands to a webserver running on the FlexRIO's onboard linux micro controller.

The IBM Power8 servers operate using PowerPC architecture that is well-suited to high throughput data processing. We are planning to deploy two of these servers, each with two 12-core 3.52 GHz Power8 64-bit CPUs, 512 GB of memory and 40 Gbps network interfaces, to evaluate their suitability for keeping up with the torrent of data produced by the NI FlexRIOs.

The result should be a configurable, state of the art, EDA that leverages Moore's Law, while paving the way for MWA expansion and the telescopes of the future.

ICRAR personnel involved in this project include Brian Crosse and Greg Sleap developing software for the IBM Power8s, Andrew Williams in monitor and control systems, and Mia Walker collaborating with NI system engineers for FlexRIO code implementation.

Left to right: Tom Booler, Mia Walker, and Randall Wayth, at the offices of National Instruments, USA.

Teaching & Outreach

Teaching 2016

Jean-Pierre Macquart
James Miller-Jones &
John Morgan

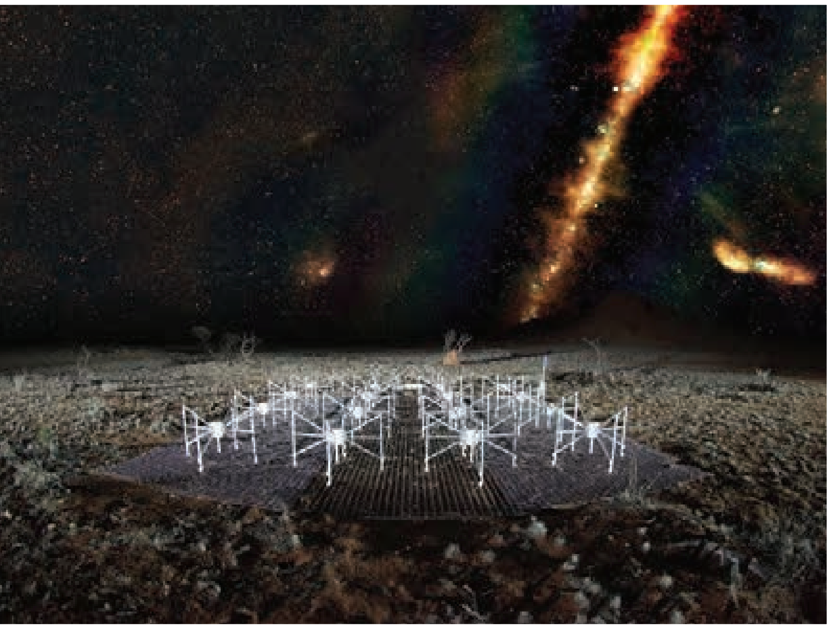
CIRA contribution to undergraduate teaching into the Physics and Engineering streams has gone from strength to strength over the past few years, and 2016 continued this trend admirably. Students were exposed to CIRA staff at every level throughout the undergraduate and post-graduate curriculum, commencing with John Morgan's Introduction to Astronomy course and Paul Hancock's input in the first-year Physics course.

James Miller-Jones and Jean-Pierre Macquart reprised the reins of their ever-popular second-year course on Thermodynamics and Statistical Mechanics, followed in second semester the The Physics of Stars and Galaxies jointly taught by Miller-Jones and Richard Plotkin, and Electromagnetism jointly taught by Macquart and Dmitry Fursa (Theoretical Physics). Ramesh Bhat and Roberto Soria continued to enthuse the students, revealing the intricacies of General Relativity to the third year cohort in their course Relativistic Astrophysics and Cosmology, while Nick Seymour introduced the students to the basic techniques and physics of radio astronomy in his unit Exploring the Radio Universe.

2016 saw a cohort of three students undertaking Honours projects with CIRA staff, while Ramesh Bhat, Cath Trott, Jean-Pierre Macquart, James Miller-Jones and Nick Seymour taught various specialist courses on pulsars, wave propagation theory, accretion physics, advanced radio astronomy, and statistics. These courses formed part of a complete Honours curriculum jointly taught across both the Curtin Univeristy and University of Western Australian nodes of ICRAR.

Engineering staff within CIRA contributed to the undergraduate curriculum with courses on Engineering Electromagnetics and Mobile Radio Communications. The former course was taught jointly by Adrian Sutinjo, Franz Schlagenhaufer, Budi Juswardi and Daniel Ung, while the latter was taught by Adrian Sutinjo, Randall Wayth, Budi Juswardi and Laurens Bakker.

Our summer studentship program in 2016 engaged with undergraduate students and exposed them to the exciting research being done at CIRA. In addition to the three ten-week studentships funded by ICRAR and iVEC, the Department of Physics and Astronomy funded a further two six-week studentships for Curtin undergraduates. The students worked on a range of science and engineering projects, including radio transients, weakly-accreting nuclear black holes, phased array design, and measurement of bandpass smoothness and the stability of low-noise amplifiers. The students concluded their summer projects by completing written reports, and giving presentations on their research to CIRA staff at one of the weekly Journal Club meetings.



An image of an MWA tile, with a low-frequency radio image of the southern sky superposed from the GaLactic and Extragalactic All-sky MWA Survey (GLEAM). Credits: radio image by Natasha Hurley-Walker and the GLEAM Team. MWA tile and landscape by Dr John Goldsmith / Celestial Visions.

Outreach 2016

John Morgan
Kim Steele

CIRA staff and students participated in a wide range of face-to-face outreach events in 2016, including two Astrofests (Perth and Mount Magnet) and Curtin Day, which included interactions with many hundreds of attendees. Of particular note in 2016 was the large number of talks given to potential astronomers of the future. For example, James Miller-Jones gave a talk to Chinese Undergraduates; and Kim Steele organised an excursion to the Scitech Planetarium for her old high school at which she, John Morgan and Wiebke Ebeling gave talks related to astronomy career paths. These and similar events reached almost 500 students in total.

The media highlight for 2016 was undoubtedly the release of the MWA GLEAM survey. This was covered well by the print media, TV and radio, including Channel 7, Channel 10, ABC Midwest, Sydney Morning Herald, Geraldton Guardian, ABC 24, 6PR and The West Australian. Natasha Hurley-Walker also gave a TEDx talk which at the time of writing has over 1M views on youtube.

Additionally, James Miller-Jones gave talks to the media specifically related to his research. Carole Jackson and Randall Wayth gave a number of interviews (radio and print media) on the MWA, SKA, and the expertise we have on Radio Astronomy in Western Australia.

Finally John Morgan provided expert commentary to the print on a variety of astronomy stories, not necessarily related to CIRA research, but which garnered particular public interest. Particularly popular was the “Planet 9” hypothesis where he gave interviews and comment to 6PR, ABC mid-west, Curtin FM, Lifehacker, Newscorp, Science Network WA.

Mia Walker at the Mount Magnet Astrofest. Image credit: ICRAR

Image credit: ICRAR

Dr Peter Curran
Image credit: ICRAR

Dr Peter Curran

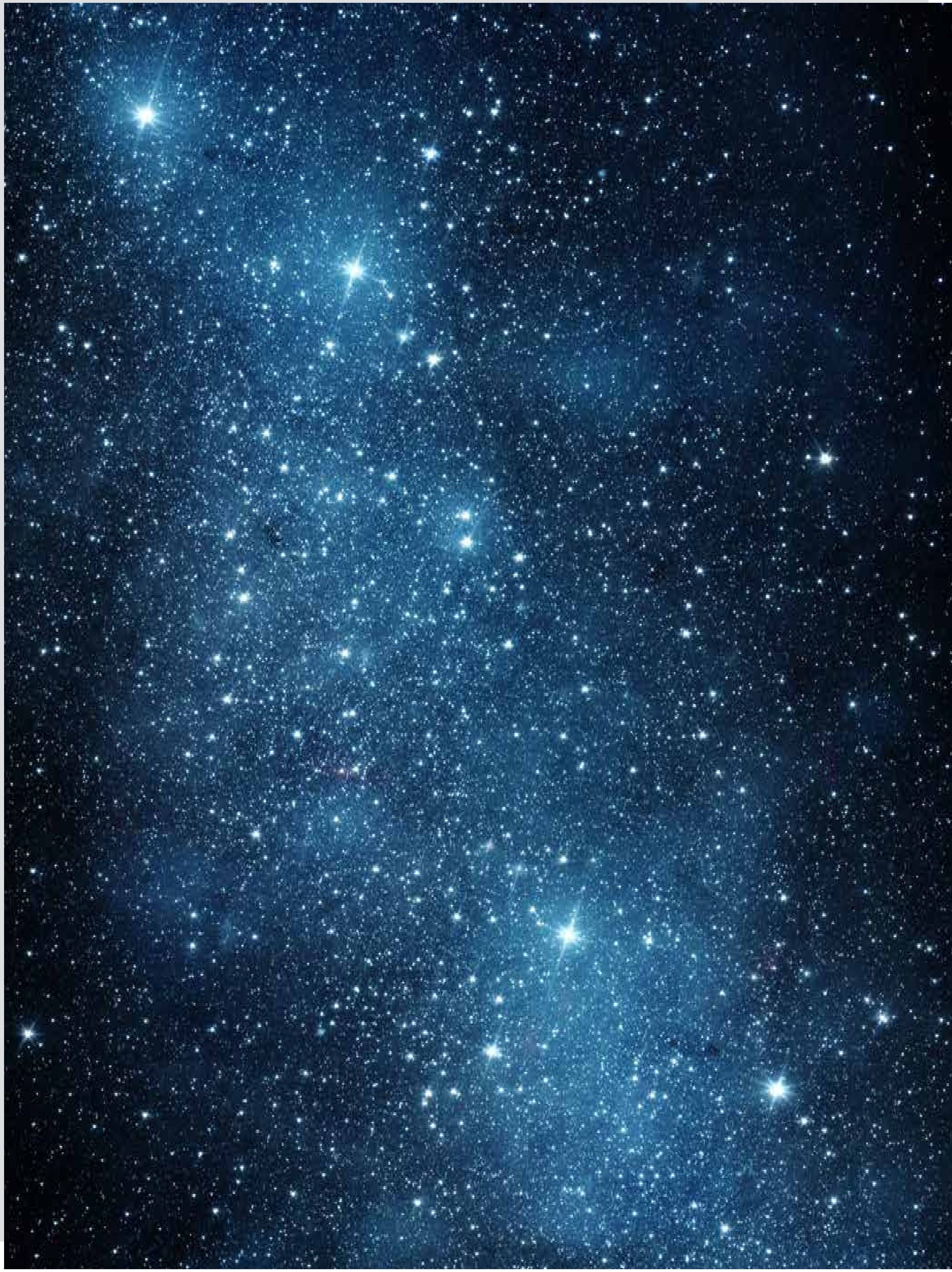
It is with great sadness that in February 2016 we said goodbye to a friend and colleague, Dr Peter Curran, who passed away after a fierce 14-month battle with an aggressive cancer.

Dr Curran earned his MSc at the University College, Cork, and his PhD from the Anton Pannekoek Institute for Astronomy at the University of Amsterdam. He joined the accretion group at CIRA in 2012, following positions at the Service d'Astrophysique, CEA-Saclay near Paris and at the Mullard Space Science Laboratory (MSSL) of University College London. In 2015, Dr Curran was awarded a prestigious Curtin Senior Research Fellowship.

Dr Curran developed an outstanding international research profile as a multiwavelength astronomer, particularly in the fields of gamma-ray bursts and X-ray binaries.

Peter was committed to mentoring students at CIRA, and he served as the inaugural chair of CIRA's development committee. His dedication and passion led to CIRA receiving a Bronze Pleiades award from the Astronomical Society of Australia's Inclusion, Diversity and Equity in Astronomy Chapter.

To recognise Dr Curran's contributions to CIRA and the accretion physics group, Curtin University dedicated one of its Curtin Research Fellowships to his memory, now called the "Peter Curran Memorial Fellowship." The Astronomical Society Group of Ireland (ASGI) has also named an award after Dr Curran, as "one of the most distinguished members of Ireland's astronomical diaspora." The ASGI will present the "Peter Curran Award" to the best graduate student presenter at each future Irish Annual Astronomy Meeting.



Refereed Publications

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24. Dr Budi Juswardy
    Research Engineer


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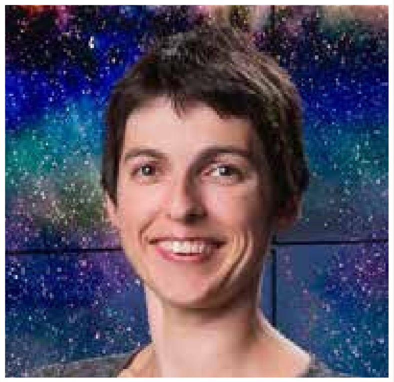
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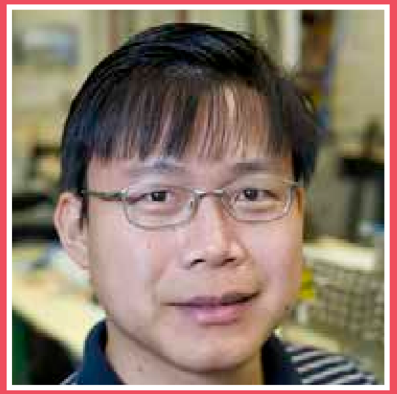
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Staff Profiles

25. Mr David Kenney
Senior Technical Officer

26. Dr Franz Kirsten
Research Associate

27. Dr Jean-Pierre Macquart
Senior Research Fellow

28. A/Prof James Miller-Jones
Associate Professor

29. Dr John Morgan
Research Fellow

30. Mr Joel Morris
Administrative Assistant

31. Dr Steven Murray
Research Associate

32. Dr Stephen Ord
Senior Research Fellow, Transients

33. Dr Richard Plotkin
Senior Research Fellow

34. Dr Thomas Russell
Research Associate

35. Ms Tina Sallis
Operations Coordinator

36. Dr Franz Schlagenhaufer
Research Engineer - Radio Astronomy


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Image Credits frames 26, 28-29, 32, 34, 36; ICRAR

Staff Profiles

37. Dr Nick Seymour
Senior Lecturer

38. Dr Ryan Shannon
Research Fellow

39. Mr Greg Sleap
MWA Data Manager

40. Dr Charlotte Sobey
Research Associate

41. Dr Marcin Sokolowski
Research Fellow

42. Dr Roberto Soria
Senior Research Fellow

43. Ms Kim Steele
Engineering Graduate Intern

44. Dr Adrian Sutinjo
Senior Lecturer

45. Mr Jonathan Tickner
Senior Technical Officer

46. Prof Steven Tingay
Professor Radio Astronomy

47. Dr Steven Tremblay
Research Fellow

48. Dr Cathryn Trott
Senior Research Fellow


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Image Credits frames 38, 40, 42-45, 47-48; ICRAR

Staff Profiles

49. Mr Daniel Ung
Support Engineer, Aperture Array

50. Ms Mia Walker
Instrument Support Engineer

51. Dr Andrew Walsh
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52. A/Prof Randall Wayth
Associate Professor

53. Mr Malcolm Whinfield
MWA Electronics Technician

54. Dr Sarah White
Research Associate

55. Dr Andrew Williams
Instrument Engineer, M&C

University Associates

56. Prof Ron Ekers

57. Prof John O'Sullivan

Students

58. Wayne Arcus
PhD

59. Andrew Brown
Honours

60. James Buchan
PhD


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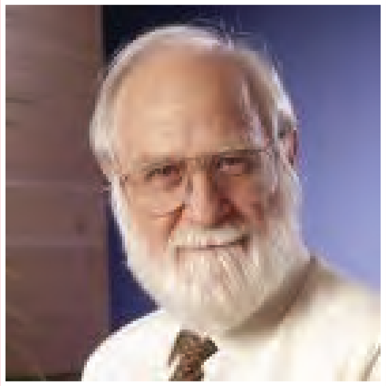
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Image Credits frames 49-50, 52, 58, 60; ICRAR

Staff Profiles

61. Robin Cook
Honours

62. Tyler Ellement
Honours

63. Ronniy Joseph
PhD

64. Samuel McSweeney
PhD

65. Bradley Meyers
PhD

66. Haihua Qiao
PhD

67. Hongquan Su
PhD

68. Chenoa Tremblay
PhD

69. Vlad Tudor
PhD

70. Ryan Urquhart
PhD

71. Mengyao Xue
PhD

72. Qingzeng Yan
PhD


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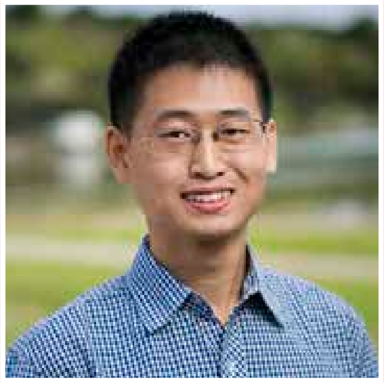
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Staff Profiles

73. Xiang Zhang
PhD

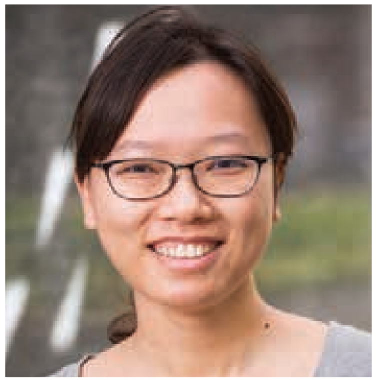
Interns

74. Rick Bude

75. Alex Guest

76. Mike Kriele

77. Tom van Nunen



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