Curtin University

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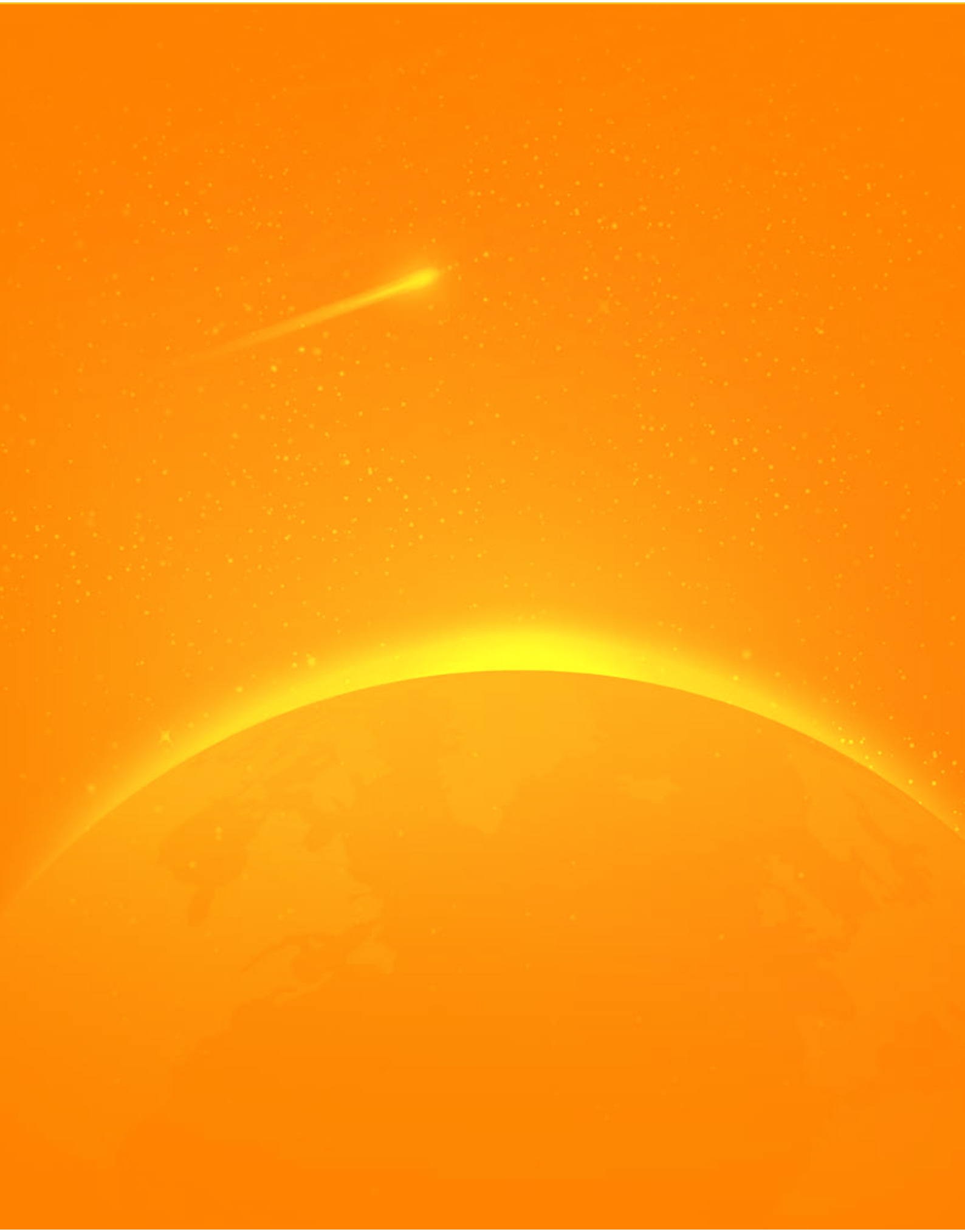
Annual Report 2015

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.

Image credit: ICRAR

Director's Report
Science and Operations

Prof. Carole Jackson

2015 was a pivotal year for CIRA: the institute endured a period of change with its inaugural director, Prof. Steven Tingay, commencing a three-year secondments to Italy on 1 January 2016 after a period of leave from mid-July 2015.

The year also brought outstanding success in the ARC Excellence in Research Australia 2015 assessments for Field of Research 0201—Astronomical & Space Sciences, with the maximum grade of '5', "outstanding performance well above world standard" awarded. This result was an improvement over 2012 that was a grade '3', "at world standard." The award is a direct reflection of three previous years of highly cited publications and major grant awards under Prof. Tingay's leadership. Clearly, the challenge for CIRA is to maintain this level of performance excellence over the next ARC assessment term. As evidenced in this Annual Report, CIRA has the environmental conditions to succeed, garnering enormous University and WA Government investment, coupled with a growing team of world-leading researchers developing core expertise in SKA related science.

Through a combination of significant 2014 ARC awards, ICRAR II funding, and new joint positions established with CSIRO, seven new astronomy postdoctoral researchers joined CIRA during 2015. CIRA's tenured faculty remains stable with four senior appointments within DIAP. The new hires firmly establish CIRA as one of the very largest research astronomy teams nationally, and more significantly, unique in having direct access to the sole SKA LOW precursor telescope, the Murchison Widefield Array (MWA).

Results from the MWA continued to flow through 2015 with the commissioning of the Voltage Capture System and completion of the second year of the all-sky survey (GLEAM). These projects and many more are evidenced by MWA accumulating 9 Petabytes of data at the Pawsey Centre. Furthermore the

continued scientific productivity of the MWA is secure and strongly anticipated with the funding of the Phase 2 upgrade during 2016/7 to provide more collecting area and long baselines.

In June 2015, three members of the CIRA team were awarded a prestigious Thomson Reuters citation award for their scientific output as part of the Murchison Widefield Array (MWA) project. These awards are assessed on quantitative publication and citation performance, and they recognise very high impact research activities in Australia.

In mid-2015, the Astronomical Society of Australia annual meeting was very successfully hosted by CIRA in Fremantle; this annual event is the single largest meeting for all aspects of Australian astronomy and attracts ~250 participants. During this meeting the Australian Astronomy Decadal Plan for 2016-2025 was formally launched: this plan states that continued development and operations of the MWA is one of five key priorities for the community.

Finally, the year ended on a high note for CIRA's ambitions with the Australian Government Innovation & Science Agenda statement announcement of a $293.7m provisional funding allocation for the next 10 years of Australia's SKA commitments.

Left to right: Tom Booler, Karen Andrews MP, and Carole Jackson at the Murchison Radio-astronomy Observatory.

Image credit: Pete Wheeler, ICRAR

Image credit: ICRAR

Director's Report
Engineering & Industry

Prof. Peter Hall

An enlightened succession policy is a mark of a mature organization and, in 2015, CIRA demonstrated its coming of age with the successful transition between science directors.

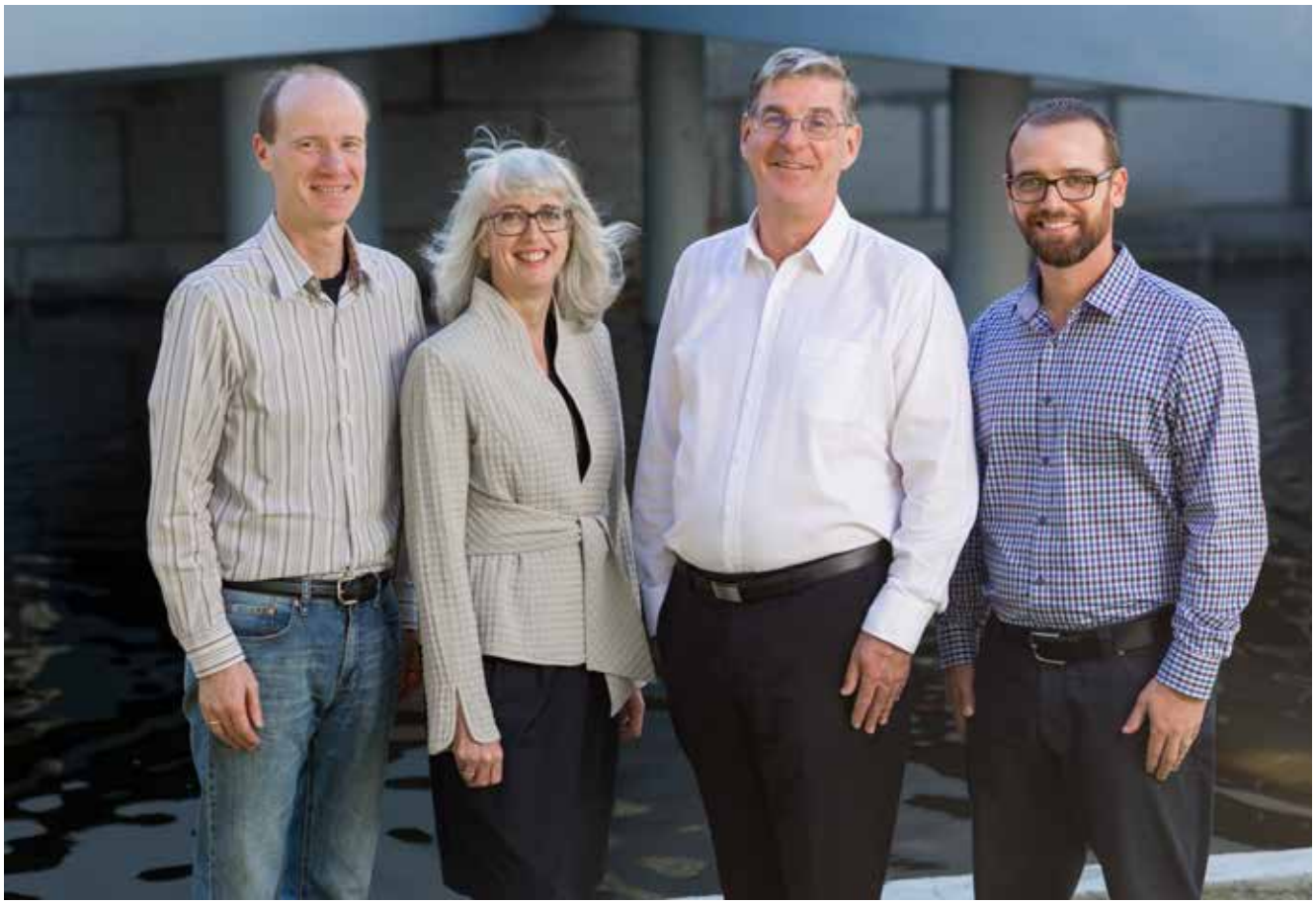
In saying goodbye to Steven Tingay, my co-founder of CIRA, it has been a pleasure to welcome Carole Jackson, a colleague of long-standing, to the position of Director, Science. In the years since 2008 CIRA has gone from strength to strength, and we recently learned that Curtin astronomy received a top-ranking score of 5 in the national Excellence in Research for Australia (ERA) rating. CIRA was the vehicle for this, and Steven and I are very proud of the accomplishment. I am certain that Carole will be central to CIRA's continuing success in both conventional research metrics (such as ERA) and forward-thinking initiatives, such as the development and deployment of radio astronomy research infrastructure for the SKA. I should also record that Curtin Electrical and Computer Engineering also received the top ERA score, underscoring the potential of the growing links between CIRA and ECE.

Still on the organizational side, it is a pleasure to record the promotion of Tom Booler to the position of Assistant Director, Engineering Operations. Tom has a distinguished project management record in military and civilian life, and, most recently, he was MWA project manager. His new role recognizes the importance to CIRA of success in projects such as SKA pre-construction (including Aperture Array Verification System 1), the upcoming MWA upgrades, and other key activities at the Murchison Radio-astronomy Observatory (MRO).

Other senior staff changes include the appointment of Dr Randall Wayth, a joint CIRA-ECE appointment, as MWA Director. Randall's appointment is fitting, recognizing his contributions both as a system scientist and as an engineering leader. CIRA has also spent quite a bit of time developing the talents of students and junior researchers, such as those in

our engineering intern program. In particular, as we approach the 400-year anniversary of Dirk Hartog's landing in WA, it is satisfying to reflect on the success of our first Dutch students from the Technical University Eindhoven and the University of Twente.

As you see from the articles in this report, work on SKA pre-construction projects is in full swing, particularly in terms of MRO infrastructure for new and upgraded telescopes. CIRA engineers and astronomers have also worked closely to develop and demonstrate verification techniques for the SKA; it is notable that we are the only institute internationally to routinely use an SKA precursor telescope as part of the path to the SKA. This is enormously satisfying, and it stems from my long-standing belief that the investment in these facilities should yield returns in terms of both science and technology trailblazing. You will also see a sample of CIRA's successful industry links. Fostered in many cases by SKA pre-construction projects, these links have established the feasibility of SKA in Western Australia and provided critical, specialist design studies and prototypes for the telescope. CIRA and its partners in ventures such as ICRAR and CAASTRO are primarily research organizations, but there is no doubting the effectiveness of high-impact industry links in helping Australia make ready for the era of SKA construction. CIRA itself intends to be a major participant in that construction, likely to start in 2019.



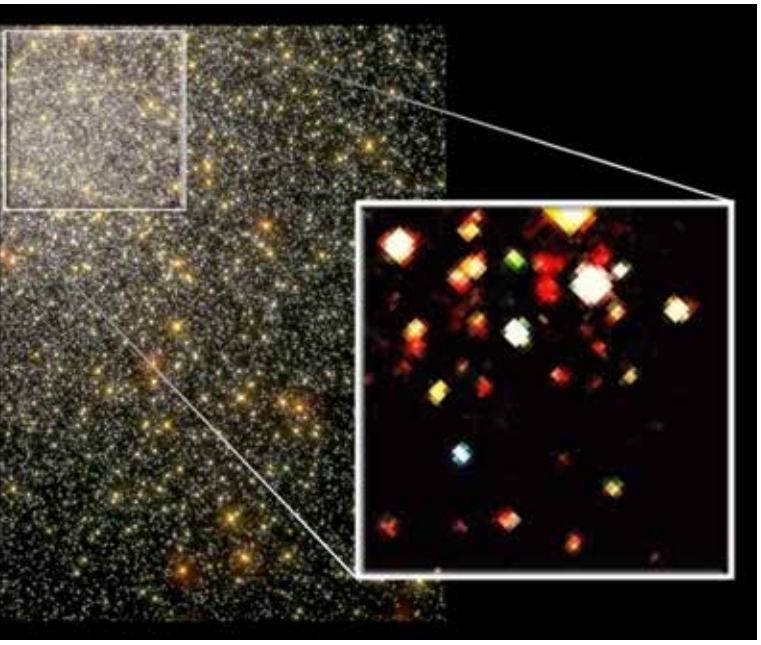
Left to right: Dr Randall Wayth (MWA Director), Prof Carole Jackson (Co-Director, Science and Operations), Prof Peter Hall (Co-Director, Engineering and Industry Collaboration), Mr Tom Booler (Assistant Director, Engineering Ops).

Image credit: Natasha Hurley_Walker

Science Highlights

Image credit: ICRAR & iVEC

Science Highlights



The central regions of the globular cluster 47 Tucanae, showing a zoom-in of the Chandra X-ray image in relation to the optical image from the Hubble Space Telescope. The black hole candidate X9 is the brightest white source towards the upper right of the X-ray image, and it is surrounded by fainter red sources that have softer X-ray emission. Image credit: X-ray: NASA/CfA/J. Grindlay et al., Optical: NASA/STScI/R. Gilliland et al.

A new black hole candidate in the globular cluster 47 Tucanae

James Miller-Jones

Globular clusters are old, dense stellar systems, containing hundreds of thousands to millions of stars all within a region of space just a few parsecs across. Our own Milky Way galaxy contains over 150 globular clusters, which provide excellent hunting grounds for exotic stellar systems such as X-ray binaries.

These double-star systems comprise a dense stellar remnant such as a black hole or neutron star in a close orbit with a less-evolved donor star. The strong gravitational field of the compact object causes it to accrete matter from its companion, and the ensuing release of gravitational potential energy leads to the emission of energetic X-ray radiation. The high stellar densities in globular clusters allow massive objects such as black holes to capture a passing companion star, leading to the formation of new X-ray binary systems at a rate much higher than elsewhere in the Galaxy; while globular clusters contain less than a thousandth of all the mass in the Milky Way, they host 10% of the known X-ray binary systems.

Until recently, it was believed that all X-ray binary systems in globular clusters hosted neutron stars. While several tens to hundreds of black holes should form early in the lifetime of a globular cluster from the deaths of the most massive stars, their large masses should cause them to sink to the centre of the cluster where they would expel one another via mutual gravitational interactions. However, recent theoretical simulations and observational studies have shown that a significant number of black holes can in fact be retained by a cluster for up to several billion years. Should those black holes exist in X-ray binary systems, they could be detected via the X-ray emission from infalling matter.

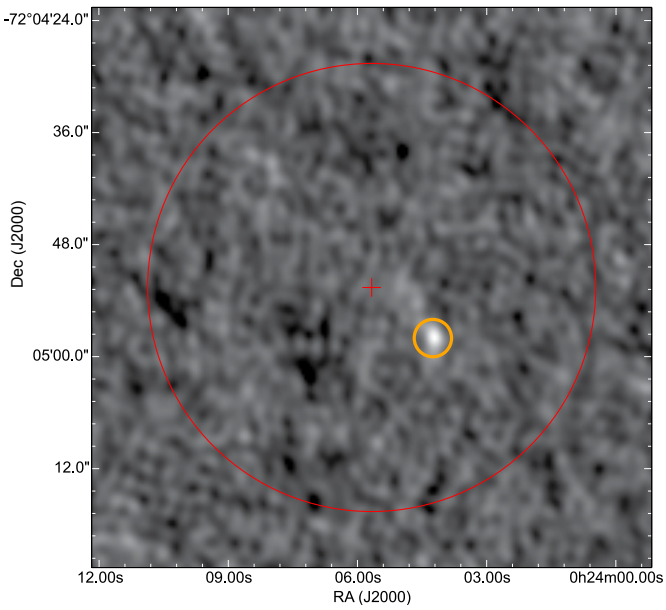
However, black hole X-ray binaries are not the only objects in a globular cluster that can generate X-rays. Accreting neutron stars and white dwarfs, as well as various kinds of less evolved binary star systems, can also produce a similar level of X-ray emission, and

owing to their faintness, it is not usually possible to distinguish between these various classes of systems via their X-ray emission alone. One way of breaking the degeneracy is if radio emission can be detected from the jets powered by the accretion process. Jets are energetic, collimated beams of plasma accelerated away from an accreting compact object at speeds close to that of light, which produce copious amounts of radio emission via the synchrotron process. Accreting black holes produce much more powerful radio jets than any of their less massive analogues, so the detection of bright radio emission coincident with a known X-ray source provides strong evidence that the system contains a black hole. This method has recently been used to detect the first black hole candidates in globular clusters within our own Milky Way galaxy, in the clusters M22 and M62.

Spurred on by these recent detections, we have conducted a deep radio survey of all nearby, massive globular clusters visible from the southern hemisphere, using the Australia Telescope Compact Array. One of our first targets was 47 Tucanae, a well-studied cluster hosting over 300 known X-ray sources. We made the deepest radio image of this cluster to date, and we detected a radio source close to the centre of the cluster that was coincident with a bright X-ray source, X9, that was first discovered in the 1980s. The ultraviolet spectrum of the counterpart was known to show strong carbon emission lines indicative of ongoing accretion, and the source had therefore been classified as an accreting white dwarf. However, our radio detection was over ten times brighter than the radio emission seen from any known white dwarf, which forced us to re-examine the nature of this intriguing system. The ratio of radio to X-ray emission, as well as the X-ray and radio spectra, the X-ray variability, and the optical-through-ultraviolet spectrum of the system led us to conclude that it was most likely to contain an accreting black hole.

However, the X-ray emission from this source is known to be persistent and relatively luminous, implying a high rate of mass transfer from the donor star. Such a high mass transfer rate can only be sustained at very long or very short orbital periods, implying either a giant or subgiant donor with a period of a few days, or else a white dwarf donor with a period of less than an hour. The former possibility could be ruled out from the optical brightness of the system, which was too faint to host such a large donor star. This therefore led us to suggest that the donor star could be a white dwarf, with an orbital period of about 25 minutes. This hypothesis is further supported by the lack of any hydrogen in the optical spectrum of the source; since white dwarfs are formed from the cores of Sun-like stars when they run out of nuclear fuel, they should not contain any hydrogen. If so, this would be the first black hole/white dwarf binary system ever discovered. To confirm this exciting possibility, we are conducting a range of follow up studies, investigating the detailed X-ray spectra of the system, interrogating archival optical and X-ray light curves to search for a periodicity that could represent the binary orbit, and conducting spectroscopic observations with the Hubble Space Telescope to place a deeper constraint on the presence of hydrogen in the system. We look forward to exciting new developments over the coming year.

Reference: Miller-Jones et al. 2015, MNRAS, 453, 3918

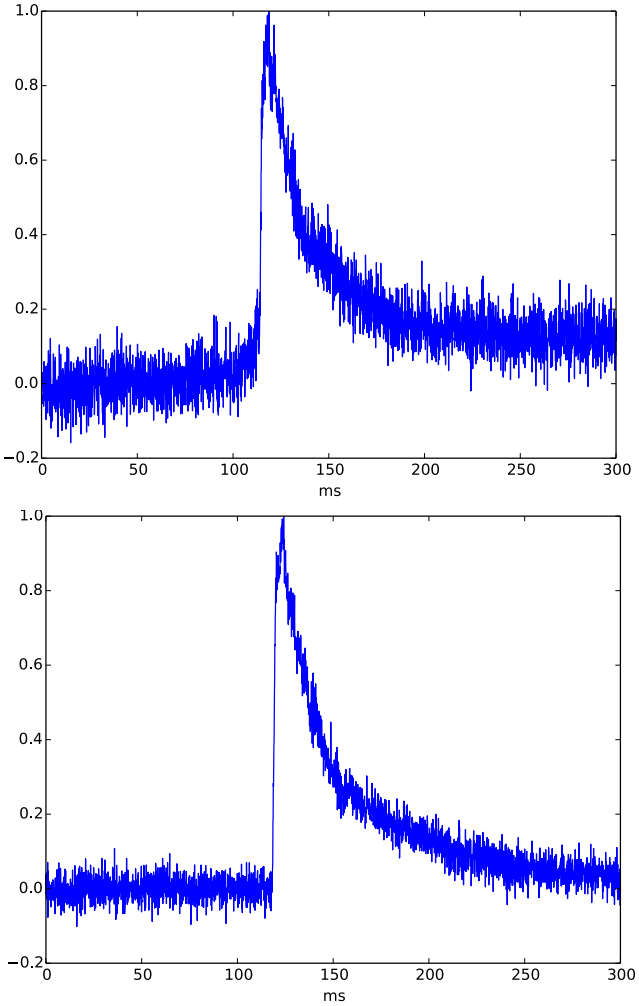


Radio image of the core of the globular cluster 47 Tucanae, taken with the Australia Telescope Compact Array, and showing the cluster centre (red cross) and core radius (red circle). The black hole candidate X9 (orange circle) is the brightest radio source in the cluster. Image credit: Miller-Jones et al. (2015).

Science Highlights

The hunt for fringes between the GMRT and the MWA

Franz Kirsten



A giant pulse from the Crab pulsar at 150 MHz observed by the Giant Meterwave Radio Telescope (top) and by the Murchison Widefield Array (bottom). Image credit: F. Kirsten, using software by M. v. Kerkwijk.

The maximum angular resolution of a telescope observing at wavelength λ depends on the physical diameter d of the telescope, with the resolving power scaling as λ/d.

Hence, the larger the dish (at radio wavelengths) or the mirror (at optical wavelengths), the smaller the angular separation between two celestial objects can be for us to be able to detect them as two sources instead of only one. Owing to the large distances and tiny motions of astrophysical sources, we continually strive to achieve ever higher angular resolution. One way is to observe at smaller wavelengths, or equivalength higher frequencies. Yet, if one desires to observe within a particular frequency regime, e.g., in order to probe certain physics, the only choice is to construct larger telescopes. The physical stability and steerability, however, place natural limits on the maximum size of a telescope. The only way to overcome such physical limitations is to perform interferometric observations – observations with multiple (dis-) connected radio telescopes observing the same patch of sky simultaneously.

In very long baseline interferometry (VLBI) we mimic a telescope as large as the diameter of the Earth by observing with radio dishes spread across the globe. With the recently launched satellite RadioAstron, this range has been expanded to several Earth radii. Typically, VLBI observations are conducted between 5 and 20 GHz, but observing campaigns going as low as 300 MHz and as high as 200 GHz are not uncommon.

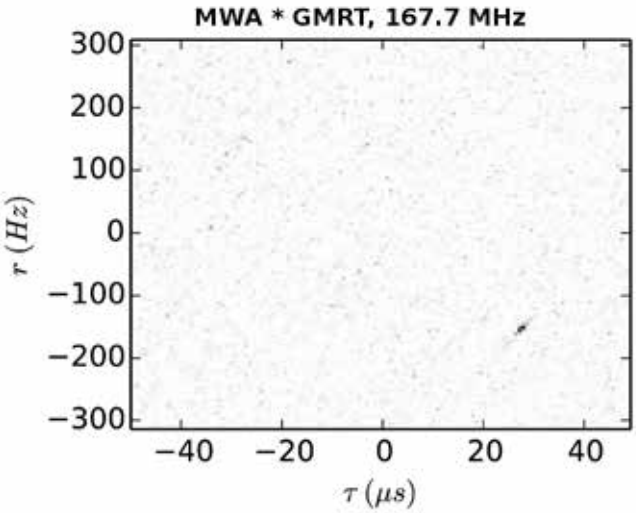
With the recent development of a coherent beamformer for the MWA, one obvious experiment is to perform VLBI observations at MWA frequencies. In the southern hemisphere, there are not many sensitive radio telescopes capable of observing at about 150 MHz and, at the same time, provide VLBI-type baseline lengths of several thousand kilometers. One such telescope is the Giant Meterwave Radio Telescope (GMRT) in Pune, India. For VLBI to work,

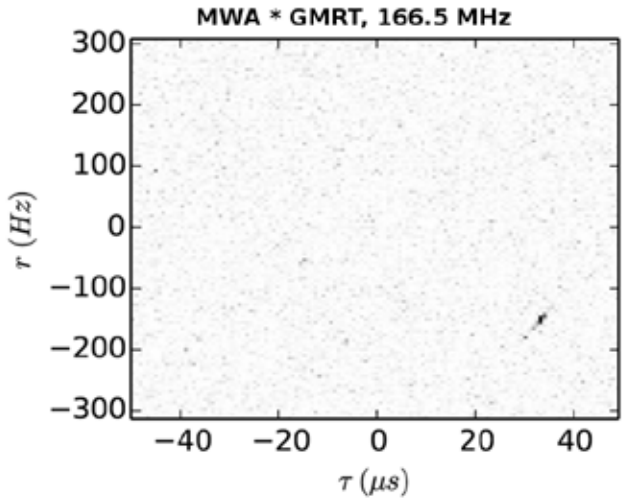
the observing frequencies need to match exactly, and the data streams need to be perfectly aligned in time. Once this is achieved, the multiplication, aka the cross-correlation, of the two signals will yield maximum signals known as fringes.

The frequency setups at the GMRT and the MWA, however, are fairly different. At the GMRT, we observe between 138 and 170 MHz (512 channels) while at the MWA the band covers 142 to 172 MHz (24 channels). On top of that, the time keeping between the two stations is far from being synchronized and can be off by seconds, making searches in delay space (time offset between the arrival time of the same signal at both stations) a real challenge.

To account for the above issues, we first re-channelized the GMRT data to match that of the MWA. Then, we developed a method to align the time streams to within tens of microseconds by using observations of the Crab pulsar. This nearby source (2.2 kiloparcsecs) has a pulse period of 33 milliseconds and emits bright (a few Jansky) giant pulses a few times per minute. These giants pulses have an intrinsic width of a few nanoseconds. Interstellar scattering, however, broadens the pulses to tens of milliseconds duration at 150 MHz (see the figure on the previous page). Nevertheless, we used these pulses to unambiguously align the time streams to within a few microseconds, which significantly narrowed down our search window for fringes.

The figure on the previous page shows the same giant pulse observed by the MWA (coherent beam) and by the GMRT. We manually aligned the two pulses to find an offset of about 1.25 seconds between the recorded arrival times of the pulse at either telescope. We managed to find fringes -- maxima in the cross-correlations -- in the two highest overlapping frequency bands (165.8-168.2 MHz, see the figure to the right) at a time delay of about 35 microseconds and a frequency rate of about 140 Hz. At the lower frequencies we have, thus far, not found any fringes. Our speculations are that we resolve the pulsar at the lower frequencies due to angular scatter broadening, which depends on the square of the frequency. So far, we have only found fringes on this particular pulse, which is the brightest one in the entire observation. We continue hunting for fringes though, so stay tuned!

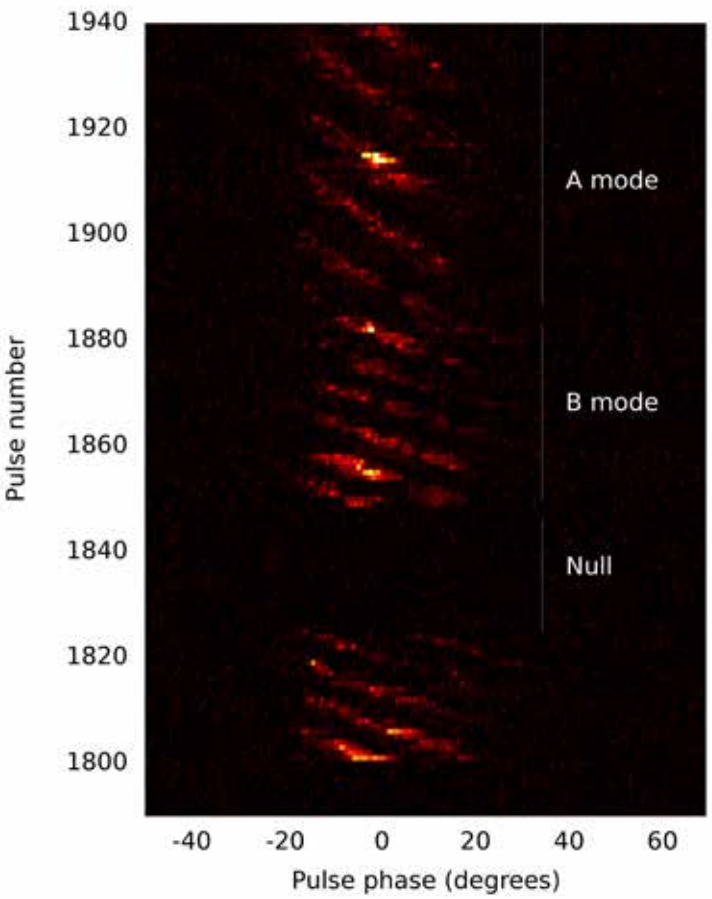




Science Highlights

Ramping up pulsar science with the MWA

Ramesh Bhat
Steven Tremblay



A sequence of 150 pulses from MWA observations of PSR J0034-0721 at a frequency of 185 MHz. The pulsar spins at a rate of approximately once every 0.94 second, and the time range displayed corresponds to about one third of the rotation. Observations show the phenomenon of "sub-pulse drifting", where sub-structures within the pulse emission window march in phase with time. Besides transitioning between different drift modes (A and B), the pulsar also exhibits the phenomenon of "nulling" during which no radio emission is detectable. Sub-pulse drifting offers one of the most elegant and powerful means for probing the complex physics in the pulsar magnetosphere that generates pulsar radio emission.

2015 saw the successful commissioning of high time resolution capabilities for the MWA, and the CIRA pulsar team is now equipped to expand several science programmes into the (sub-millisecond) time domain.

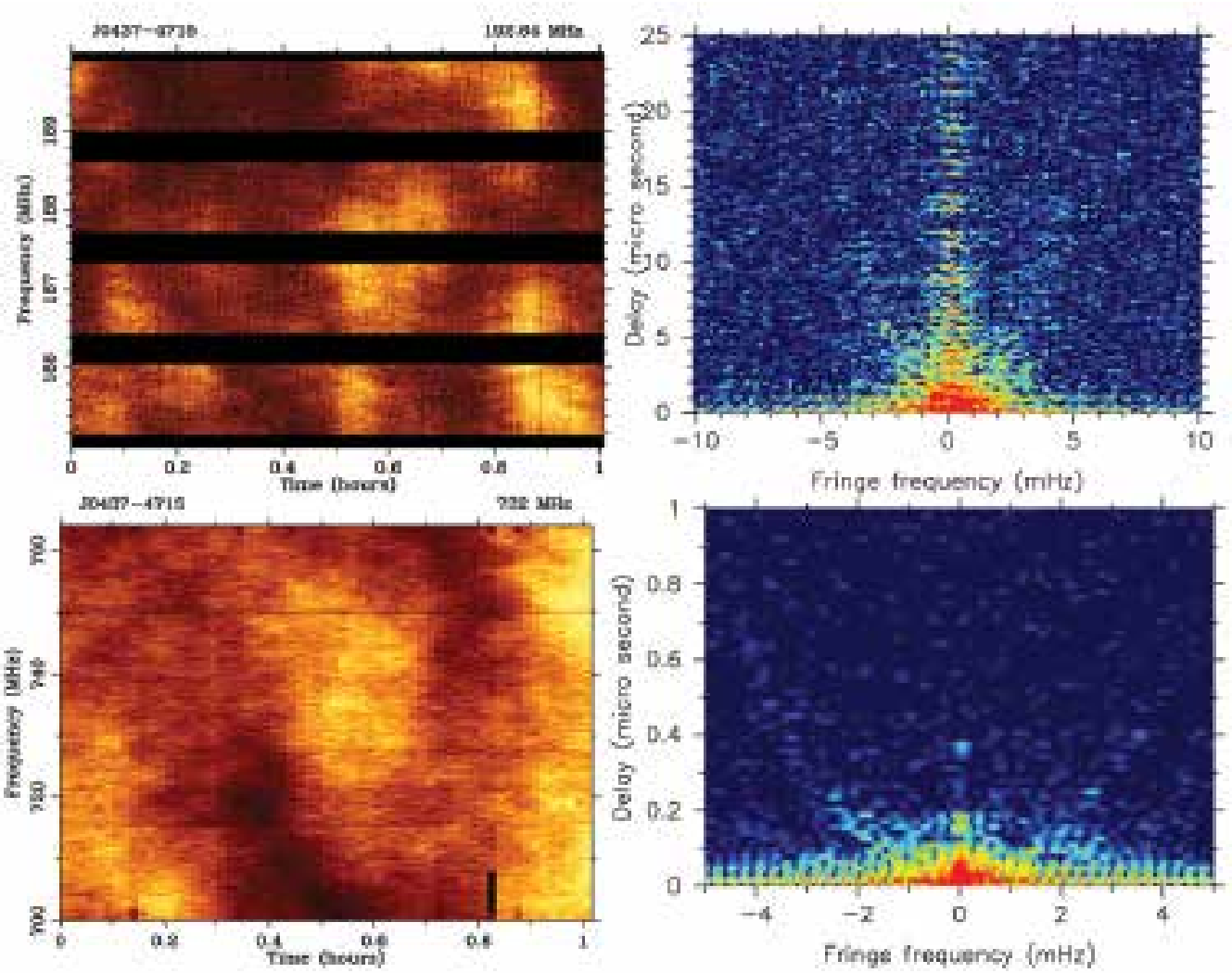
Key aspects of the commissioning include: (1) the voltage capture system (VCS), which records voltage signals from all 128 tiles of the array; and (2) an intricate processing pipeline (run on the Galaxy supercomputer) that performs a coherent addition of the VCS signals to form a tied-array beam on the sky. This new MWA functionality, combined with the telescope's large field-of-view, will allow a variety of exciting new studies on pulsars.

Early results utilising the new capabilities exemplify the potential of MWA pulsar science now that the sub-millisecond domain has been opened. For example, in reprocessed commissioning data of the well-known millisecond pulsar MSP J0437-4715, we discovered parabolic scintillation arcs in its secondary spectra. Parabolic scintillation arcs are created when tiny fractions of pulsar radiation deflects off of the intervening turbulent interstellar medium, thereby causing the signal to take indirect paths to the telescope and to arrive at the telescope with measurable time delays. Prior to this discovery, parabolic scintillation arcs had only been seen from bright, long-period pulsars in observations taken by large, single-dish telescopes like Arecibo and Green Bank. The MWA observation of MSP J0437-4715 marks the first detection of parabolic arcs from an arrayed telescope.

MSP J0437-4715 is a top-priority target for the Parkes pulsar timing array project, which is the

current leading experiment of its kind. Our MWA detection of the parabolic arcs allowed the CIRA team to locate the underlying scattering screen to an impressive precision of a few light years. The inferred location of 375±10 light-years matches well with the estimated distance to the edge of the Local Hot Bubble, which is in the direction of this pulsar. This result will be reported in a forthcoming publication in the Astrophysical Journal led by Ramesh Bhat. Besides improving our knowledge on this well-known pulsar, our discovery underscores the MWA's unique potential to serve as an interstellar medium weather monitor for pulsar timing array experiments.

The increased sensitivity post-VCS commissioning also transformed the MWA into an exceptional instrument for in depth investigations aimed at understanding pulsar emission mechanisms—an outstanding problem even after five decades of pulsar research. The MWA's low-frequency band is particularly advantageous for this goal, because observing at lower frequencies allows one to probe a much larger volume of a pulsar's magnetosphere. Pilot studies with the MWA exhibit great promise, which is vividly demonstrated by observations of PSR J0034-0721, a pulsar well known to display an interesting sub-pulse drifting phenomenon.



Dynamic spectra of the millisecond pulsar J0437-4715 from observations made with the MWA (top left) and the Parkes telescope (bottom left), showing the integrated power of the pulsar as a function of time and frequency. The faint parabolic-shaped features seen in the secondary spectra (right panels) are known as "scintillation arcs", and they offer powerful means to determine the precise location of the interstellar material (i.e. scattering screen) that causes the pulsar to twinkle (scintillate). The inferred distance of 375 ± 10 light-years to the screen compares well to the predicted distance to the edge of the Local Hot Bubble - a large elongated cavity that envelops the Solar neighbourhood..

Sub-pulse drifting is seen as regular marching of organised sub-structures within the pulse emission window, and it offers an elegant means of nailing down the complex physics that governs radio emission. MWA observations show that the pulsar indeed exhibits frequent transitions between different states of drifting bands, as well as frequent (and long) time periods where the emission switches off (i.e. pulse nulling). In 2015, we also undertook simultaneous observations of the Crab pulsar with the MWA (192 MHz) and Parkes (1382 MHz). This joint campaign revealed that only ~50% of giant pulses from the Crab pulsar are seen in both bands, which suggests a flattening in the distribution of spectral indices from giant pulse-emission (Oronsaye et al. 2015).

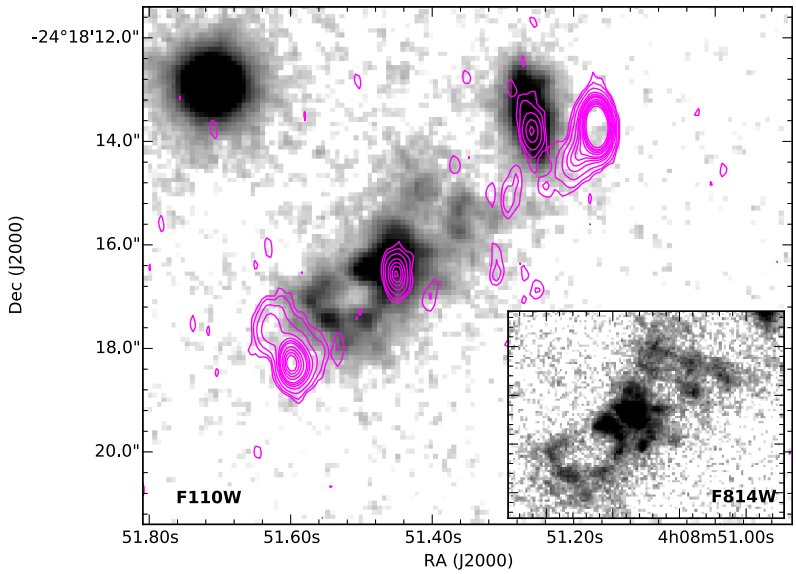
The VCS team documented the system in a publication last year (Tremblay et al. 2015), and since opening up for science early this year, the VCS mode of the MWA has received an increasing number of proposals. However, with a data rate of nearly 30 TB per hour, it is the most data-intensive mode of the MWA, posing significant challenges related to data transport and management. The VCS team is working hard to streamline this process, and we endeavour to support a larger number of projects in the coming years. Besides the primary applications toward pulsars and fast radio burst searches, plans are are underway to broaden the scope of the VCS, through, e.g., spectral-line observations, passive radar applications, and the search for extraterrestrial intelligence.

The aforementioned new developments and science potential of the MWA continue to attract promising students to pursue their post-graduate studies at CIRA. Curtin Honours students Bradley Meyers and Samuel McSweeney were successful in winning APA awards and will join the pulsar group to commence their PhDs in early 2016. Additionally, Mengyao Xue, who completed her Masters at Beijing Normal University, was successful in winning a four-year scholarship from the China Scholarship Council to pursue her PhD research at Curtin. Mengyao's PhD research will focus on a low-frequency census of pulsars in the southern sky, including high time resolution polarimetry. Other notable additions to the group include Dr. Ryan Shannon and Dr. Charlotte Sobey, as joint Curtin-CASS appointees, who will also facilitate strengthening links between the Curtin and CASS pulsar groups. Ryan Shannon is an expert in precision pulsar timing and in detection techniques for gravitational waves, and he led the high-impact Science paper reporting the most stringent limit on the strength of the gravitational waves from binary supermassive black holes (Shannon et al. 2015). Charlotte Sobey comes to CIRA from ASTRON in The Netherlands, and she brings with her valuable LOFAR pulsar experience.

Besides establishing close links with prominent pulsar groups within Australia, the CIRA pulsar team is also developing strong international links. The successful award of a research grant from Universities Australia and the German Academic Research Exchange will enable the CIRA pulsar team to closely work with the group based at the University of Bielefeld, led by Jr. Prof. Verbiest. This two-year programme will commence in early 2016 and will support regular extended visits between members of the two groups. Under the auspices of this programme, the collective CIRA and Bielefeld team will work on important verification of pulsar software pipelines in use for the MWA and the German LOFAR stations, and the team will undertake new projects that exploit the combined use of MWA and LOFAR data. The CIRA pulsar team is also strengthening their collaborative links with groups based in India and in the USA, particularly Raman Research Institute in Bangalore and the University of Wisconsin-Milwaukee, both of which are MWA partners with active pulsar research programmes.

The coming years promise to be an exciting time for pulsar and time-domain science with the MWA, as the CIRA pulsar team ramps up a variety of science programmes. Pulsar research is a key science theme for the Square Kilometre Array (SKA). The MWA, which is the official precursor for SKA-low, is now geared up to play a key role in leading pulsar science into the SKA-era.

Image credit: ICRAR



Composite view of the radio galaxy MRC 0406-244 (at redshift z=2.43). The main frame is an ultraviolet image from the Hubble Space Telescope, and the inset corresponds to an optical image. The magenta contours show radio emission at 8.4 GHz.

Science Highlights

Disentangling emission from supermassive black holes and their host galaxies during peak activity in the distant Universe

Guillaume Drouart

In the history of the Universe, a peak of activity in galaxy formation is observed when the Universe was roughly 3 billion years old (at a redshift z~2.5).

This peak of activity is displayed not only by the galaxy itself (composed of stars, dust, and gas), but also by the supermassive black hole (SMBH) embedded at the centre of the galaxy. The galaxy and SMBH are believed to influence each other's evolution, but the degree to which they actually affect one another is not yet understood. In the local Universe, galaxies and SMBHs follow a tight correlation, where the mass of the SMBH appears to be roughly one 500th of the mass contained within the central regions of the host galaxy. How was this correlation established? Since redshift z~2.5 marks a crucial evolutionary period in the histroy of the Universe, observations of galaxies that display both strong star formation and an active SMBH at that redshift provide key clues.

Powerful radio galaxies are ideal objects to observe and investigate the interplay between active SMBHs -- also referred to as active galactic nuclei (AGN) – and host galaxies. Radio galaxies are particularly bright (and therefore can be observed even at large distances), and, critically, they contain both an AGN, as is evident from the existence of giant radio lobes (which originate from collimated streams of particles launched away from the SMBH at relativistic speeds; see the magenta contours in the above figure), *and* they display intense star formation (which is revealed by dust emission at sub-millimeter wavelengths).

Galaxies and AGN are composed of several different components, with a variety of physical processes at play. Each of these processes tends to emit light at certain frequencies. Hence, by combining observations with telescopes that are sensitivie to different energy bands of the electromagnetic spectrum, the underlying physics of multiple galaxy/AGN components can be teased out, and we can attain insight into how galaxy evolution proceeds.

The technique of interpreting the amount of electromagnetic radiation emitted at different energies is called spectral energy distribution (SED)

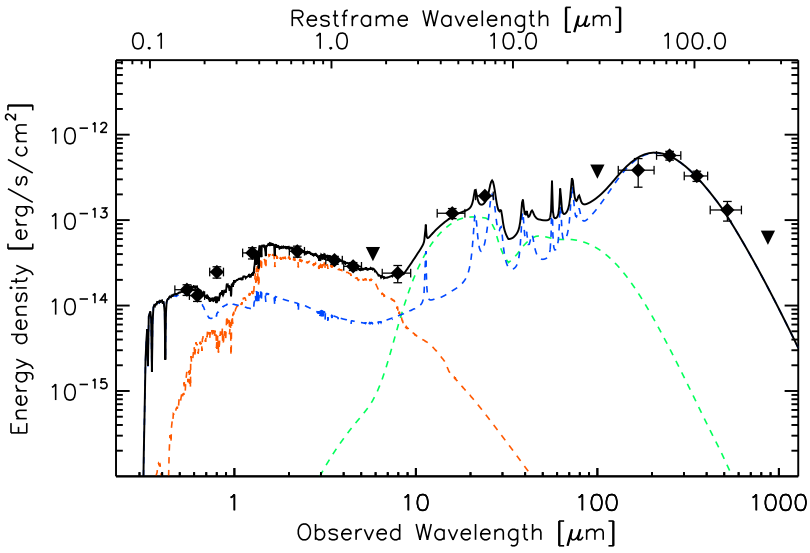
fitting. By comparing observations to models that encompass different evolutionary scenarios, we are able to infer physical properties like masses of galaxies (including the amount of mass in dust and gas), ages of stars within galaxies, and star formation histories.

By combining a high quality set of multi-wavelength data with two advanced models -- one for the AGN and one for the host galaxy -- we derived estimates on the properties of different components of the high-redshift radio galaxy MRC 0406-244. We found that three model components are necessary to reproduce the data (see the figure below). First is the host galaxy (in orange), which is the most massive component, containing a stars with a total mass over 100-billion times the mass of our Sun (or equivalently, over 10 times the mass of all the stars in our own Milky Way galaxy). This host galaxy component also contains the oldest stars, which is indicated by a dominance of stars less massive than our Sun, and by radiation peaking in the near-infrared.

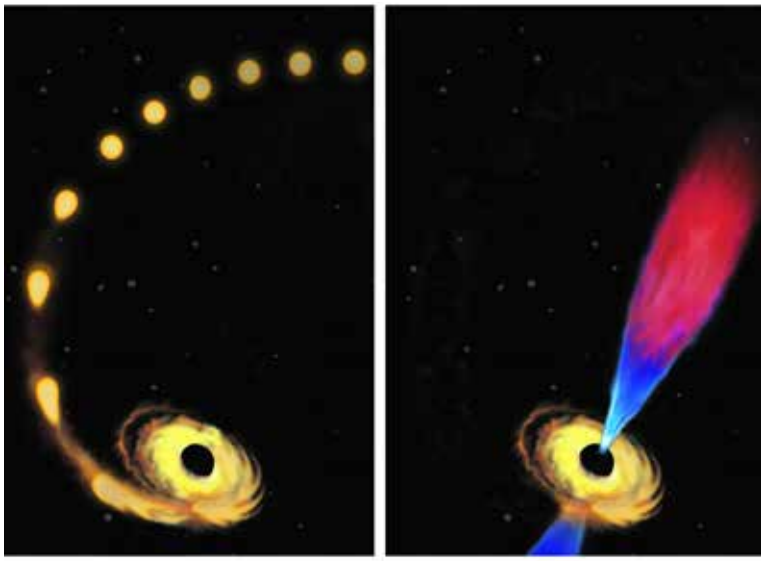
The second component (blue line in the figure below) is from a burst of star formation, which is necessary to reproduce the considerable amounts of emission observed at far-infrared energies. This emission comes from dust heated by radiation from young stars that are more massive than our Sun. This young component is fairly massive as well, containing a mass comparable to 10 billion Suns, and forming stars at a rate as high as 1000 Solar masses per year (for reference, our Milky Way forms stars at rate of 2 Solar masses per year).

Finally, the last component (green) originates from a dusty torus that surrounds the SMBH. Intense radiation from the AGN heats dust in the torus to high temperatures, causing the torus to emit radiation predominantly in the mid-infrared. In order to produce such radiation, significant accretion onto the SMBH is necessary, on the order of 10 Solar masses per year, assuming the SMBH that is around one billion times the mass of our Sun.

The existence of such extreme systems like MRC 0406-244 challenges our understanding of how galaxies formed and evolved after the Big Bang. More specifically, the age of the host galaxy suggests a very rapid formation within less than a billion years. The same reasoning seems to apply to the starburst as well, since understanding how to form so many stars in such a confined volume poses a challenge. To sustain such intense activity, a large amount of gas and very efficient physical processes are required. Moreover, the emission of the AGN is also incredibly intense and localised in the galaxy, releasing an equivalent amount of energy as the starburst, but from a region one thousandth of the volume. The co-existence of these two extreme phenomena (the starburst and the AGN) in the same host galaxy provides us with constraints on a critical phase of galaxy evolution, which will in turn be used in cosmological simulations to understand the formation of some of the largest structures in the Universe.



Best SED fit for the powerful radio galaxy MRC 0406-244 (z=2.43). The orange, blue and green dashed lines represent evolved stellar-, starburst-, and AGN-components, respectively. The sum of the components is displayed by the dark line, and the black diamonds represent multiwavelength observations of the radio galaxy (downward triangles denote upper limits).



Artist's impression of a tidal disruption event. We see the star being drawn toward a black hole and destroyed, and the black hole later emitting a radio jet of plasma composed of the high-speed debris left from the star's destruction. Modified from an image by Amadeo Bachar.

Science Highlights

The first detection of radio jets from an optical and X-ray bright stellar tidal disruption by a supermassive black hole

Gemma Anderson

Supermassive black holes (SMBHs) at the centres of galaxies are known to be powerful generators of radio and X-ray emission as they accrete gas and dust from their surrounding environments.

However, what happens if a SMBH "eats" a star? Such an episode is known as a tidal disruption event (TDE) and occurs when a star strays too close to the event horizon of a black hole. The star gets ripped apart and forms an accretion disk as the matter spirals towards the black hole. Astronomers think that there is a more than one million solar mass SMBH lurking at the centre of every massive galaxy, including our own Milky Way, but it is very unusual to observe a SMBH actively accreting a star. In fact, they are so rare that we have only observed about 30 of them to date.

For guidance toward understanding TDEs, we can turn to accreting stellar mass black holes in our own Milky Way galaxy. Stellar mass black holes are about time times more massive than our Sun, and we find them in X-ray binary (XRB) systems when they accrete matter from a companion star. XRBs sometimes undergo bright X-ray outbursts due to instabilities in the incoming flow of accreting material, and during these outbursts their X-ray luminosities can increase by up to 100 million times. Astronomers observe two very distinct modes when an XRB goes through an outburst, where the X-ray spectrum moves from a non-thermal (high energy) X-ray state into a thermal (low energy) accretion disk dominated state. During this time of transition, we usually observe the launching of a transient and bright radio jet.

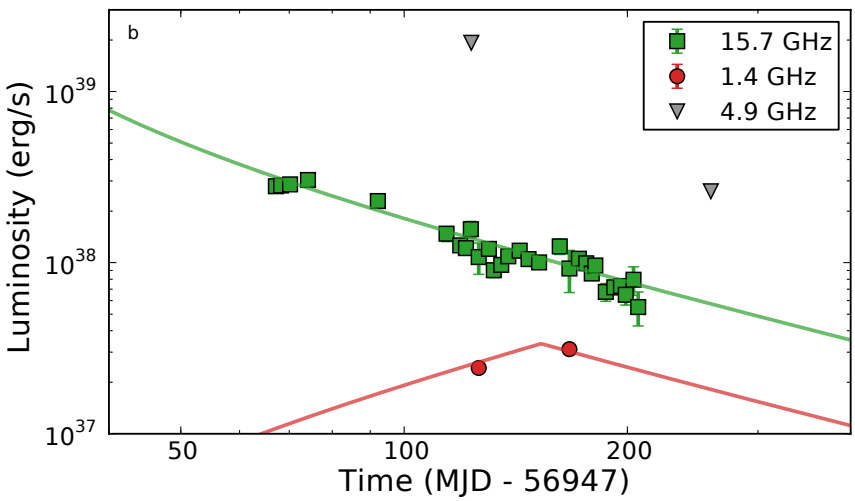
The stellar mass black holes in XRBs, which undergo these outbursts within the period of several months, are considered to be low-mass analogues to the massive black holes at the centres of galaxies. However, the evolution timescales for outbursts from SMBHs are several millions to billions of years long, as interstellar gas falls onto the black hole, which is an impossible timescale for humans to observe. This is not the case for a TDE, however, as the entire mass of a star is transferred into an accretion disk within a very short period of time. A TDE therefore allows astronomers to observe the entire outbursting process from a SMBH within a few years, and therefore on human timescales.

The most common types of TDEs are found by observing very bright optical or low-energy X-ray emission at the centre of a distant galaxy. This type of emission is produced by an accretion disk formed by the disrupted star. Such events are known as thermal TDEs. However, there is also a much rarer type of TDE where relativistic X-ray and radio jets have been observed to be radiating away from the black hole. What is surprising is that radio observations have never detected a jet from a thermal TDE. This calls into question expectations from XRBs, from which we predict that thermal TDEs from suddenly active SMBHs should also launch relativistic jets, observable in the radio waveband.

On 2 December 2014, the All-Sky Automatic Survey for Supernovae detected a TDE called ASASSN-14li, which is in the nearby galaxy PGC 043234 that lies about 300 million light years away. It was discovered through the detection of its bright optical and ultraviolet emission, and it was also detected at low energy X-ray frequencies with the Swift X-ray Telescope. Just 22 days following its discovery, we began observing ASASSN-14li at radio frequencies (15.7 GHz) with a radio telescope known as the Arcminute Microkelvin Imager (AMI). Over a period of five months, we observed fading radio emission emanating from a relativistic jet, which was launched during the sudden accretion event. The energy produced by the jet was more than our Sun would produce over 10 million years! Our discovery marks the first time that astronomers have ever observed relativistic jets outflowing from a thermal TDE.

So what made ASASSN-14li different from the other thermal TDEs? Why have astronomers only ever detected radio emission from this particular event? ASASSN-14li was observed at radio wavelengths within 30 days of the peak outburst. The majority of other thermal TDEs were often observed up to three years following their outbursts. ASASSN-14li is also much closer than nearly all of the other known TDEs. We investigated how bright ASASSN-14li would appear at radio wavelengths at the distance of the other known thermal TDEs, and we found that the radio observations taken of these events were just not sensitive enough to detect a similar associated radio jet. ASASSN-14li was therefore detected because of our early radio observations and the relative closeness of its host galaxy. Our investigation suggests that all thermal TDEs produce radio jets, just as accretion physics predicts, but that they have all escaped detection until now. Our team has demonstrated that in order to detect radio jets from TDEs, one must look at the right time with enough sensitivity. With the increased sensitivity that will be provided by the Square Kilometer Array, we expect to be able to detect faint jets from other events produced by tidally-disrupted stars, allowing us to learn even more about this unusual and rare phenomenon.

Reference: van Velzen, Anderson et al. 2016, Science, 351, 62

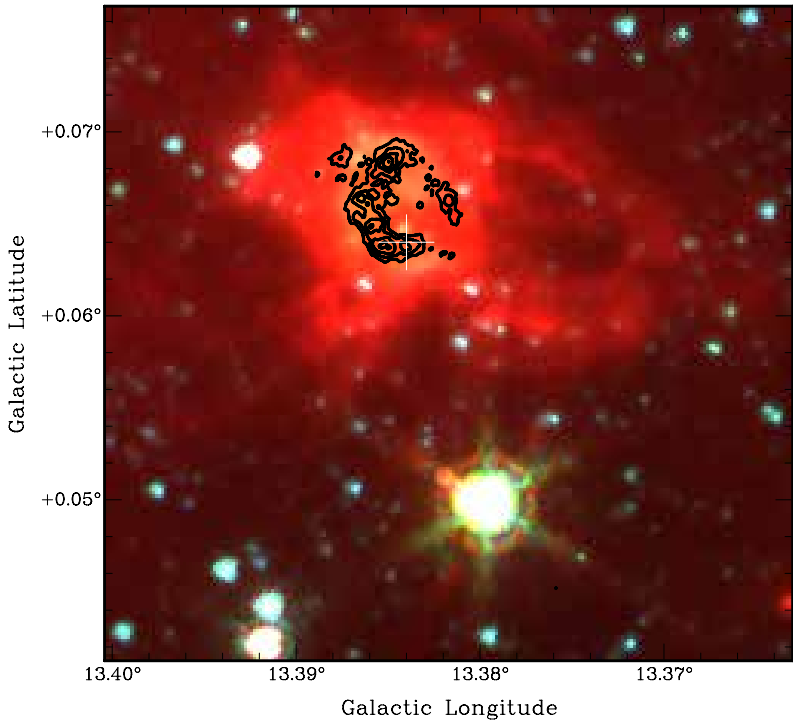


The luminosity evolution of the radio jet from ASASSN-14li. The green line shows the 15.7 GHz AMI detections of ASASSN-14li. We also obtained detections at 1.4 GHz with the Westerbork Synthesis Radio Telescope, which are shown in red. The two grey triangles show the stringent luminosity upper limits of early-time 5 GHz radio non-detections of previous thermal TDEs, if they had been as close as ASASSN-14li. Those radio observations were simply not sensitive enough to detect transient radio emission similar to that produced by the jet of ASASSN-14li.

Science Highlights

A search for isolated high mass star formation

Chenoa Tremblay



The star-forming region G13.382+0.064 (toward the top of the image), as observed in the infrared from GLIMPSE. The three colour image is set with blue at 3.6 μm, green at 4.5 μm, and red at 8.0 μm. The contours on the image show CORNISH 5 GHz radio continuum emission from 2 mJy/beam to 10 mJy/beam in steps of 2 mJy/beam. The white cross represents the pointing centre with ATLASGAL. The bright star toward the bottom of the image is unrelated to the star-forming region.

The formation of low-mass stars, such as our Sun, is fairly well understood. It starts when a cloud of dust and gas within a galaxy is disturbed, causing clumps to form, and for gas to be drawn inwards.

These clumps eventually collapse into a core, which flattens out and starts to rotate the dust and gas around it in a disk. As this disk rotates faster and faster, more of the dust and gas are fed inwards to the core, creating a protostar. The protostar increases in temperature as it draws material into itself. When it gets hot enough, hydrogen atoms start to fuse, releasing significant amounts of energy. After millions of years, bipolar outflowing jets blow away the remaining dust and gas, leaving behind a star.

For a high-mass star that is greater than eight times the size of our Sun to form, the process changes, although we do not yet know exactly how or why. The formation characteristics that differentiate low-mass stars from high-mass stars are that high-mass stars form faster and have a shorter life span. This means that high-mass protostars must pull in or accrete larger amounts of dust and gas at a faster rate than low-mass protostars. There are two competing theories about how this may happen. In one theory, the high-mass star forms within a cluster of stars, which creates a "funnel" effect that feeds the star gas and dust at a rate that is faster than the spinning action of the protostar alone would typically provide. In the other scenario, all of the gas and dust that the star requires is gravitationally bound from the beginning of the protostar creation, but an increase in turbulence and pressure produces a larger star.

One way of differentiating which of these two theories are possible routes to high-mass star formation is to find a high-mass star that has formed in isolation. If stars could form in isolation, even if it is rare, then the initial mass function of star formation within a galaxy would be different. When considering this on galactic

scales, there is a dramatic impact on the number of high-mass stars within a galaxy and, therefore, an effect on the level of chemical enrichment and radiative feedback within that galaxy.

In many other searches for high-mass stars forming in isolation, only infrared data is utilized. Infrared light cannot penetrate the dust layer around a forming star; so the star has to be fully formed before it can be identified. However, high-mass stars are known to move away from their natal environments, making the actual identification of isolated formation difficult. Light emitted in the radio part of the electromagnetic spectrum does not suffer from dust obscuration, so stars can be studied in the radio while they are still within their natal cloud of dust and gas. Therefore, to search for high-mass stars forming in isolation, we have applied a new approach to compare data from the infrared survey ATLASGAL and the radio survey CORNISH. By using a comparison of radio and infrared data, we also remove other sources that can pollute the sample, such as planetary nebula and intermediate-mass stars.

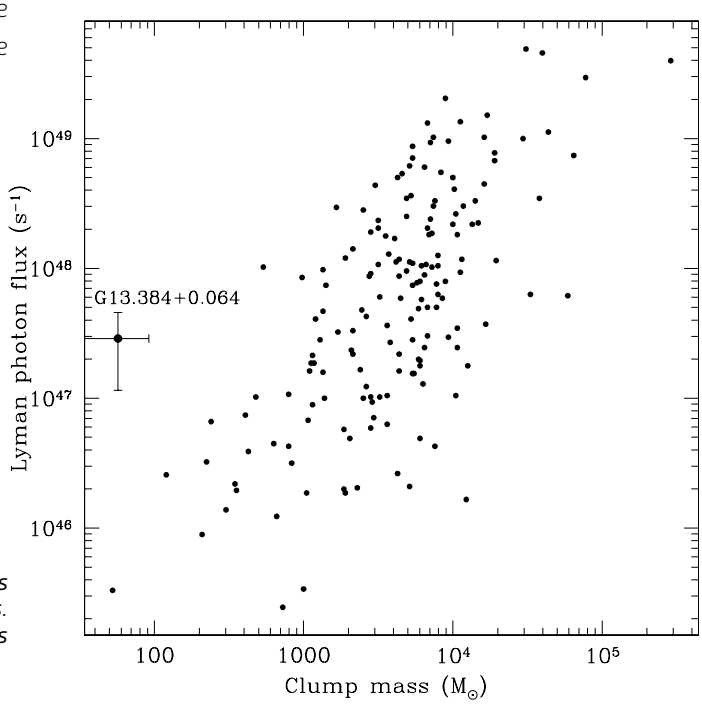
In a comparison of approximately 200 sources, the region of G13.382+0.064 stood out as unique. The star-forming region has a small amount of gas left surrounding the forming star, and a high amount Lyman-alpha continuum (a measure of the energy emitted by the hydrogen in the forming star). From a collection of data from the community of Galactic observational programs, we have found that there is, at least, a single star approximately 11 times the mass of our Sun within this cloud.

The biggest challenge in determining if this star has formed in isolation is in measuring the distance between the Earth and the star-forming region. By looking at the density of objects around the star-forming cloud and studying the properties of the gas, we have found it likely to be 1.9 kiloparsecs (6200 light years) away. At this distance, it is unlikely that the gas is hiding a large cluster of unidentified low-mass stars.

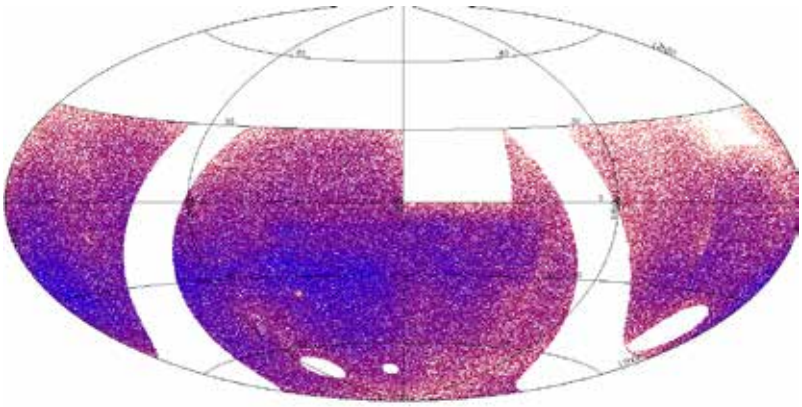
As an additional test to determine if this high-mass star is alone within the cloud of dust and gas, we performed a simulation based on different star cluster properties. Out of approximately 68,000 simulated clusters, we did not find a single match to the properties observed from this star-forming region.

We conclude that the high-mass star within G13.382+0.064 being was formed in isolation. Further observations with high-sensitivity telescopes would confirm if a cluster of small stars resides within the cloud. However, we have verified that the technique of comparing the Lyman flux with the cloud mass is an appropriate screening method for cases of isolated high mass star formation.

Reference: Tremblay, Walsh et. al., 2015, PASA, 32, e047



Plot of clump mass versus Lyman photon flux for a series of approximately 200 ATLASGAL and CORNISH sources. The star-forming region of G13.384+0.064 is noted as being unique compared to the other regions.



The full GLEAM extragalactic catalogue (330,000 low-frequency radio sources) plotted as a function of right ascension (vertical black contours) and declination (horizontal contours). The colour indicates the local noise level around each source -- note the relatively smooth noise characteristics. For every source, there are a further 260 spectral and morphological data points, which cannot be plotted here!

Science Highlights

The GaLactic and Extragalactic All-sky MWA Survey: A catalogue of 300,000 sources

Natasha Hurley-Walker

Since late 2013, the Murchison Widefield Array (MWA) has been engaged in an observing programme titled the GaLactic and Extragalactic All-sky MWA survey (GLEAM), to completely survey the southern sky.

2015 marked several milestones includingthe introduction of the radio-astronomy-focussed supercomputer Galaxy at the Pawsey Centre, the culmination of the development of advanced radio interferometric techniques, and the final imaging run of over 5,000 observations that up the first year of GLEAM observations. The resulting ~40,000 images were knitted together and carefully calibrated, creating a complete survey over ~25,000 square degrees of sky, at the novel, wide frequency range of 72--231 MHz.

The first major product of the survey is a catalogue of ~330,000 radio sources, each with 20 frequency measurements and a host of morphological information. The distribution of these sources over the sky is shown in the figure above. Many of these are distant radio galaxies, consisting of a supermassive black hole pulling in surrounding matter to make a bright accretion disk, and launching jets many times the size of the host galaxy into the surrounding universe. The resolution of GLEAM is very similar to that of the human eye, about two arcminutes (1/30th of a degree).

If we assign colours to GLEAM such that the low frequencies are shown as red, the middle frequencies as green, and the higher frequencies as blue, then we can see the sky with radio eyes, and we can identify the life stages of radio galaxies. The figure at the bottom of the following page shows a small section of the GLEAM survey region, with a colour coding that reflects the brightness in each of three frequency sub-bands of the MWA:

— "red" sources are bright at low frequencies and dim at high frequencies. They tend to be fading, dying radio jets, such as the one detected around NGC1534 in the CIRA-led paper by Hurley-Walker et al. (2015);

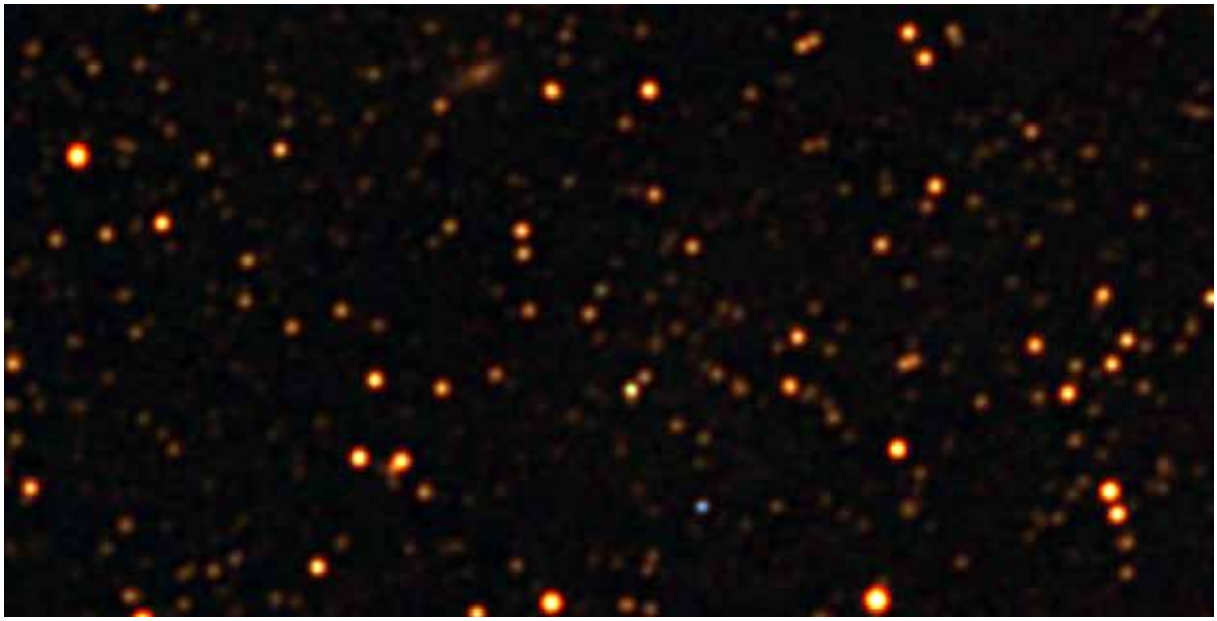
— "white" sources have similar flux densities at all frequencies, and they are purely the result of accreting matter around a radio galaxy's central black hole. These sources are often blended with steeper-spectrum radio jets in MWA observations, but cross-matching with other surveys allows us to unpick the structure;

— "blue" sources are bright at high frequencies and dim at low frequencies, and currently they are something of a mystery. These sources are thought to be radio galaxies in the first stages of their active lives, with radio jets stuggling to escape the dense clouds of gas surrounding them. GLEAM reveals many thousands of blue sources, providing a new window into this engimatic population.

The GLEAM survey also reveals many nearby spiral galaxies, such as M83, also known as the Southern Pinwheel Galaxy (see the figure to the right). While not all spiral galaxies are as resolved as M83 at low-frequencies, combination of GLEAM with ancillary datasets allows us to explore the composition of these galaxies, which are not dissimilar from our own Milky Way. For instance, the spiral arms of M83 are offset between the radio and the infrared, showing that the 'empty' space between them is actually full of high-energy electrons and magnetic fields, producing synchrotron emission.

The GLEAM survey also allows us to constrain the flux scale of the southern sky at these low frequencies to a degree never before attained. We have achieved better than 10% accuracy for 90% of the survey area. One overarching goal is to provide a sky model ready to calibrate the low-frequency component of the Square Kilometer Array, which will start construction on the same site as the MWA toward the end of the decade. With the data, experience, and algorithms developed at CIRA, this goal is within our sight!

The left panel shows the GLEAM 200MHz view of M83, with a spatial resolution of 2 arcminutes; the right panel shows an optical (blue) and infrared (red) combined view of the same galaxy. Interestingly, the spiral arms are offset between the radio and the infrared, implying the gaps between the arms are actually full of high-energy electrons and magnetic fields, producing synchrotron emission.

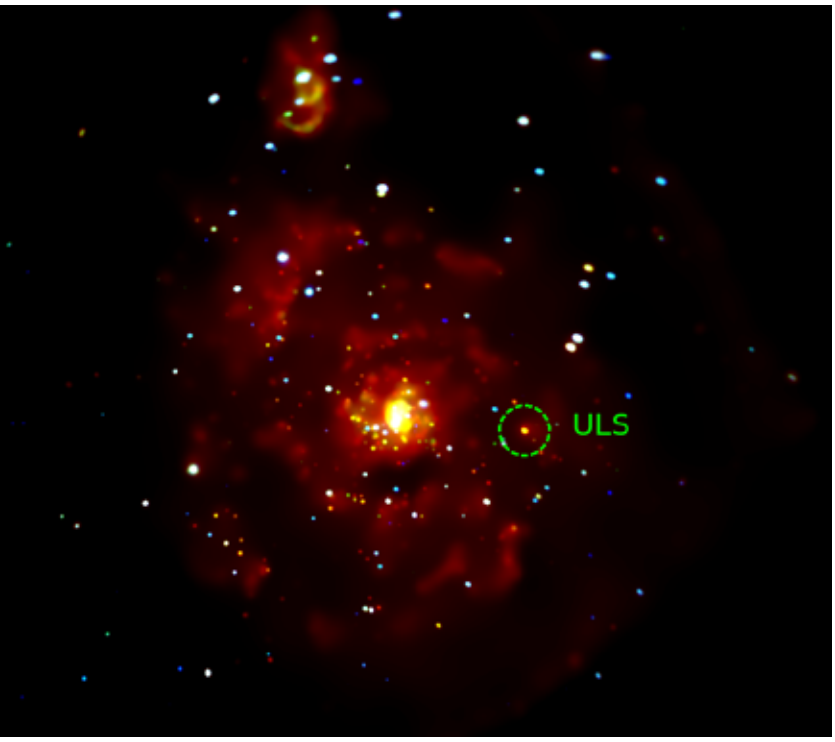


The GLEAM extragalactic sky. Red colours represent 72-103 MHz, green represents 103-134 MHz, and blue represents 139-170 MHz. An engimatic "blue" source is visible near the bottom of the image. Several "white" active radio galaxy cores are visible, and the field is generally dominated by lobes of older, expanding radio jets. Synchrotron emission from the nearby spiral galaxy NGC55 is visible as an extended diagonal cloud at the top left.

Science Highlights

A survey of the most rapidly feeding black holes

Ryan Urquhart



A three-colour X-ray image of the Whirlpool Galaxy, M51, taken with the Chandra telescope. The source inside of the green region is one of the low-temperature ULSs from our survey.

Black holes are massive objects so dense that not even light can escape their gravitational pull. As black holes do not give off any light, astronomers detect them via their interaction with surrounding matter, primarily when they are feeding on surrounding material.

This feeding process is known as accretion, whereby gravitational potential energy is converted into radiation. The amount of radiation emitted is directly related to the accretion rate; the brighter the source, the faster it is feeding. However, there is a theoretical upper limit to the rate at which black holes can accrete, and therefore to the amount of radiation that can be emitted. This limit is referred to as the Eddington limit.

Recently, more and more sources have been discovered that violate the Eddington limit. These objects generate so much light that they produce radiation pressure strong enough to drive matter away from the black hole. These sources are prime targets for understanding black holes feeding at the highest possible rates. So-called ultraluminous supersoft sources (ULSs) comprise one class of these rare, rapdily accreting sources. ULSs are unlike any other compact accreting—with incredibly high luminosities, very low temperatures, and large physical sizes—and there are numerous hypotheses attempting to explain their physical properties.

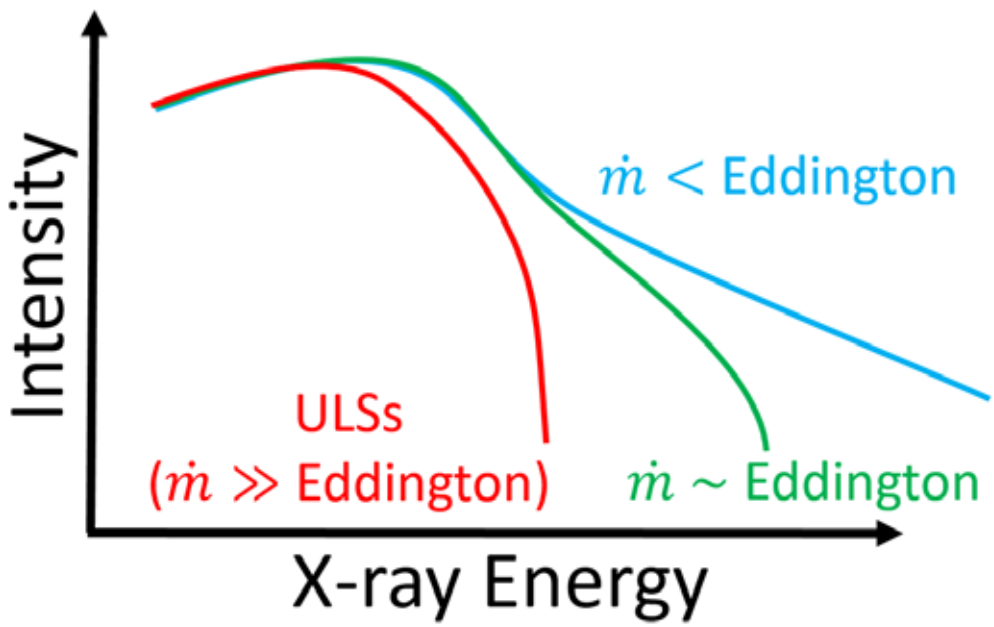
Three of the most popular interpretations include: (1) white dwarfs undergoing nuclear burning on their surfaces; (2) bright and relatively cool accretion disks feeding intermediate-mass black holes (black holes with masses around 10-10,000 times the mass of our Sun); or (3) stellar-mass black holes (about 10 times more massive than our Sun) accreting far above the Eddington limit. At CIRA, we conducted a survey for ULSs, with the goal of discovering enough sources within this peculiar population to being distinguishing between these three interpretations. Below, we discuss each of the three interpretations in turn.

(1) White Dwarfs: ULSs may be the extreme end of a special class of accreting white dwarfs. This class of white dwarfs were first discovered in the Large Magellanic Cloud, and their supersoft X-ray emission is thought to be due to nuclear burning of hydrogen on the white dwarf surface. In this case, the large radii of ULSs would be the result of expanding layers of material propagating outward from the white dwarf. However, ULSs appear to be far too luminous to be white dwarfs, as they would exceed the Eddington limit by up to two orders of magnitude. Thus, we find the white dwarf interpretation for ULSs to be unlikely.

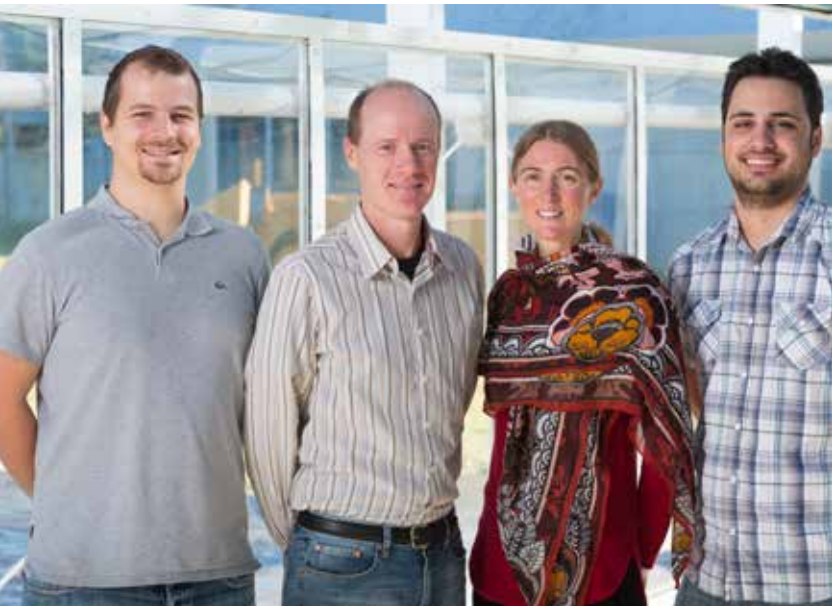
(2) Intermediate-Mass Black Holes: the correspondingly larger accretion disks around intermediate-mass black holes (compared to those of stellar-mass black holes) would be both cooler and more luminous, in line with observations of ULSs. However, emission from a surface of constant area (i.e. a static accretion disk) would follow a power-law relationship between luminosity and temperature. We do not observe this trend in ULSs, and the intermediate-mass black hole interpretation is therefore also unlikely.

(3) Stellar-Mass Black Holes: finally, ULSs may be powered by stellar-mass black holes accreting upwards of hundreds of times above the Eddington limit, what we denote as 'hyper-Eddington.' Such incredibly high accretion rates, and therefore correspondingly strong radiation pressure, results in so much mass being driven away from the black hole that not even light can pass through. The ejected matter can completely envelope the region close to the black hole, blocking out all light from the interior of the system. The enveloping material drastically alters the light that we do see, resulting in the low temperatures that we observe in ULSs. The outflowing material then begins to expand as it is driven out, cooling as it goes. These strong outflows not only help explain the large physical sizes of ULSs, but they also give rise to an anti-correlation between radius and temperature that we have observed among the popualtion of known ULSs.

From our new ULS survey, we propose that ULSs are compact stellar-mass black holes accreting far beyond the Eddington limit. ULSs appear to be surrounded by thick clouds of material driven away from the black hole by intense radiation pressure. The outflowing material is so dense that not even light can pass through it unaltered. We suggest that ULSs are simply the extreme, and relatively unexplored, end of a population of compact accreting X-ray sources, making ULSs among the fastest feeding stellar-mass black holes in the known Universe.



A cartoon representation of the spectra of accreting black holes, depicting how spectra change as the accretion rate ($\dot{m}$) changes. The blue curve shows the spectrum of black holes accreting below the Eddington limit. The green curve shows the spectrum of black holes accreting at the Eddington limit. The red curve shows the spectrum of ULSs, which we theorise to be black holes accreting greatly above the Eddington limit.



Members of the Epoch of Reionisation science team. Left to right: Drs Steven Murray, Randall Wayth, Cathryn Trott, Christopher Jordan.

Science Highlights

Detecting hydrogen from the early Universe: analysing MWA data with a new technique

Cathryn Trott
Randall Wayth

Exploring neutral hydrogen from the first billion years of the Universe provides a wealth of information about the ionisation state, the spatial structure, and the temperature of the intergalactic medium, as well as observational constraints on the growth of the first stars, galaxies and black holes in the Universe.

In the local Universe, we probe neutral hydrogen through its radio frequency emission line, which nominally emits at a frequency of 1.4 GHz (or a wavelength of 21 cm). However, because the Universe is expanding such that the farther away we peer, the faster objects move away from the Earth, light from the distant edges of the Universe is 'redshifted' to lower and lower frequencies. In turn, detecting the neutral hydrogen emission line during the first billion years of the Universe requires observations with low-frequency radio telescopes.

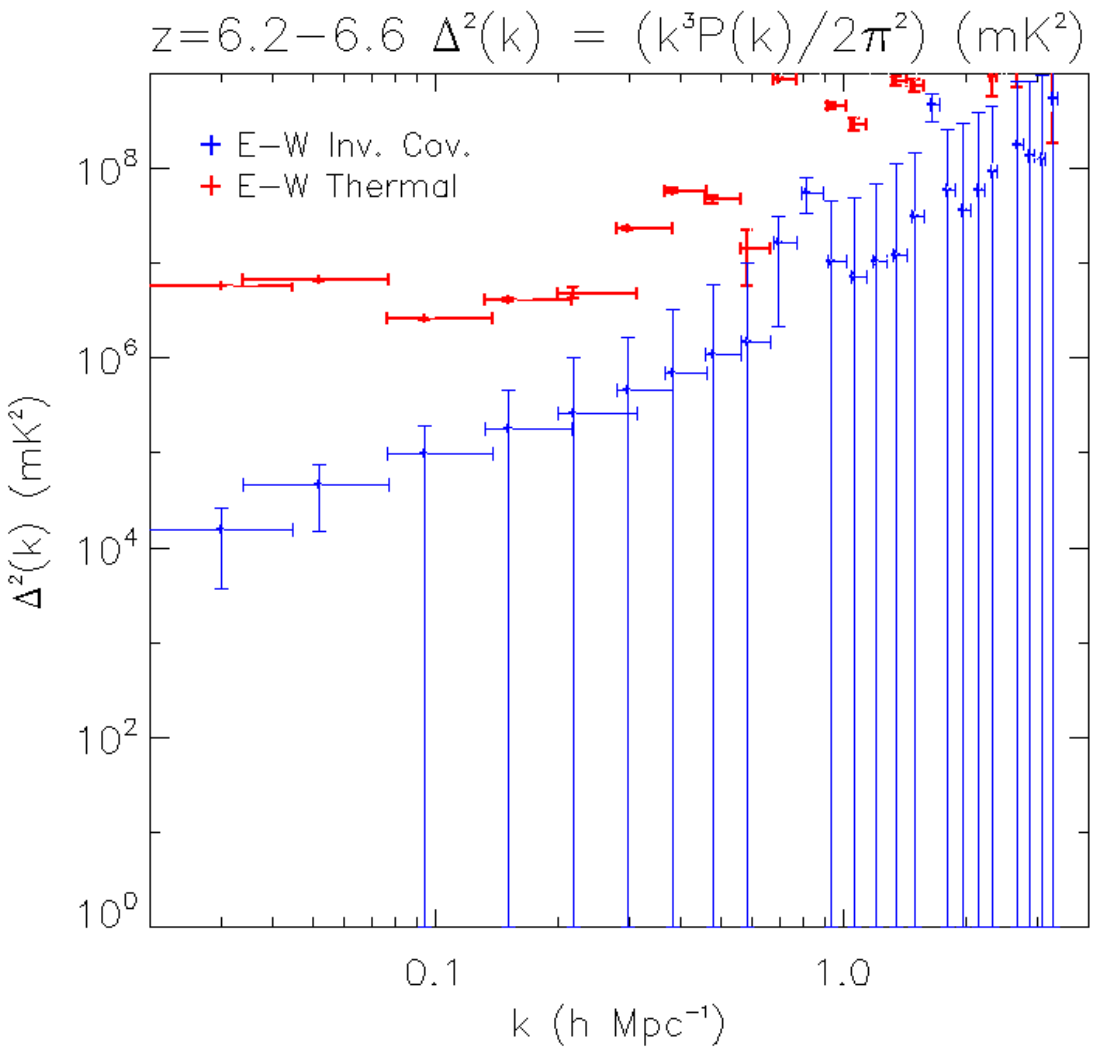
We are using the Murchison Widefield Array (MWA) to detect 12 billion year-old hydrogen, in an attempt to provide a first glimpse into the evolution of the Universe at this early time, a period called the Epoch of Reionisation (EoR). The hydrogen signal from the EoR reflects information about the first population of objects in the Universe radiating stongly enough to ionise hydrogen, a highly signifcant moment in the history of the Universe.

As part of the MWA EoR project, we have designed, built, and launched a sophisticated data analysis tool to take the complex data from the telescope and extract the tiny EoR signal from the early Universe. The CHIPS Estimator (the "Cosmological HI Power Spectrum Estimator") builds on signal detection theory and a sound knowledge of the characteristics of our telescope, to seek an optimised measurement of the EoR signal.

One of the primary challenges of EoR science with early Universe hydrogen is the extraction of a tiny signal from the bright contaminating signal of foreground astrophysical sources, such as

active galactic nuclei, star-forming galaxies, and synchrotron radiation from own Galaxy. In CHIPS, we applied a new technique to model and account for this foreground contamination, allowing us to fully use all information in the data, thereby providing the best chance of detecting the weak cosmological signal. As one of the two primary signal estimation pipelines for the MWA, CHIPS uses data calibrated through the MWA Real Time System (RTS) to extract signal from the contaminated and noisy data.

In our work, we define a mathematical framework for the CHIPS estimator, and we then apply it to three hours of test data from the MWA EoR experiment. As a small subset of the >1000 hours of the full experiment, this three-hour "golden set" of data is being used by multiple groups to test and refine their analysis methods. The CHIPS estimator was demonstrated to produce the expected signals from the three-hour dataset, and from it we obtained an an upper limit on the strength of the early Universe EoR signal.



Output signal power as a function of spatial scale on the sky. This quantity measures the amount of structure in hydrogen in the early Universe as a function of size, and it is a primary metric used to constrain different models for the growth of structure and properties of the intergalactic medium. Our results are consistent with expectations: the signal is dominated by noise and residual contamination from bright foreground galaxies and black holes.

Science Highlights

Studying the impact of the ionosphere on ground-based Epoch of Reionisation observations

Marcin Sokolowski
Randall Wayth
Steven Tremblay
Steven Tingay
Jonathan Tickner
David Emrich
Franz Schlagenhaufer
David Kenney
Morgan Lewis

After the Big Bang and recombination, the Universe was filled with neutral hydrogen and immersed in darkness, a period colloquially referred to by cosmologists as the "Dark Ages".

A few hundred million years later, during so-called Cosmic Dawn, the first stars and galaxies started to form and re-ionise the neutral hydrogen, initialising the Epoch of Reionisation (EoR). The redshifted 21cm line of neutral hydrogen, potentially observable at low radio frequencies (50-200 MHz), is a promising probe of the physical conditions of the intergalactic medium during Cosmic Dawn and the EoR.

In the global EoR approach, a single antenna averages low frequency (50-200 MHz) radio signals from the entire visible sky. Then, many spectra are averaged together, in order to increase the signal-to-noise ratio, and to try to identify the very tiny EoR signal (on the order of 100 milli-Kelvin) from sources of contaminating foreground light (which are brighter by a few orders of magnitude). Although conceptually simple, this approach is very difficult due to requirements for extremeley precise instrument calibrations. Furthermore, one must subtract very bright (and poorly-characterised) foregrounds, while also accounting for complicated effects like signal propagation in the Earth's ionosphere.

The BIGHORNS total power radiometre was developed and built at CIRA between 2011-2014. In October 2014, a system equipped with a bespoke conical log-spiral antenna (also designed and built at CIRA) was deployed at the Murchison Radio-astronomy Observatory (MRO). MRO is a remote and very radio quiet location, and it is the future site of the SKA-low telescope. Many months worth of data collected between 2014-2015 enabled data analysis aiming

to achieve the required milli-Kelvin precision, and to understand the main challenges of global EoR measurements.

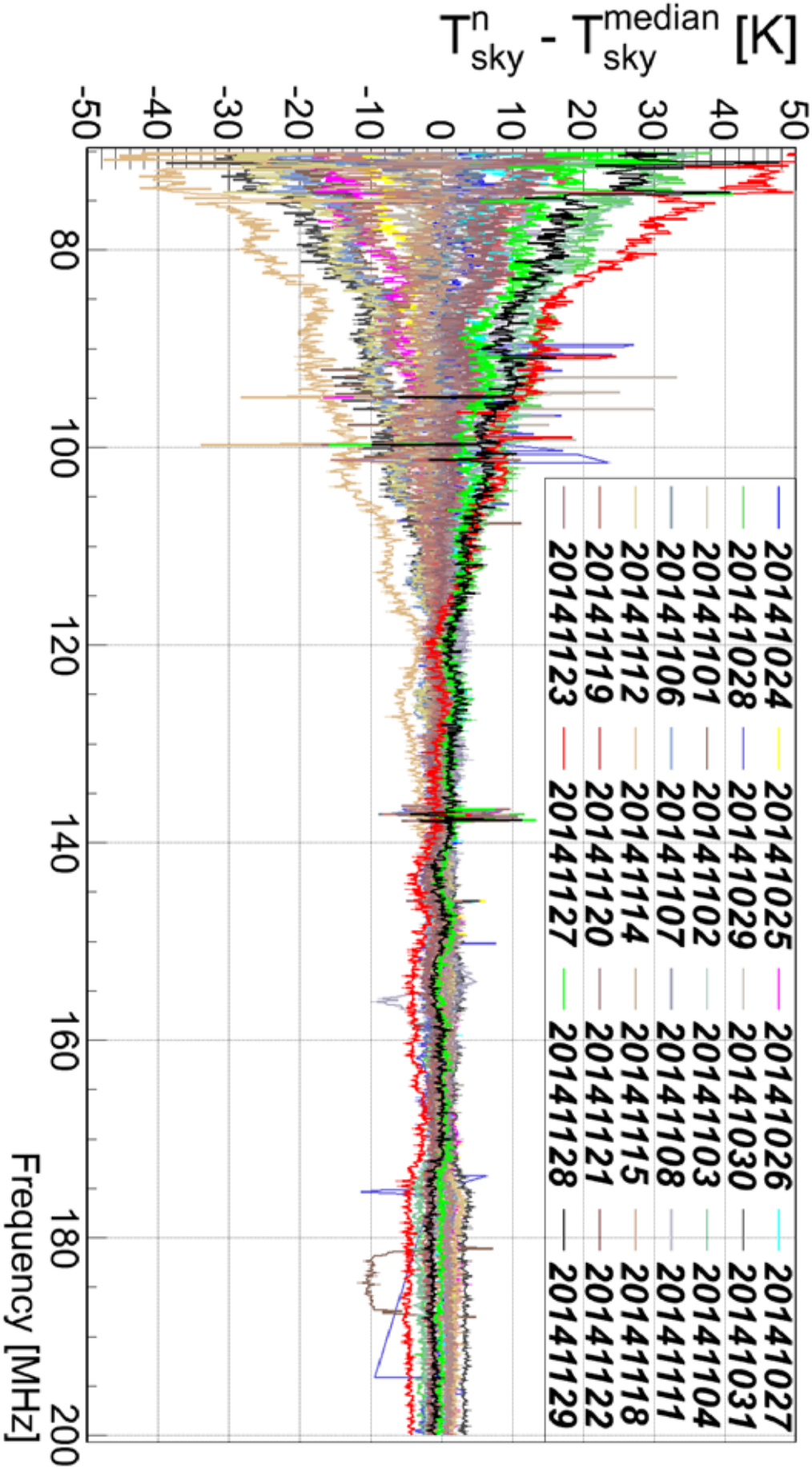
In principle, a signal-to-noise ratio higher than 10 can be achieved after averaging over only 48-hours of data (collected over several days, as only nighttime data can be used). However, the detected radio signals are affected when they propagate through the Earth's ionosphere. The ionosphere changes its properties on timescales of hours, which introduces stochastic errors into the observed sky-averaged radio spectrum.

Recent studies (Datta et al. 2015), based on global position system (GPS) observations of ionospheric properties, suggest that the stochastic error may have pink (or flicker) noise characteristics. Such noise does not have a well defined mean value, which means that ground-based instruments may not be able to suppress the noise in the sky-averaged radio spectra to the requisite precision of EoR studies of a few milli-Kelvin. Hence, CIRA scientists used the large amounts of collected data to study the effects of the ionosphere on ground-based detection of the global EoR, and to tackle a vital question whether global EoR signature can indeed be detected from the ground.
Our data analysis showed that the effects of intraday variations in the ionosphere are clearly visible in the BIGHORNS data (as shown in the figure below). These variations are dominated by absorption and thermal emission, which are a few times more significant than refraction. The additional fluctuations introduced by the ionosphere increase the required integration time. However, after a sufficiently long time (tens of hours), the signal-to-noise ratio increases as expected, i.e., as the square-root of the integration time. In attempting to understand this result, our team studied the power spectrum of the signal fluctuations. We found that the flicker noise characteristics seem to only affect short-timescales, and they turn over at a period of about a day; long-timescales therefore remain unaffected by the ionosphere. These encouraging findings brighten the prospects for ground-based EoR experiments, provided that the ionospheric contribution is properly accounted for in the data analysis.

The large amount of data collected by BIGHORNS at the MRO also allowed analysis of the RFI environment of the future SKA-low site over the 70-300 MHz band. Our findings once more confirmed that MRO is an extremely radio-quiet location. The excision rate (occupancy) in "quiet" channels is of the order of 1-3% and results mainly from relatively high power transmissions from ORBCOMM communication satellites (at 137-138 MHz) and aircraft (118-137 MHz), which occasionally saturate the receiver and require excision of the entire spectrum. On rare occasions, and only during the summer, entire spectra needed to be excised due to broadband emission from lightning at the MRO or its close vicinity. Although the military satellite communication band (242-272 MHz) is almost entirely lost to any astrophysical data analysis, in the FM band (88-108 MHz) there are only a few channels, mainly from high power kilo-Watt transmitters in Geraldton (about 300 kilometres from the MRO), that are excised in more than 40% of cases. Statistical analysis of the observed occupancy and RFI power are providing valuable input for designers of the SKA-low telescope.

The advantage of large and uniform datasets collected by BIGHORNS in 2014/2015 enabled interesting studies on the challenges of global EoR measurements, and on the RFI environment of the future SKA-low telescope site.

See diagram page 32



Each curve corresponds to a difference of a nighttime spectrum (list of nights in the image) averaged over 0-1 hour local sidereal time (LST) bins, and a median spectrum calculated for the same LST bin. Each curve therefore represents ionospehere-induced variation of the all-sky spectrum (compared to the median spectrum) during a particular night at LSTs between 0-1 hours.

Engineering Highlights

Artist's impression of LFAA at the MRO. Image credit: SKA.

Engineering Highlights

First results and updates from a low-frequency aperture array demonstrator at the MWA site

Adrian Sutinjo
Budi Juswardy
Tim Colegate &
Franz Schlagenhaufer

The Square Kilometre Array (SKA) Project aims to construct the world's largest radio telescope – around 50 times more sensitive than present instruments – by around 2025, with early science commencing in 2020. SKA1_LOW, a sparse aperture low frequency array with >130,000 dipole antennas covering 50-350 MHz, will be built at the Murchison Radio astronomy Observatory (MRO) site in Western Australia, home of the Murchison Widefield Array (MWA) and ASKAP precursor telescopes.

The Low Frequency Aperture Array or 'LFAA' is the collecting element of the SKA1_LOW that is to be built at the MRO. The LFAA is being designed by a consortium of Universities and research groups from Australia, the UK, the Netherlands, and Italy, including Cambridge University, Oxford University and the National Radio Astronomy Institutes of Italy and the Netherlands. This group is collectively known as the Aperture Array Design and Construction (AADC) Consortium. CIRA is a member of the AADC Consortium and leads the design of the local infrastructure for the LFAA, as well as all prototyping and on site activity.

Deployment of the >130,000 individual LFAA antennas that will be included in SKA1 (SKA2 is planned to include >2,000,000) will be a complex and costly logistical and engineering exercise. A deployment of antennas of this (numerical) scale is unprecedented in radio-astronomy. As a result there is a high level of perceived risk associated with this aspect of the LFAA. Specialist knowledge, careful planning, and novel methodologies (including techniques and equipment) will likely be required to deploy the LFAA in an effective and cost efficient way.

CIRA is responsible for investigating and planning the deployment of the LFAA as part of the SKA1_LOW construction program. As operational leader of the Murchison Widefield Array (MWA) Project, Curtin led the deployment and commissioning of the MWA at the MRO. This experience makes CIRA uniquely qualified for the task.

MWA construction and deployment activities. Image credit: Curtin University and MWA

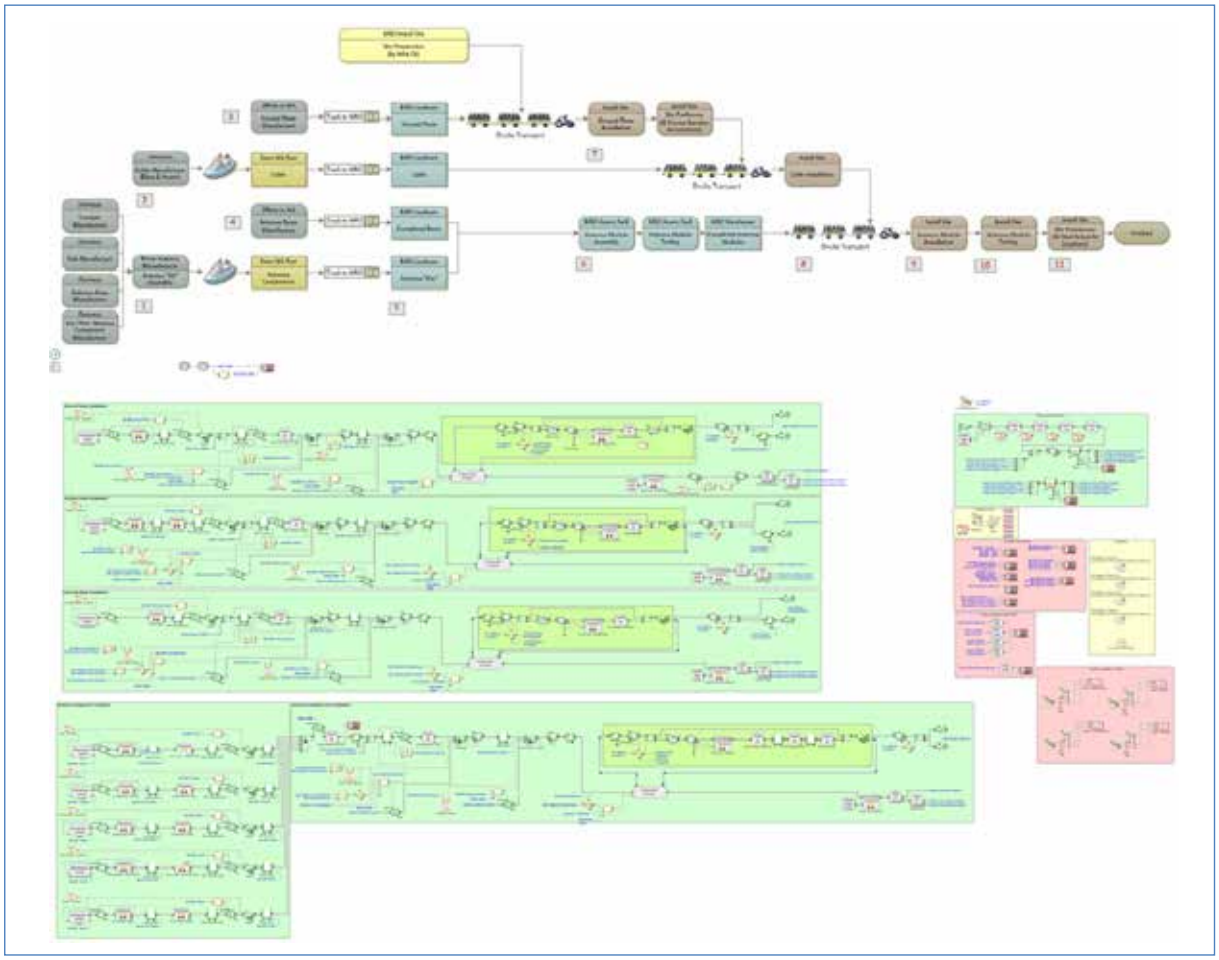
In Stage 1 of SKA pre-construction, which culminated with a design review in early 2015, CIRA was tasked with demonstrating that the deployment and installation of the LFAA was feasible within realistic cost and schedule constraints. The project information environment at the time meant that Stage 1 investigations were necessarily based on a variety of assumptions across a range of project level issues. Nevertheless 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 during Stage 1 was that it was developed in isolation and not within the context of a holistic SKA1_LOW construction and roll-out program. CIRA's focus in Stage 2 of pre-construction, having established basic feasibility during Stage 1, is on developing a realistic deployment and installation plan that is informed by and supports an SKA1_LOW rollout and integration strategy that has since been adopted by the SKA Project. It will seek to develop procedures and plans that leverage the opportunities a phased roll-out affords, while minimising any negative impacts and risks that it introduces.

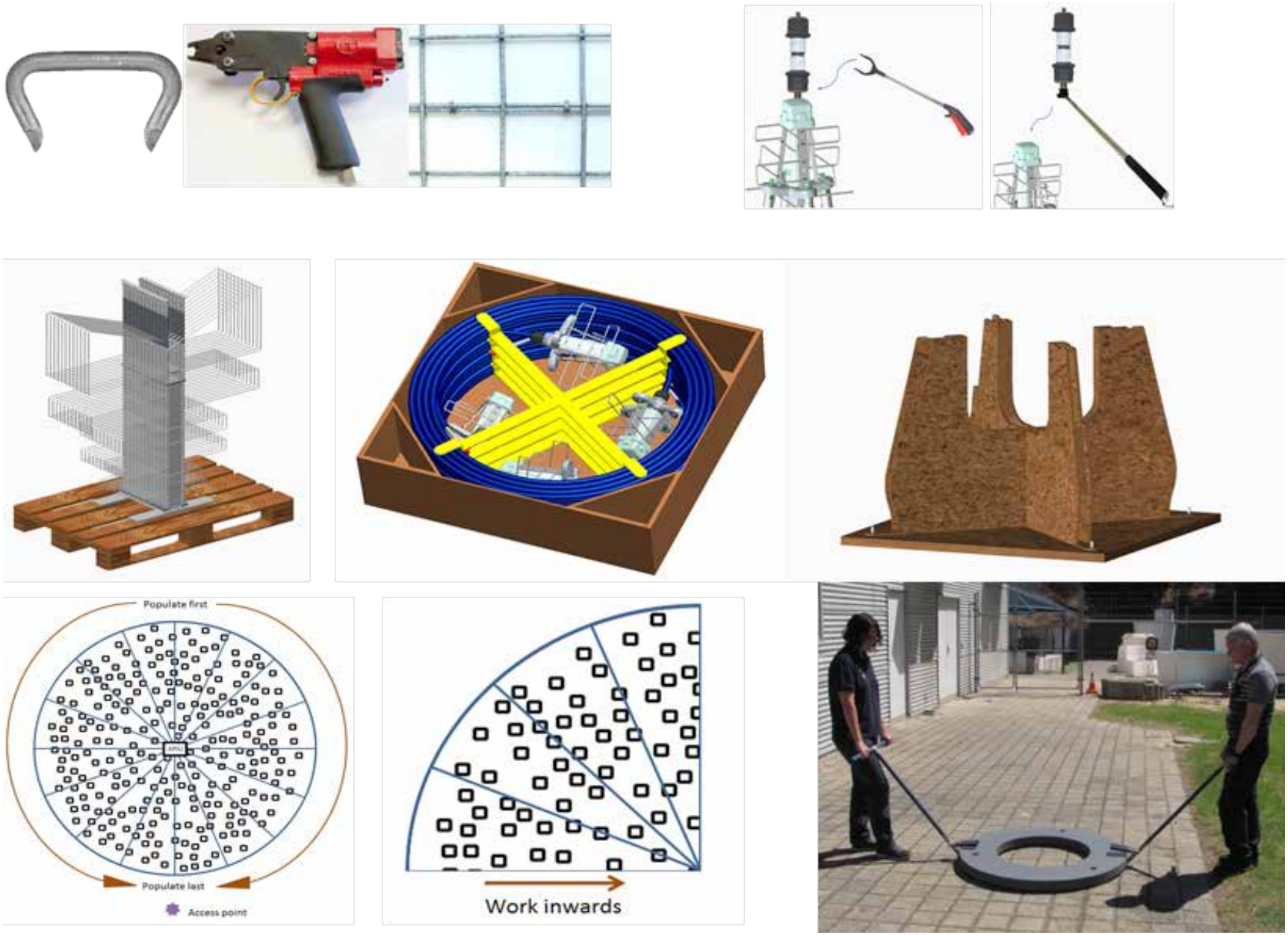
Throughout 2015, CIRA developed a process for installing an LFAA field node with limited support. It reflects the procedures, tools, and equipment employed for the installation of the AAVS1, an LFAA demonstration system, at the MRO, and it will be applicable to future installations that are not large enough to justify the cost of capabilities that can only be cost-effectively deployed in support of larger deployment activities.

This work will be extended and evolved into the context of an LFAA scale deployment activity by CIRA industry partner GCo Electrical. GCo Electrical has a long history of working on the MRO site for projects, including beging the prime contractor for delivery of the MWA site infrastructure. GCo Electrical has planned and executed a number of large 'solar farm' installations—the closest common analogue to the deployment of the LFAA, and it can draw upon a robust local network of businesses across a variety of domains to ensure that the plan developed is informed by the insights that only locals can provide.

CIRA engaged subject matter experts from around Raytheon Australia in workshops designed to synthesise viable deployment concepts from the myriad possible approaches. Image credit: Raytheon Australia



Raytheon's collaboration with CIRA culminated in a concept for the LFAA deployment (top) and a detailed model (bottom). A sophisticated process modelling and simulation tool was used to demonstrate the feasibility of the LFAA deployment. Image credit: Raytheon Australia

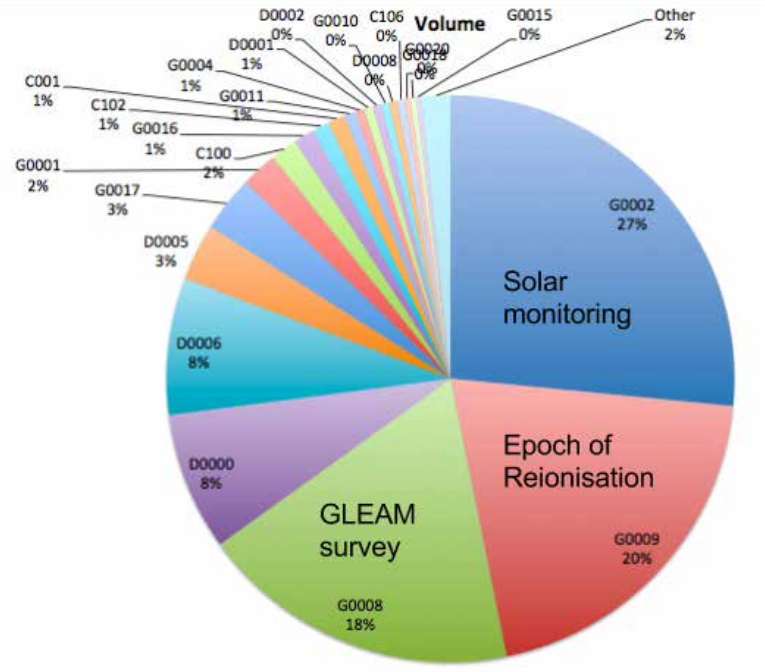


Some of the tools, techniques and procedures CIRA has developed to support small-scale LFAA deployments. Image credit: CIRA and UCAM

Engineering Highlights

MWA operations summary

Randall Wayth



The breakdown by volume of visibility data acquired by the MWA as of December 2015.

2015 was a very successful year for MWA science programmes, with an unprecedented amount of data collected. The 2015-A semester (January-June) saw a record 17 proposals to use the telescope, both from MWA science teams and external parties. Highlights of the 2015-A semester include:

- The completion of the second full year of the GLEAM survey observations, which will increase the sensitivity and image fidelity of the GLEAM data products
- Demonstration of coherent beamforming for pulsar science.
- Successful shadowing of the new K2 mission fields for the Kepler space telescope, to have contemporaneous monitoring of the Kepler fields.

2015-B did not have a formal call for proposals due to the uncertainty surrounding NCRIS funding, on which the MWA relies to support observatory operations. Instead, the 2014-B program was mirrored into 2015-B, with modifications as recommended by program Principal Investigators and the MWA Director. Over the full year, the MWA collected 3.6 PB of visibility data over 4200 observing hours, taking the total visibility data collected with MWA to around 8 PB since the commencement of operations in mid-2013. The chart above shows the breakdown of visibility data volume as of December 2015. The majority of the data are for the MWA solar, survey and EoR key science programmes.

Awards and recognition

Three CIRA-based members of the Australian MWA team were recognised in the prestigious Thompson-Reuters Citation and Innovation Awards in 2015: Prof. Steven Tingay, Dr. Randall Wayth, and Mr. Mark Waterson (now at the SKA office in Manchester, UK) were part of a larger Australian team receiving

the recognition. Prof. Tingay and Dr. Wayth attended the award ceremony in Melbourne as CIRA representatives. The MWA was the winner in the "Space Sciences" category of the awards "in recognition of their outstanding contribution to research."

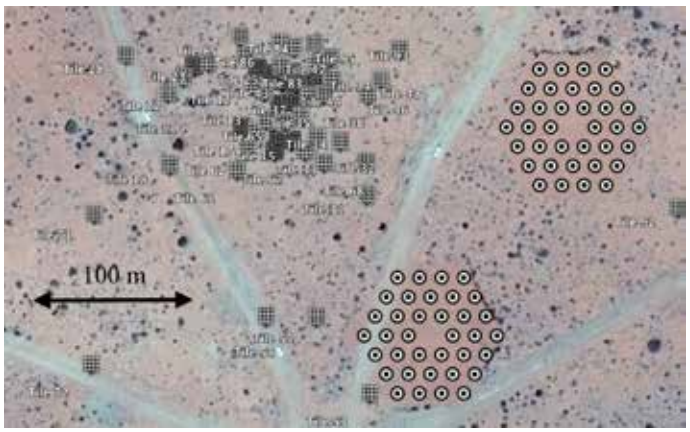
ARC LIEF success

In early 2015 the MWA international partner institutions, including two new partners in Western Sydney University and the University of Toronto, pulled together to submit an application to the Australian Research Council (ARC) for a Linkage, Infrastructure, Equipment and Facilities (LIEF) grant to support the expansion of the MWA into a larger, more sensitive, MWA "Phase 2" array.

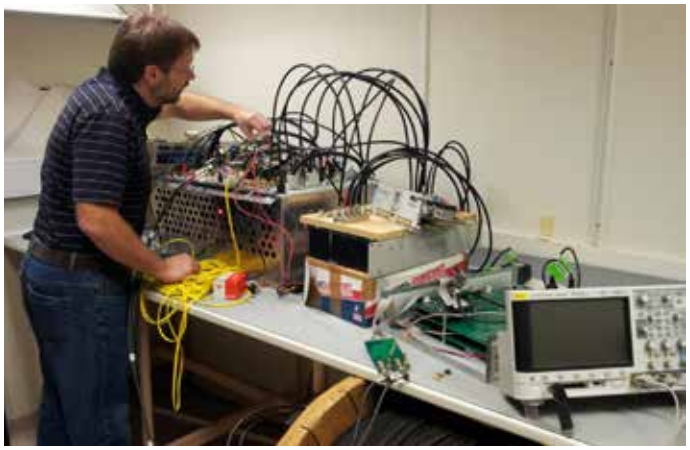
In late 2015, the ARC announced that the grant was successful and awarded the MWA project $1M, bringing the total funds available for expansion to $2.6M when combined with the partner institution's contributions.

The expanded MWA will see 128 new antenna "tiles" added to the array: 72 tiles will be placed in two sets of 36-tiles arranged in a regular hexagonal pattern (see figure below) and a further 56 tiles will be placed between 3 and 5 km from the MWA core to expand the image resolution and fidelity of the array. Infrastructure works for the expansion began in late-2015, and the deployment of the new hexagonal configuration tiles is due for completion mid-2016. Development and prototyping of MWA Phase 2 (and future) hardware is ongoing within the ICRAR Engineering laboratory, which is based at Curtin University.

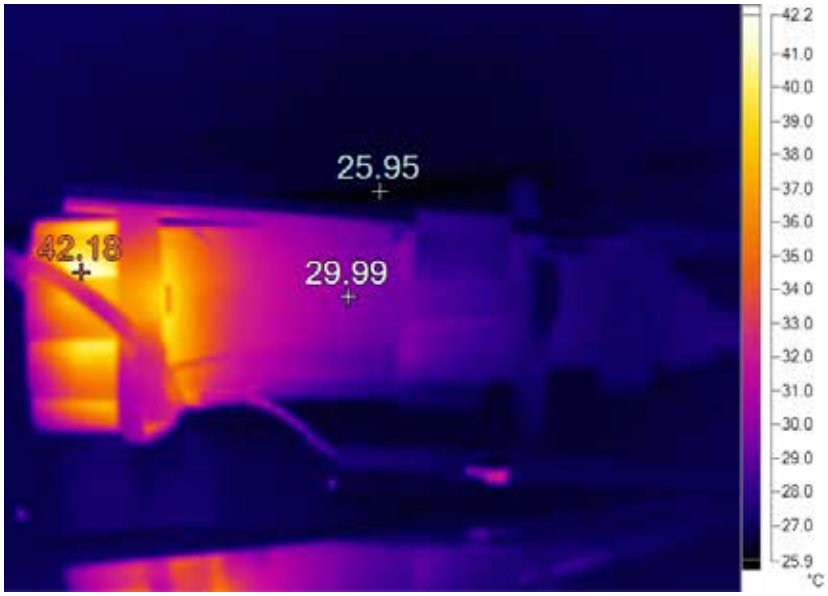
Representatives of the Australian MWA collaboration receiving their Thompson-Reuters Innovation and Citation awards. Left to right: Prof. Frank Briggs (ANU), Dr. Randall Wayth (Curtin), Prof. Steven Tingay (Curtin), Prof. Rachel Webster (University of Melbourne), and Ms. Kate Gunn (CAASTRO).



The layout of the expanded MWA, showing the inclusion of two sets of 36-tile sub-arrays arranged ina hexagonal pattern



Engineer Mr Brian Crosse working with prototype MWA receiver and long-distance beamformer controller hardware in the MWA laboratory at Curtin.



Infrared image showing the distribution of heat inside the enclosure.

Engineering Highlights

Temperature stability evaluation of outdoor electronics for radio astronomy receivers

Budi Juswardi

The low-frequency Square Kilometre Array (SKA_LOW) is expected to consist of over a hundred thousand low-frequency antennas, placed in a sparse aperture configuration in an area up to 65 kilometres in diameter. Among the primary goals of SKA_LOW is the detection of very faint radio signals, such as radiation from the early Universe during the so-called Epoch or Reionization (EoR), which requires highly-stable and well-calibrated radio receivers.

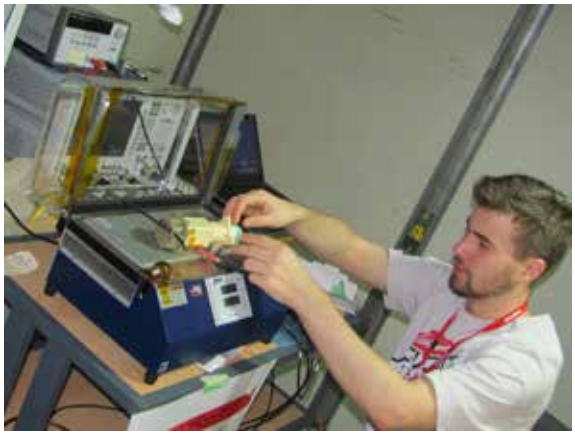
The low frequency aperture array is the collecting element of SKA_LOW, and its front-end receiver channel include the antenna element, a low noise amplifier, analogue radio-frequency-over-fibre optical links, fibre-optic cables, and an analogue-to-digital converter. Except for the analogue-to-digital converter, all of the other components to the low frequency aperture array will be exposed directly to the outdoor elements at the Murchison Radio-astronomy Observatory (MRO).

The performance of the SKA_LOW receiver ultimately depends on the ability of the receiver blocks to withstand temperature fluctuations in the Australian outback environment at the MRO, while still meeting stability requirements for detecting faint astronomical radio signals. Another crucial requirement is the ability to measure temperature differences experienced by antenna elements that are separated by a few tens of metres, which corresponds to the physical diameter of an SKA_LOW station.

Throughout 2015, CIRA engineers tackled the above issues by conducting field measurements at the MRO, and by performing temperature characterisations in our laboratory. The purpose of these measurements was to assess temperature variations in the field, and to understand the impact of temperature variations on the stability of the electronic components when they are placed outdoors. We performed the latter characterisation tests by simultaing outdoor temperatures variations within a controlled laboratory enviornment.

Contributions to the above effort involved one Curtin University fourth year Electrical Engineering student (Mr. Chris Punzalan) and one ICRAR Summer Student (Mr. Skevos Karpathakis). The students developed the test set-up, and they performed measurements of electronic modules. Their work made use of state-of-the art equipment and data processing/analysis techniques.

The measurements and experimental results so far demonstrate the feasibility of the technology that will potentially be used in the radio-frequency receiver blocks for reliable signal transport for SKA_LOW. We now have a deeper understanding on the behaviours of the electronics component, as well as the fibre optic cable that will be used for radio-frequency signal remoting in Australian outdoor environments, in particular at the MRO. From the field measurements and subsequent analysis, we provided critical information to the Aperture Array Design Consortium on the optimal strategy for calibration, as well as on the methodology required to verify the performance of the developed modules for deployment at the MRO.



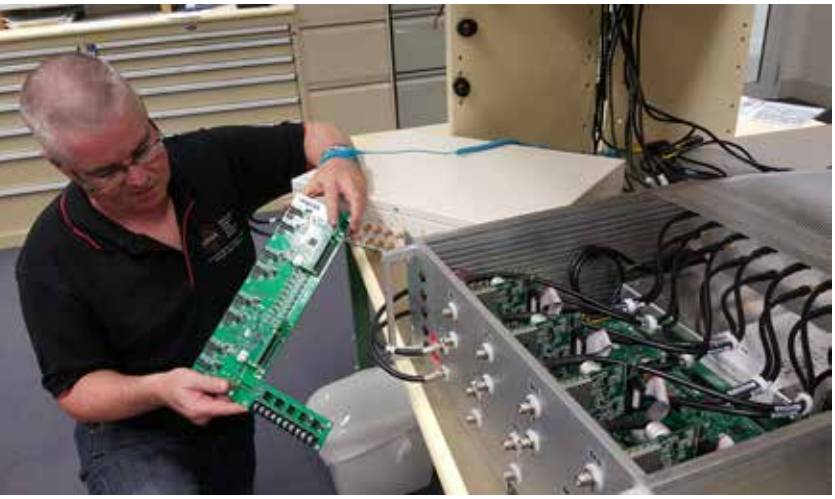
ICRAR/Curtin Summer Student, Skevos Karpathakis (UWA) measuring the temperature contribution from the power dissipation from the electronic modules used at the MRO.

Temperature probes in the field at the MRO.

Temperature measurement set-up around the Aperture Array Verification System (AAVS 0.5) location at the MRO.

BIGHORNs antenna at the Murchison Radio-astronomy Observatory. Image credit: Carole Jackson

Antenna at CIRA (Brodie Hall) decorated for the holiday season.
Image credit: Wiebke Ebeling



David Kenney in front of one of two Engineering Development Array (EDA) Beamformer Control boxes that he designed and built. He is holding a control board fitted with two Raspberry Pi computers running Linux. These two Beamformer Control boxes, to be connected to 32 standard MWA beamformers, will handle the 256-dipole EDA station.

Engineering Highlights

MWA monitor and control software

Andrew Williams

2015 saw several developments toward the monitor and control software for the Murchison Widefield Array (MWA). In this article we highlight three achievements, including new abilities for the MWA to follow-up transient astropysical events, progress on the Engineering Development Array (EDA), and improvements to archived MWA metadata that eases a user's ability to assess the quality of MWA observations.

MWA follow-up observations

One of the most successful aspects of MWA software development in 2015 was the establishment of targeted follow-up observations for other groups – Parkes for the SUPERB collaboration search for Fast Radio Bursts, LIGO for gravitational wave events, and ANTARES for neutrino bursts.

For the SUPERB follow-up work, new code was written to use incoming data on the Parkes position and status (sent to our server by the Parkes telescope controller). This software dynamically generated MWA observations that allowed us to observe wherever in the sky Parkes was pointed, for the whole duration of SUPERB observing blocks. MWA observations taken in this tracking mode put an upper limit on the low-frequency emissions from FRB 150418, which was reported in Nature on 26th February 2016 (Keane et al. 2016, Nature, 530, 453).

Further code was developed that now also allows MWA to respond to gravitational wave alert triggers from the Laser Interferometer Gravitational-Wave Observatory (LIGO), with observations (at the peak of the position probability density) starting within a few seconds of the trigger. This follow-up code was

running on the MWA at the time of the now-famous gravitational wave transient GW150914, but because LIGO were still commissioning their alert system, they issued this alert manually nearly two days later. Future triggers will be observed automatically, however, overriding most other MWA observations in progress.

Engineering Development Array (EDA)

The EDA will be a station consisting of 256 MWA dipoles, arranged in a pseudo-random array around 40 metres in diameter, similar in scale to an SKA-LOW field node. The 256 dipoles will use a two-stage analogue beamformer to produce a single station beam, which will be correlated with the rest of the MWA (replacing a single MWA tile). The 256 dipoles will be controlled by 16 ordinary MWA beamformers, and the outputs of these 16 beamformers will be connected to the inputs of the 'Kaelus' analogue beamformer, which has a slightly longer maximum delay, and a smaller time quantisation.

All seventeen beamformers will be controlled by software running on 'Raspberry Pi' computers – tiny, cheap, single-board computers running Linux. These controllers have already been tested in the lab, pointing the beamformers (not connected to tiles) as required to follow actual MWA observations in real time.

PPDs and metadata files

The MWA has been recording regularly spaced full-spectrum average powers, from every tile, since it started running. However, up until now, the spectral data (the 'PPDs') were only used for plots on the status pages, and the data were stored in an on-site SQL database difficult for researchers to access. New code running on-site now generates a FITS file containing these PPDs for every observation (plus more FITS files for the gaps between observations), and these FITS files are now part of archived MWA datasets at the Pawsey Centre. It is now straightforward for users to access these PPDs in order to find out if an observation is likely to have exceeded the dynamic range of the 5-bit output from the receiver The PPDs also make it easy for a user to spot radio frequency intereference that might be out of band for an individual observation, but still affect the overall data.

Engineering Highlights

CIRA engineering fieldwork

Dave Emrich
Luke Horsley

Trials of SKALA antenna base designs.

The CIRA engineering fieldwork team spent a lot of time on site at the Murchison Radio-Astronomy Observatory (MRO) during 2015. With many different activities and experiments in progress—including the Murchison Widefield Array (MWA), Bighorns, the Aperture Array Verification System (AAVS), the Engineering Development Array (EDA), and a cosmic ray detection experiment—the site program was very busy. The fieldwork team also supported a range of visitors to the MRO.

CIRA relies heavily on the expertise and support of local businesses and industry to effectively operate, maintain and expand its activities at the MRO. 2015 was no exception, with local people and companies making very significant contributions to CIRA's achievements at the MRO throughout the year.

In 2012 GCo Electrical was the prime contractor managing the six month site-works program for the construction of the MWA telescope. In 2015 GCo was asked to consult on the layout and deployment of two ~5.5 kilometre fibre cables, which will carry analogue radio frequency signals from four AAVS field nodes to the CSIRO Central Processing Facility These new field nodes will permit testing of up to 400 SKA Low-frequency Antennas (SKALA) and associated support infrastructure.

The preliminary design of the SKALA antenna proposed for SKA1_LOW includes a concrete base to provide stability in high winds. Geraldton based concrete component manufacturer GNC Concrete helped CIRA to understand the considerations and costs involved in the design, manufacture, handling, and transport of concrete components. A number of samples produced by GNC were deployed on the site to help CIRA engineers evaluate different approaches to the specification, design, and deployment of the antenna base.

Geraldton surveyors Hille Thompson & Delfos (HTD) set out several accurately surveyed control points, which will be the basis for setting out the AAVS field nodes and the locations of the MWA expansion tiles. HTD have been regular visitors to the MRO for many years, and their familiarity with the site is critical to the efficient installation and maintenance of the accurate reference points needed to support the location, and to set up our instrumentation in the field.

In 2015, Geraldton based company Central Earthmoving was contracted to undertake civil works for several Curtin projects planned for the MRO. The first activity was for the initial part of the MWA expansion – clearing space for two hexagonal arrays of new MWA tiles to be installed in the existing core area. Central Earthmoving also cleared the ground for the four new AAVS field nodes. Finally, they performed a short horizontal-boring activity, and they trenched approximately 80 metres to install sections of underground conduit that will protect short lengths of the 5.5 kilometre fibre cables. To ensure proper consideration, care, and respect are paid to the land and its indigenous heritage, CIRA consulted with the local indigenous community who recommended Indigenous Elders to be Heritage Monitors during these works. These Elders were on-site during all heavy earthmoving to identify any itmes of Aboriginal significance that may have been unearthed.

Site cleanup with Wajarri Holdings.

Ground clearing for AAVS field nodes.

Packing cast offs and other rubbish have been slowly accumulating on the MWA site since it was first constructed. In 2015, a local indigenous owned company, Wajarri Holdings, helped us to carry out a major clean up. Wajarri Holdings employs local indigenous people who are enthusiastic about helping us take good care of the MRO environment. Additionally, Central Earthmoving also engages Wajarri Holdings, to provide labourers and machine operators.

A number of local indigenous people are regulars at the MWA site employed through several companies. CSIRO manages the overall MRO site, and they employ several Pia Wajarri people as casuals who work on many different aspects of the site. As part of their work, some of these people helped us to assemble a new, independent, MWA-style tile that is being used as part of an experiment designed to detect the radio signature corresponding to cosmic ray events in the upper atmosphere.

In addition to supporting all of the above contracted works, the CIRA engineering team made significant progress in improving the availability and reliability of the MWA throughout 2015. On a field-trip early in the year, CIRA engineers replaced several of the Low Noise Amplifier (LNA) circuit boards housed in the MWA Dipole antenna hubs, after the signal quality coming from those antennas had degraded to an unacceptable level.

Laboratory diagnosis on the faulty boards revealed significant corrosion of the copper circuit board and metallic parts of the electronic components. This corrosion was traced to a highly acidic sludge (tests revealed a pH of 4) that forms after wind-blown dust settles on the circuit boards and later attracts moisture during humid weather. The LNA circuits were conformal-coated during manufacture, but the acidic conditions we discovered are outside the specifications for the coating. CIRA researched and applied an additional coating method to protect the boards. This information is critical for the designers of SKA_LOW field electronics, and it has been conveyed to the relevant Consortium partners for their consideration.

Previous years saw several days during the peak of summer when some of the MWA receivers were unable to maintain the required internal temperature to operate safely. Apart from the typically high ambient temperatures exceeding 45 degrees, receivers are normally fully exposed to direct sunlight, and to reflected heat from the ground. When added to the internally generated heat, these affects can raise the total internal heat load above the level that the integrated air-conditioners can manage.

Canvas receiver shading helps prevent loss of telescope operating time during summer

During 2015 we identified suitable canvas shelter structures. After a trial on one receiver, we opted to cover all 16 receivers to provide shading from direct sunlight and reflected ground heat. Early indications are that the shlters have prevented the loss of telescope operating time during the summer months toward the end of 2015.

About the authors

Dave Emrich has led the fieldwork program since early 2009. Luke Horsley joined the fieldwork team as a full-time staff member in 2015, after previously working as a student casual during the construction of the MWA.

Pia Wajarri people helped assemble a tile to detect cosmic rays.

Group photo of CIRA engineers.

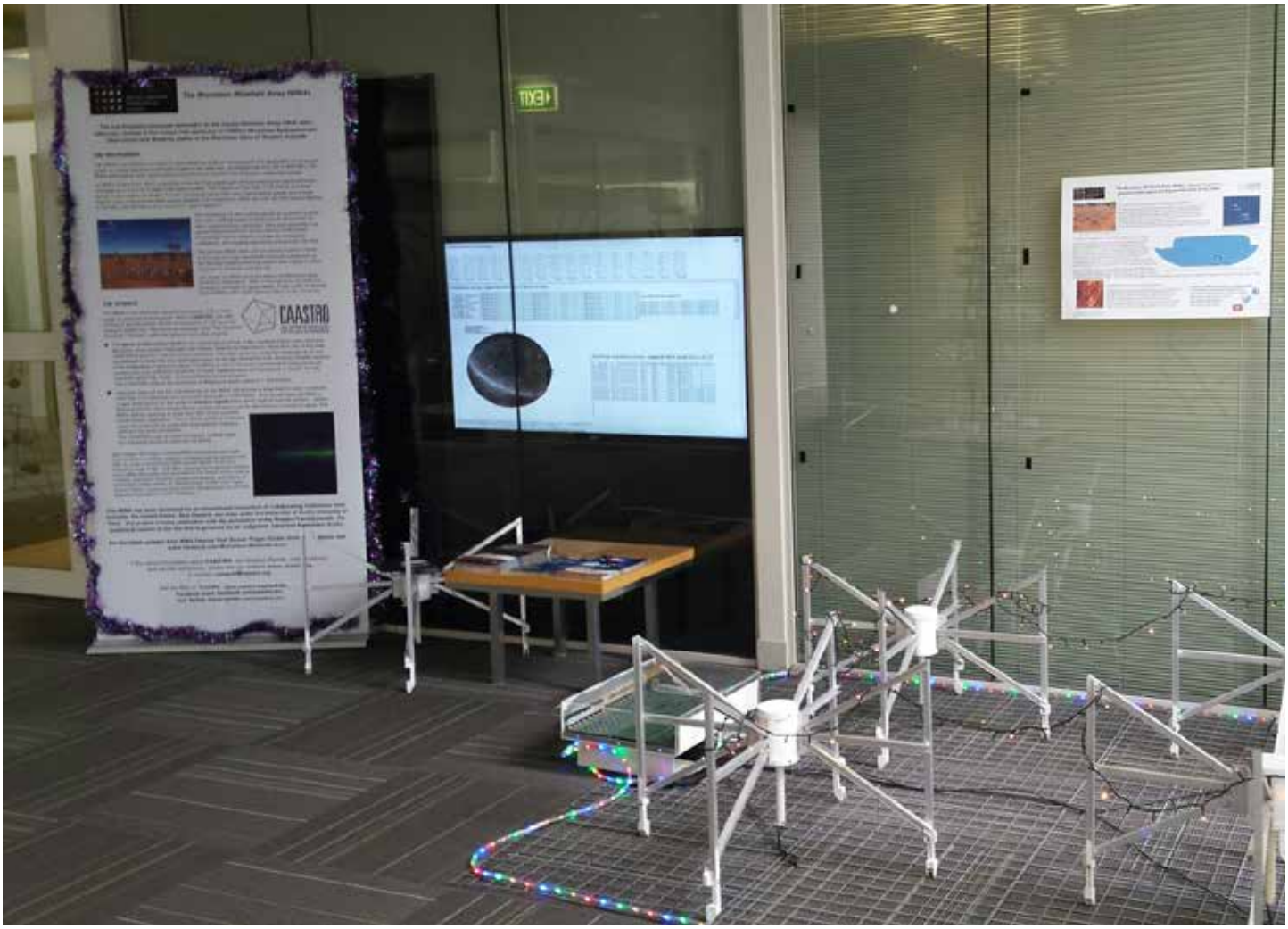


Image credit: Wiebke Ebeling

CIRA staff at the ICRAR annual retreat. Image credit: ICRAR

Scenes from the 2015 Astronomical Society of Australia Annual Scientific Meeting

Hosted by Curtin University

Drs. Andrew Williams and Cathryn Trott welcome attendees to Fremantle

Vice Chancellor Prof. Deborah Terry opens the meeting

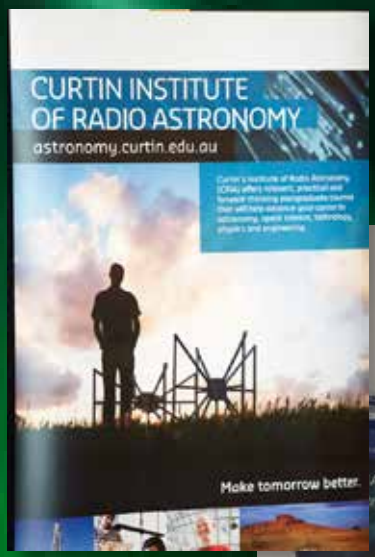


Image credits: ICRAR

Prof Elaine Sadler gives the Ellery lecture (U Sydney/CAASTRO).

Dr James Miller-Jones gives an invited talk on black hole accretion.

Dr Andrew Walsh in the audience.

Tea break between meeting sessions.

Group photograph of all attendees in Fremantle. Image credits: ICRAR

Teaching & Outreach

Image credit: Adrian Sutinjo

Teaching & Outreach Highlights

Teaching

John Morgan
Jean-Pierre Macquart &
James Miller-Jones

CIRA continues to play a major role in the delivery of undergraduate units into the Physics stream at all levels, in addition to supervision of undergraduate, Honours, Masters and PhD projects. Paul Hancock and John Morgan provide our undergraduate cohort with their first exposure to CIRA staff, teaching first year Physics and the ever-popular Astronomy 101 course, respectively.

Other core Physics units taught by CIRA staff include the second-year Statistical Mechanics and Thermodynamics taught by James Miller-Jones and Jean-Pierre Macquart, and the second-year Electromagnetism unit co-taught by Jean-Pierre Macquart. In addition to the core Physics units, CIRA takes full responsibility for the specialist units for the Astrophysics stream, many of which are also taken by students from the Mathematical Physics stream. The first of these to be taken by our undergraduates is James Miller-Jones's whistlestop tour of all basic astrophysics in his second-year, second-semester unit on the Physics of Stars and Galaxies. Roberto Soria and Ramesh Bhat then cover Relativistic Astrophysics and Cosmology in the first semester of the third year, and Nick Seymour introduces the students to basic radio astronomy in the second semester, with his unit, "Exploring the Radio Universe". Finally, several members of CIRA staff are responsible for modules of the fourth-year Honours course run jointly with UWA.

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

As in previous years, we ran our standard summer studentship program in 2015, aiming to engage with undergraduate students and expose 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 and weakly-accreting nuclear black holes. We also hosted an international student from Europe, funded for a three-month studentship by the Department of Physics and Astronomy to work on a sample of ultraluminous X-ray sources in the Virgo cluster. 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.

Undergarduate students during an engineering course. Image credit: Adrian Sutinjo

A group of CIRA undergraduate students.

CIRA students learning about wave interference and radio interferometry using the MWA. Image credit: James Campbell

Teaching & Outreach Highlights

CAASTRO education & outreach

Wiebke Ebeling

CIRA is one of seven Australian partner organisations in CAASTRO, the Centre of Excellence for All-sky Astrophysics of the Australian Research Council (2011-2018). In 2015, 18 CIRA members were part of CAASTRO – approximately 10% of its national and international membership – who contributed to CAASTRO research in "The Evolving Universe" and "The Dynamic Universe" themes. CIRA is also home to the CAASTRO Education & Outreach portfolio.

Working in close collaboration with CAASTRO members at CIRA and at other partner institutions, Education & Outreach Manager Dr. Wiebke Ebeling leads CAASTRO's public and school engagement efforts. The portfolio promotes science awareness through traditional media, such as press releases and face-to-face events, but also features a strong digital media component. The CAASTRO website, for example, is the primary conduit to highlight ongoing research and new results by way of short summary stories that cut through the technical language and make publications accessible for a non-expert audience. In 2015, 12 out of these 40 research stories related to CIRA first-author publications, which mirrors the high productivity of the CIRA team. The stories were further collated and printed into two 2015 editions of the "CAASTRO Reader's Digest" booklet, with distribution to science centres, amateur astronomy societies, and high schools Australia-wide.

Two new initiatives were started in 2015 to extend this program and appeal to younger audiences, both of which have CIRA as the driving force behind them. "Bright Stars" links recent research stories to the personal profiles of CAASTRO researchers and mentors high school students who are considering STEM disciplines in their career choice. CIRA has employed project intern and science communicator Jessica Scholle to work with Dr. Ebeling on this new initiative. The first twelve profiles are scheduled to be launched in April 2016, in collaboration with the "CAASTRO in the Classroom" seminar series (University of Sydney) and the "Telescopes in Schools" outreach program (University of Melbourne). Among these twelve researchers are one CIRA student and one CIRA postdoc. Communicating science research to even younger audiences, Dr. Ebeling – on behalf of Curtin – commissioned the production of a

children's story book to Perth-based author Cristy Burne and illustrator Aśka, under the guidance of a CAASTRO working group. The book is scheduled to be launched in March 2017. This will not only be an excellent legacy product of CAASTRO, but it will also be a valuable resource for CIRA, and Curtin more generally, for years to come.

The other major legacy product of the CAASTRO Education & Outreach portfolio – with the bulk of work completed in 2015 – is the new full-dome planetarium production that launches nationally on 21 March 2016. In partnership with Museum Victoria and under project management by Dr. Ebeling, this show has been produced over a two-year period to showcase Australian research efforts into Dark Energy and the Epoch of Reionisation. Stunning visuals of two next-generation telescopes, SkyMapper in New South Wales and the Murchison Widefield Array (MWA) here in Western Australia, are accompanied by narration by Academy Award winning actor, Australian of the Year in 2012, and self-confessed astronomy enthusiast Geoffrey Rush. CAASTRO gratefully acknowledges members of the MWA science and engineering teams at CIRA who assisted in the show production.

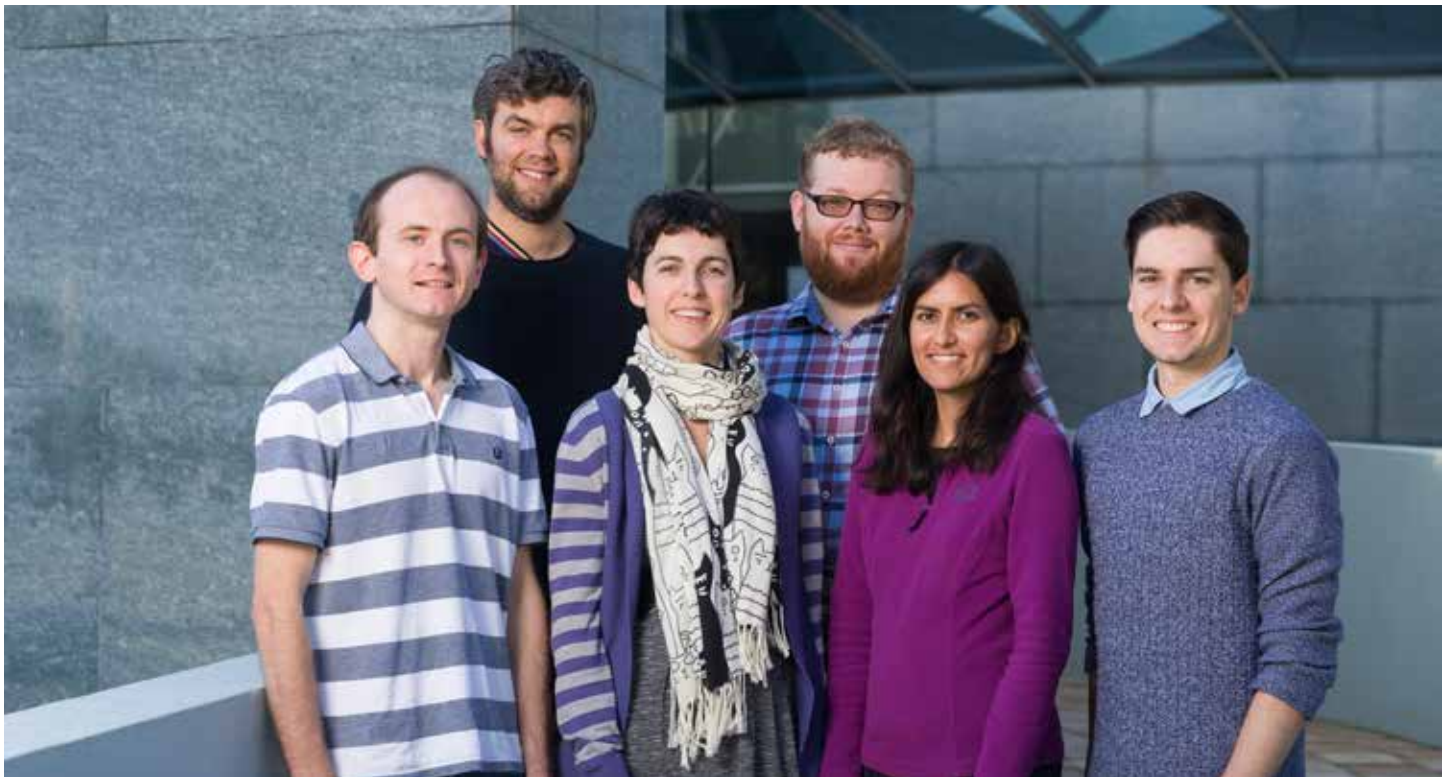
The spectacularly successful 2015 "Video Press Release" about tubular plasma structures in Earth's ionosphere. Credit: Wiebke Ebeling

Smaller scale, CIRA in-house video productions also proved very powerful and popular, in particular in conjunction with press releases, and 2015 saw the most successful CAASTRO "Video Press Release" yet. Filmed at CIRA and produced by Dr. Ebeling, the video "Cosmic cinema: astronomers make real-time, 3D movies of plasma tubes drifting overhead" attracted over one million views on Youtube within six weeks. The MWA featured as the centrepiece of both, this cutting-edge research and the explanatory video which made use of aerial drone footage that was obtained at the Murchison Radio-astronomy Observatory earlier in 2015.

This plethora of hands-off or digital media efforts in CAASTRO's Education & Outreach portfolio was counter-balanced by a number of hands-on science engagement activities. The CAASTRO information stall at the annual Perth Astrofest in March 2015, for instance, was staffed by CIRA members Samuel Oronsaye, Dr. Marcin Sokolowski and Dr. Steven Tremblay. As part of the outreach partnership with Voyages Indigenous Tourism Australia, Dr. Hancock was the "Astronomer in Residence" at Ayers Rock Resort in May/June 2015, and Prof. Steven Tingay and Dr. Wiebke Ebeling attended the "Uluṟu Astronomy Weekend" in August where they also hosted a special session on using the MWA for outreach purposes. Thanks to the help of the MWA engineering team at CIRA, CAASTRO was able to deploy three new "MWA tile displays" at Mount Burnett Observatory in Melbourne (January 2015), at RiAUS in Adelaide for an exhibition (April-June 2015), and at the Murchison Settlement for the Murchison Astrofest (September 2015).

In 2015, CIRA was once again a very accommodating host to the CAASTRO Executive (September 2015) and CAASTRO Advisory Board (November 2015) – the latter of which meetings was held shortly after Advisory Board Chair Dr. Alan Finkel had been appointed as the new Chief Scientist of Australia.

Interactive MWA demonstration for Dr Karl and guests of the "Uluru Astronomy Weekend" 2015. Image credit: Kate Gunn



Members of the MWA and GLEAM science groups. Left to right: Thomas Franzen, John Morgan, Natasha Hurley-Walker, Paul Hancock, Sarah White, Robin Cooke.

Members of the compact objects and accretion group. Left to right: Franz Kirsten, Ryan Urquhart, James Miller-Jones, Roberto Soria, Jean-Pierre Macquart, Vlad Tudor, Gemma Anderson, Richard Plotkin, Wayne Arcus..

Refereed Publications During 2015

Refereed Publications

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Theses

Thomas Russell, PhD thesis, "The connection between inflow and outflow in accreting stellar-mass black holes"

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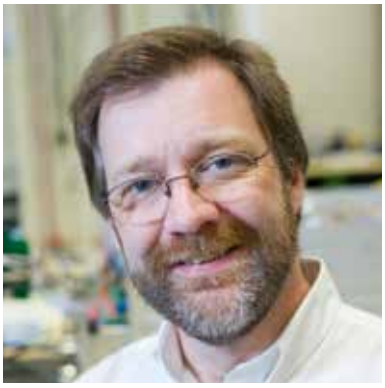

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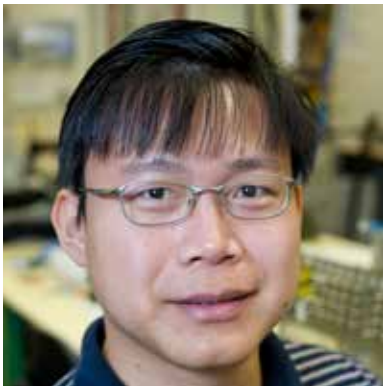

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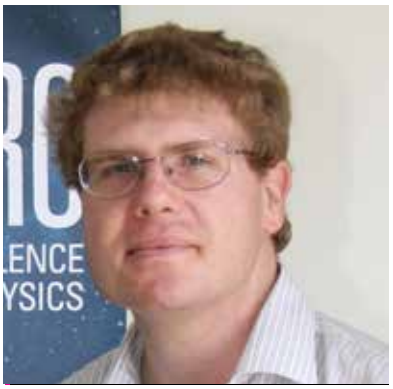

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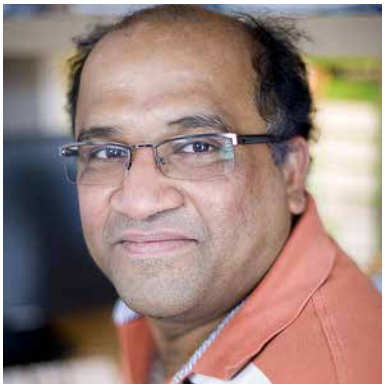

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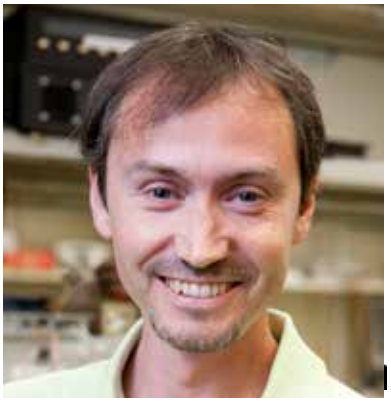

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Students

49. James Buchan
    PhD

50. Chittawan Choeysakul
    PhD

51. Samuel McSweeney
    Honours

52. Bradley Myers
    Honours

53. Rakesh Nath
    PhD (withdrawn August 2015)

54. Samuel Oronsay
    Masters

55. HaiHua Qiao
    PhD

56. Alfonso Rossi
    Masters (withdrawn July 2015)

57. Thomas Russell
    PhD

58. Balwinder Arora Singh
    PhD

59. Teresa Slaven-Blair
    Hons

60. Hongquan Su
    PhD

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Staff Profiles

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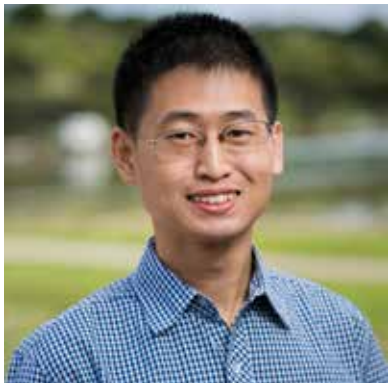

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Image Credits frames 49-50,53-55,57,58,60: ICRAR

Staff Profiles

61. Chenoa Tremblay
    Masters

62. Vlad Tudor
    PhD

63. Ryan Urquhart
    PhD

64. Mengyao Xue
    PhD

65. Qingzeng Yan
    PhD

66. Xiang Zhang
    PhD

Interns

67. Rene Baelmans

68. Robert Grootjans

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Staff Profiles

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