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The CIRA science program is focused heavily on radio astronomy, and closely aligned with several of the major projects planned for the Square Kilometre Array (SKA). In particular, our staff and students make extensive use of the Murchison Widefield Array (MWA), for which Curtin is the lead and managing organisation on behalf of a broad international consortium. Our close connection and daily interactions with the CIRA Engineering group enable our scientists to make the best use of the telescope, and to implement novel and innovative operating modes and experiments. To handle the large volumes of data flowing from both the MWA and the Australian Square Kilometre Array Pathfinder (ASKAP), our scientists make extensive use of the nearby Pawsey Supercomputing Centre, as well as other local and national high-performance computing facilities.

Our staff work across five primary science themes, as outlined below. These themes tie in directly to SKA science drivers and working groups, with our staff and students possessing the necessary observational, theoretical and computational expertise to enable high-impact results in these fields.

Five Primary Science Themes are as follows:

- Accretion, Jets and slow transients
- Epoch of Reionisation
- Extragalactic Radio Astronomy
- Pulsars and Fast Transients
- Stars & Stellar Evolution
Accretion, jets and slow transients

**Project Lead:** Prof James Miller-Jones

**Project members:** Dr Gemma Anderson, Dr Arash Bahramian, Dr Paul Hancock, Dr Adela Kawka

**Student Members:** Ms Pikky Atri, Mr Elliott Charlton, Mr Jaiverdhan Chauhan, Mr Brendan Hennessey, Mr Steve Prabu, Mr Alessandro Paduano, Mr Jun Tian

**SYNOPSIS:**

This project seeks to investigate some of the most extreme environments in the universe, using powerful, explosive events to probe physics under conditions of high energy, strong gravity, and/or strong magnetic fields. We use radio observations to determine how energy and matter is fed back into the surrounding environments during cataclysmic events such as the deaths of stars in supernovae or gamma ray bursts, the merging of two neutron stars, or the accretion of gas onto a supermassive black hole as it rips apart a passing star that wanders too close.

We also study similar processes in stellar-mass black holes accreting from a binary companion star in our own Milky Way galaxy, or in their less massive neutron star or white dwarf binary analogues. This allows us to determine how jets are launched in real time, and how the nature of the accreting source affects their properties.

For this project, we use observational data from right across the electromagnetic spectrum, and take advantage of the new insights provided by the recent advances in multi-messenger astrophysics, from gravitational waves to neutrinos.

Finally, we use the techniques developed to detect new transient and variable radio sources to track satellites and space debris in low-Earth orbit, as they reflect FM-band radio signals back down to Earth, which can then be detected by the MWA.

Explore the 12 Projects on offer that investigate the science behind Accretion, Jets and slow transients.
Black holes are among the most mysterious objects in the Universe. Stellar-mass black holes are formed from the deaths of the most massive stars in the Galaxy, sometimes via energetic supernovae. An unknown fraction of black holes in the Galaxy are born in binary star systems. The population and evolution of these binaries has been studied in theoretical models and simulations. However, probing them observationally is particularly challenging.

While identifying black holes in tight interacting binaries (in which the black hole accretes from the companion star) is generally feasible (through the signatures of energetic flow of matter interacting with the black hole), it is very difficult to identify and study them in non-interacting or weakly-interacting binaries (where the binary appears a single star in observations and the black hole is hidden with little or no electromagnetic signature). It is thought that many black holes may lurk undetected in such binaries.

Over the last few years, a handful of such “hidden” black holes in binaries have been discovered in new large observational surveys. This implies that many more such systems may be found with new high-precision astrometric surveys such as the one currently being conducted by ESA’s Gaia observatory, which will improve our understanding of the black hole population of our Galaxy.

In this project, we aim to study dynamical properties of black holes, using both new and ongoing large observational surveys of the sky, and more targeted observing programs. Particularly, we will use the ongoing Gaia survey (which has provided precise measurement of distance and motion for more than 1.2 billion stars for the first time, with more measurements underway; see Figure), and obtain new observations (e.g., using radio very long baseline interferometry) to achieve a deep observational characterization of black hole kinematics. Particularly, we will:

1- Develop tools and data models to mine and explore Gaia’s upcoming massive datasets to search for hidden black hole candidates and study known black holes in the light of new data.
2- Perform and analyze new observations (e.g., precise radio astrometry) to study new and known black holes and characterize their properties (like distance and mass).
3- Constrain the population of hidden black holes (in binaries) in our Galaxy, which will greatly influence our understanding of stellar evolution and black hole formation.

Left: Artist’s impression of a binary stellar system in which a black hole has trapped another star and feeds off the material from the star. Right: Top view of our Galaxy with distribution of stars for which the Gaia survey has so far estimated distance and proper motion.
Gamma-ray bursts (GRBs) are one of the most violent and energetic explosions observed in the Universe. They release energies of the order of $10^{53}$ - $10^{54}$ ergs in the intervals ranging from fraction of a second (short GRBs) up to several hundreds of seconds (long GRBs). They were serendipitously discovered during the Cold War era (specifically 1960s) by the VELA satellites monitoring the space for possible violations of nuclear ban treaty. Instead they discovered an entirely new astrophysical phenomena. Since then, several thousands of GRBs were discovered by a few generations of satellites dedicated to study these astrophysical processes (BeppoSAX, CGRO, HETE, Integral, Swift, Fermi and Polar). Their counterparts in optical, radio and other electromagnetic wavelengths have been observed including the recent observation of gravitational wave event GW170817 accompanied by a short (< 1 second) GRB 170817A. GRBs are truly one of the most fascinating astrophysical processes (Abbott at at, 2017).

They are expected to produce low-frequency radio afterglows which could potentially be observed months or even years after the GRB explosions (when the GRB ejecta collides with the interstellar medium surrounding the progenitor). However, so far there has been no observational evidence of these predictions. This project aims in establishing existence or non-existence of GRB afterglows within the limitations of the Murchison Widefield Array (MWA; Tingay et al 2013) sensitivity. The main goal is to take advantage of large data archive from the MWA and the corresponding calibration database and search for low radio-frequency counterparts of the known, archive GRBs which can be found in the databases of the several satellite missions detecting GRBs. The idea is to analyse as many GRBs as possible, which have multiple MWA observations over the span of several years.

The potential positive detection of the first low radio-frequency afterglows of GRB would be a very important discovery. Alternatively, if there are no positive detections the upper limits can be derived, which given the known estimates of GRB energies and other characteristics, can lead to conclusions on the surroundings of the GRB progenitors (possible way to extend to a PhD project).
Monitoring low-frequency radio sky for transients

Although low-frequency (<400 MHz) radio sky is not reported to be highly variable in terms of transient objects, there have been increasing number of transients detections by new low-frequency instruments. Sensitivities of the existing instruments are not sufficient to detect all (or at least many) of the low-frequency counterparts of transients detected at higher electromagnetic energies (up to gamma-rays). However, there have been several recently reported low-frequency transient detections. Such as for example detection of the outburst of the black hole candidate X-ray binary MAXI J1348-630 at 154 MHz and 216 MHz with the Murchison Widefield Array (MWA; Tingay et al. 2013) by J. Chauhan et al (2019) or detection of a very bright transient (> 800 Jy) of unknown nature by the Long Wavelength Array (Varghese, S. et al. 2019). Hence, although the abundance of low-frequency radio transients is small there are events (including some of unknown nature) which can be observed at low radio-frequencies.

This project aims to develop tools for automatic identification of transients in the MWA data. Over the last two years many observations of calibrator sources were reduced, calibrated and imaged in order to develop a database of calibration solutions for the MWA, specifically for the All-Sky Virtual Observatory (ASVO). Hence, there is a large set of images of the calibrator fields which could be analysed in search for transients as a first and minimal step of the project.

The project can be extended further to enable near-real time reduction, imaging and transient search of MWA observations collected daily by the telescope (for instance create a few images per each observed field), which can also be easily imaged using the earlier mentioned calibration database (daily updated with new calibration solutions). Finally, the next extension would be to perform all-sky scans with the MWA every few months in order to monitor sky variability on a few-month timescale (pilot observations have been collected and a new proposal for future observations is being prepared). All these efforts will aim towards a real or near-real time transient detection system for the upcoming low-frequency component of the Square Kilometre Array (SKA-Low) including all-sky images from the precursor stations (AAVS2 or EDA2).
The release of gravitational energy as mass is suddenly dumped onto a black hole powers some of the most explosive phenomena in the Universe. This is the most extreme example of a universal process called accretion, which is responsible for the growth of all astrophysical systems, from stars to galaxies. In this project, the student will seek to understand how black holes transform the material they consume into powerful outflows, and quantify how much energy these jets can carry away. You will study the most powerful black holes to probe how this process works at its most extreme limit known as the Eddington limit, investigating short-lived, explosive events to unveil how the process proceeds in real time. These include stellar-mass black holes rapidly consuming material torn off a binary companion star, known as transient ultraluminous X-ray sources (ULXs), and supermassive black holes tearing apart unlucky stars that wander too close, known as tidal disruption events (TDEs).

The new X-ray telescope eROSITA was launched in 2019, and is conducting sensitive surveys of the X-ray sky. These are projected to discover large numbers of transient ultraluminous X-ray sources and tidal disruption events. The PhD student will join an international team following up newly-detected explosive events detected by eROSITA. They will be expected to perform and analyse follow-up radio and optical observations of these rapidly-evolving systems, using facilities such as the Australia Telescope Compact Array (ATCA), the South African Square Kilometre Array (SKA) pathfinder telescope MeerKAT, and the SKA low frequency precursor the Murchison Widefield Array (MWA; based in Western Australia). Such observations will probe the powerful jets that are launched by these rapidly accreting black holes, exploring of the connection between the infalling matter and the launching of jets in some of the most extreme environments known in the Universe.

**Research Field**

Accretion and slow transients

**Project Suitability**

PhD, Masters, Honours

**Project Supervisor**

Dr Gemma Anderson
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**Co-Supervisors**

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Radio transients in the Galactic Plane: Exploring the low-frequency properties of X-ray binaries with the MWA

The process of accretion, whereby matter falls onto a compact object such as a black hole, is responsible for powering the most energetic phenomena in our Universe. The energetic radiation and powerful jets liberated by accretion onto supermassive black holes at the centres of radio galaxies are responsible for triggering or shutting off star formation, regulating the evolution of their host galaxies, and possibly even reionising the Universe. However, due to the long timescales on which such systems evolve, we cannot investigate how these processes of accretion, ejection and feedback proceed in individual supermassive black holes.

Since processes close to a black hole are governed by strong gravity, the physics should be very similar regardless of the black hole mass. We can therefore gain important insights into the physics of accretion and jet production by studying smaller black holes and neutron stars in our own Galaxy, with masses just a few times that of the Sun. If these stellar-mass compact objects accrete matter from a less-evolved donor star, the accreted mass builds up in a disc surrounding the central object until instabilities cause that mass to fall inwards, liberating gravitational energy, which powers a bright outburst in which the system increases in luminosity by several orders of magnitude, right across the electromagnetic spectrum. These outbursts lead to the ejection of powerful jets that can be studied at radio frequencies.

The Murchison Widefield Array (MWA) is a new, low-frequency radio telescope in Western Australia, which is operated by Curtin University as one of the precursor facilities to the Square Kilometre Array (SKA). The wide fields of view provided by the MWA enable us to efficiently survey the entire visible Galactic Plane and Galactic Bulge, where the majority of black hole and neutron star systems are located. The sensitivity of the MWA will allow us to detect outbursts of black hole or neutron star X-ray binaries anywhere in this region, determining how much kinetic energy is channelled into the jets in these outbursts, and allowing us to quantify their feedback effect on the surrounding environment. Over the past three years we have conducted fortnightly monitoring of the visible Galactic Plane and Bulge regions, and have been developing the software pipelines required to analyse the data in this technically challenging region of the sky.

In this project, you will use this Galactic Plane monitoring data to investigate the outbursts of known X-ray binary systems and search for new Galactic radio transients. You will use a newly developed technique to perform image subtraction to search for transients, therefore refining existing pipelines and implementing them on the powerful facilities available at the nearby Pawsey supercomputing centre. You will also test new techniques for transient detection, helping to inform the observing strategies for more sensitive monitoring campaigns with both the newly-upgraded MWA, and eventually the SKA.

Mosaicked MWA image of a section of the Galactic Plane, made at three different frequencies. The Galactic Centre is on the right, and the Plane is filled with supernova remnants. Image credit: David Kaplan and Steve Croft.
Some of the smallest stars in our Galaxy, with masses as low as one tenth of our Sun, can produce flares that are ten thousand times more powerful than the solar flares we see on the Sun. These “superflares” are extreme examples of stellar magnetic activity, and impact the atmospheres, habitability, and formation of the surrounding planets, motivating our desire to understand the emission mechanisms that produce these events. The most magnetically active stars produce powerful X-ray/gamma-ray (high-energy) superflares that are detected by telescope (satellites) such as Swift and MAXI. These space missions then send immediate alerts to a network on the ground, allowing telescopes such as the Murchison Widefield Array (MWA) to rapidly begin observing the event.

The MWA is a low frequency (80-300 MHz) radio telescope operating in Western Australia and the only operational Square Kilometre Array (SKA)-Low precursor telescope. The MWA is an entirely electronically steered instrument, meaning that it can ‘slew’ to any part of the sky nearly instantaneously. The MWA also has an extremely large field of view. The large field of view and fast slew time means that the MWA is uniquely placed to provide the fastest follow-up radio observations of transient (explosive or outbursting) events, including flare stars.

The MWA has been automatically responding to high-energy stellar superflares detected by Swift and MAXI, obtaining 30 minutes of observations following each outburst. If the candidate is interested in pursuing a PhD, they will also have the opportunity to process similar rapid-response data taken at higher radio frequencies with the Australia Telescope Compact Array (ATCA), allowing for a direct comparison of such flares at both high and low radio frequencies.

Using these triggered radio observations, you will investigate whether the same magnetic event that produces bright high-energy superflares can also produce low frequency radio flares, which will aid in providing a more unified understanding of plasma physics in these stellar systems. This project will therefore test transient strategies for the Square Kilometre Array by demonstrating the importance of radio telescopes having a rapid-response capability for fast transient follow-up.

### Research Field
Radio Astronomy

### Project Suitability
- PhD
- Honours, 3rd year

### Project Supervisor
- Dr Gemma Anderson
  - Gemma.anderson@curtin.edu.au

### Co-Supervisors
- Dr Paul Hancock

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**Artist's impression of bright flaring activity from a magnetically active flare star**

IMAGE: NRAO/AUI/NSF; DANA BERRY / SKYWORKS
Rapid response to external transient alerts with the Engineering Development Array

In the era of automatic observatories operated by computers, rapid response to transient alerts has become a routine observing mode of many telescopes. There are several transients distribution network, such as for example The Gamma-ray Coordinates Network (GCN) or VOEvents, providing alerts about transient events shortly (within seconds) after their discovery. For instance, very recently several high impact gamma-ray events have been reported from Soft Gamma Repeater (SGR 1935+2154) which were also immediately followed-up by radio telescopes and detected as a fast radio-bursts (FRBs). Moreover, FRBs have recently been observed even down to 328 MHz (Pilia, M. et al (2020)), but they are yet to be detected at frequencies below 300 MHz.

The Engineering Development Array 2 (EDA2; Wayth et al in preparation) is a precursor station of the low-frequency component of the Square Kilometre Array (SKA-Low), which will be built at the Murchison Radio-astronomy Observatory in Western Australia in the next decade. The EDA2 is composed of 256 MWA dipoles with analogue signals from each individual antenna digitised enabling nearly immediate re-pointing of the array beam in a specified direction in the sky. The main goal of this project is to develop automatic triggering system for the EDA2 and use it to automatically trigger EDA2 observations by alerts from external instruments. The triggering system will only react to alerts with sufficiently precise localisations (of the order of a few degree beam size of the EDA2). We anticipate that several events (such as Gamma Ray-Bursts, outburts from SGRs or FRBs) will be triggered during the timeline of the project leading to either positive detections or upper limits on the flux densities of their low radio-frequency counterparts - both extremely interesting from a scientific perspective.
Real-time radio imaging of black hole jets

Accreting black holes are known to launch powerful, relativistic jets that move away from the black hole at close to the speed of light. These jets provide a key source of feedback of energy and momentum to the surrounding environment. When a black hole is feeding sedately the jets are fairly steady, but when it accretes at higher rates the jets become more powerful but episodic, appearing as individual clouds of radio emission moving away from the black hole.

Using the technique of very long baseline interferometry (VLBI) we can zoom in on these powerful jets, tracking their motion in real time as they move outwards. This technique involves combining the signals from multiple different telescopes separated by thousands of kilometres, and assembling an image from the combined data. This is the same technique recently used by the Event Horizon Telescope (EHT) Consortium to take the first image of a black hole shadow, and can provide sufficient resolution for an observer in Perth to make out a coin located in Sydney.

At such high resolutions, the jets from nearby stellar-mass black holes can move significantly over the course of an observation, as well as brightening or fading. This violates the fundamental assumptions that go into imaging radio astronomical data (which assume a source that is constant over the timescale of the observation), and therefore requires new approaches. In one recent case, we split a four-hour observation up into two-minute chunks to observe the jets evolving in real time (as shown in the Figure). While this highly manual approach yielded new insights into the dynamics of the black hole jets, new imaging algorithms have recently been developed by the EHT team that could both automate the process and use all available information to get a more complete view of the jets.

In this project, you will investigate the application of some of these new imaging algorithms to VLBI data on black hole X-ray binaries, aiming to provide higher-fidelity imaging of time-variable structures. This will allow you to extract new science from existing data sets, probing how jets evolve and propagate in real time. In cases where we can couple the time-variable jet behaviour to the changes observed in the inflowing gas around the black hole (as seen in the X-rays), we can aim to probe the universal link between accretion and ejection phenomena around black holes.

A montage of images showing the evolution of the radio jets in a stellar-mass black hole X-ray binary system, over a period of just 20 minutes. In this project, you will investigate the performance of new imaging algorithms for making high-fidelity images of moving and evolving jets.
Relativistic jets from feeding black holes

The release of gravitational potential energy as matter falls onto a compact object such as a black hole powers the most energetic phenomena in the Universe, allowing us to study higher energies and stronger gravitational fields than could ever be reproduced in a laboratory here on Earth.

As matter falls in towards a black hole, some fraction of the infalling material can be diverted outwards in powerful oppositely directed jets moving at close to the speed of light, and carrying away large amounts of the gravitational energy released, and depositing it into the surrounding environment. The jets from the most massive, rapidly-feeding black holes, known as quasars, can affect the evolution of their host galaxies, and even the galaxy clusters in which they reside. However, such massive systems evolve slowly, making it difficult to study the physics linking the launching of powerful jets and the inflow of gas in the accretion flow that feeds them.

Happily, smaller, stellar-mass black holes in our own Milky Way galaxy are governed by similar physics, but evolve on much faster timescales (days and weeks rather than millennia). These ‘quasars for the impatient’ act as excellent probes of the physics governing the link between accretion and outflow around black holes. We can study explosive outbursts of these systems as they evolve in real time, providing new insights into their radiative and kinetic feedback that, when extended to the supermassive black holes in quasars, can have an impact on cosmological scales.

In this project, you will work as part of a large international team conducting multi-wavelength observational studies of the explosive outbursts of stellar-mass black holes in X-ray binary systems, aiming to understand how these powerful events evolve, and in particular the connection between the changing conditions in the inflow and the launching of relativistic jets. You will use leading radio telescopes in Australia and around the world (including SKA pathfinder and precursor facilities) to study the jets launched by these stellar-mass black holes, aiming to determine how they are launched, and how they carry energy outwards into the surroundings.

Left: A schematic of a black hole accreting matter from a donor star via an accretion disk. Relativistic jets (shown in blue, as observed in right panel) are launched from the inner regions of the accretion flow.
Searching for radio transients at low radio-frequencies (50 - 350 MHz) using the Engineering Development Array 2

The low-frequency (<400 MHz) radio sky is not reported to be highly variable in terms of transient objects. However, these makes any potential detections at these frequencies highly valuable from a scientific perspective. The number of astrophysical transients of unknown origin detected at low radio-frequency is increasing with the increasing sensitivity and number of the instruments operating the these frequencies.

There have been several recently reported low-frequency transient detections, such as for example detection of a very bright transient (> 800 Jy) of unknown nature by the Long Wavelength Array (Varghese, S. et al (2019)) or detection of radio emission associated with Soft Gamma Repeater (SGR 1935+2154). Moreover, fast radio-bursts (FRBs) have been observed even down to 328 MHz (Pilia, M. et al (2020)), but they are yet to be observed below 300 MHz.

The Engineering Development Array 2 (EDA2; Wayth et al in preparation) is a precursor station of the low-frequency component of the Square Kilometre Array (SKA-Low), which will be built at the Murchison Radio-astronomy Observatory in the next decade. The EDA2 consists of 256 MWA dipoles with analogue signals from each antenna individually digitised, which enables formation of all-sky images at frequencies between 50 and 350 MHz. Instantaneous all-sky imaging is a very attractive feature of low-frequency radio-telescopes which is not available at higher radio-frequencies.

Many long observations (exceeding 24 hours) have already been conducted with the EDA2, but the data are still to be fully analysed. The goal of this project is to analyse already collected data in search for radio-transients and other forms variability of astrophysical origin. The project will also gravitate towards development of the real-time all-sky monitoring system for the EDA2 and SKA-Low stations in general. As the project progresses new data can be collected with the transient monitoring running in real-time. Therefore, development of automatic classification of detected candidates will be a significant component of this project.
Tracking Space Junk using Smart Phones: Citizen Science Eyes on the Sky

Using low light imaging apps on smart phones, very wide field of view images can capture satellites and space junk as they orbit the Earth. As the images are accurately time stamped and geo-tagged, they can be used to determine and update the orbits of the objects. This is a very important task for Space Domain Awareness (SDA) – figuring out where everything is and where it is going, to predict and avoid collisions (think the movie Gravity with George Clooney and Sandra Bullock).

If a large number of people with smart phones image the same object from different locations, an accurate orbit can be determined from the database of observations. Thus, this can be rolled out as a very simple Citizen Science project in order to gather a lot of data and get a lot of people interested in space junk and science in general.

The resulting data and orbit determinations will be uploaded to a national database for SDA (a so-called DataLake) and would be used alongside data from other SDA sensors around Australia and around the world.

Aims of project:

(i) Using python code, develop the software to process the images captured using smart phones, detect the satellites (prototype software has already been developed), and use those data to determine the orbits of the objects;

(ii) Develop a website that allows Citizen Scientists to upload their smart phone images, with the software developed on the back end processing those images. The website would provide feedback to people who have submitted images;

(iii) Develop an interface to the Australian national DataLake for SDA, so that the processed images and orbit determinations can be utilised as part of a multi-sensor national database;

(iv) Publish a series of papers on the software, the observations and data processing, and the orbit determination results;

(v) Present results at international Space Science and Education and Outreach conferences.

This image was taken with an iPhone 6+ and was processed to detect the satellite (a Falcon 9 upper stage rocket body, in this case). Left image is the full field of view of the camera (the satellite track is shown as a small red box and blue points). Right image is a zoom in of that box, showing the detected satellite track in detail, along with its predicted location (red dots) and a trajectory fitted to the observations (green dots).
Epoch of reionisation

Project lead: A/Prof Cathryn Trott
Project members: A/Prof Randall Wayth, Dr Chris Jordan, Dr Ben McKinley, Dr Christene Lynch, Dr Jack Line, Teresa Slaven-Blair.

Students: Ronniy Joseph, Bella Nasirudin, Michael Kriele, Shih Ching Fu, Kariuki Chege, Jishnu Nambissan Thekkeppatu, Lauren Springer, Jaiden Cook

The Epoch of Reionisation (EoR) project aims to untangle the evolution of the universe during its first billion years. This will be achieved through observations of the redshifted hydrogen line signal, emitted by the neutral hydrogen gas that was present in abundance during this epoch.

Structural features of the formation of the first ionising sources during the EoR are traced by the neutral hydrogen gas signal. The spatial and temperature distribution of the hydrogen line observations allows us to probe this evolution, and explore the growth of structure during the cosmic dawn.

Radio telescopes such as the Murchison Widefield Array (MWA) and future Square Kilometre Array (SKA) located in Western Australia will play a key role in detecting this hydrogen line signal and understanding the mysteries of the early universe.
Are polarised variable sources important as a foreground to the Epoch of Reionisation?

The formation of the first luminous sources and their subsequent reionisation of the intergalactic medium, called the Epoch of Reionisation (EoR), was a pivotal period in the history of the Universe. The most promising method to observe the EoR is via tomography of the redshifted 21 cm line of neutral hydrogen. Due to the expansion of the Universe, 21 cm emission from the EoR redshifts to radio frequencies between 100 – 200 MHz. Detecting this cosmic signal is a goal for current and next-generation low-frequency radio telescopes, including the Murchison Widefield Array (MWA).

A significant challenge to radio EoR experiments is identifying and removing foreground emission produced by a variety of astronomical sources. Most egregious is the instrumental coupling between polarised and total intensity radio emission, commonly referred to as 'leakage'. This coupling can produce emission structures that have similar characteristics as the EoR signal. Because the level of polarisation leakage is expected to be below the instrumental and sky noise, it is challenging to identify (see Figure 1). This makes it one of the least explored effects that could potentially contaminant the EoR.

In particular, the intrinsic spectral structure of variable polarised sources could contaminate the EoR signal via leakage. Rowlinson et al. (2016) conducted a blind search for total intensity variable sources using the MWA, revealing no new low-frequency variable sources. However, Lynch et al. (2017a, 2017b) showed that much greater sensitivities could be achieved with the MWA using polarised images, detecting polarised variable sources below the sensitivity of total intensity MWA imaging. The results of this work suggest that there may be weak, polarised transients that would not have been detected by Rowlinson et al. (2016). It is currently unknown if these polarised sources contribute significantly to the polarised foreground for the EoR.

The goal of this project is to constrain the importance of polarised transient sources as a foreground to the EoR. The proposed project will involve developing models for different types of variable sources to characterise them as foreground sources as well as processing and analysis of large observational datasets from the MWA to measure the occurrence of polarised variable sources.

**Figure 1:** Foreground components must be removed one at a time to detect the EoR signal. First bright extragalactic point sources will be removed using most recent sky-models. Next total intensity Galactic emission will be removed using its spectral smoothness. Removing polarization leakage will come at the very end.
CMB spectral distortion at low radio frequencies – radio background, first stars, galaxies and the sources of first light!!!!

The Cosmic Microwave Background (CMB) i.e. the relic radiation from the Big Bang is the oldest electromagnetic radiation in the Universe. CMB has been precisely measured by the COBE/FIRAS instrument between 30-600 GHz and it is shown to be a thermal blackbody at a 2.725K. Since then, various ground, space-based and balloon-borne experiments measured the CMB temperature covering the frequency range of 0.4 to 600GHz. At frequencies lower than 400 MHz the CMB temperature measurement is increasingly difficult due to instrumental complexity and galactic and extragalactic radiation that are at least 3 orders of magnitude brighter than the CMB. However, at these frequencies, in the absolute temperature spectrum of the CMB, hidden is the answer to one of the most important question of the cosmology: how and when did the first sources of light come to exist.

Below 200 MHz, the CMB is expected to deviate from its blackbody temperature of 2.725K and exhibit a specific spectral signature that resulted from the interaction between the CMB photons with the primordial neutral hydrogen at very early times, even before the first sources of light began to form. This is known as the redshifted 21cm signal, detection of which is one of the biggest challenges of present-day cosmology. When detected, it will provide a information about the early Universe, structure formation, nature of the first sources and evolution history of the Universe. Detection of the 21cm signal is identified as the science priority in various decadal surveys. Over a dozen experiments attempted to detect the redshifted 21cm signal using the single element radio telescope over past decade with only two producing any data of scientific significance.

This project will make a precision all-sky radio background measurement between 30-150MHz to detect the redshifted 21cm spectral signature in the CMB. It is a unique opportunity to build and deploy a second generation, single element radio telescope leveraging a vast number of recent developments in instrument design and data analysis. Resulting publications will be in the field of engineering, science and computation. It is particularly suitable for someone with an inclination to experimental radio astronomy, especially with a solid background in Electrical/ Telecommunication/Computer Science Engineering, Experimental Physics/Astrophysics. A good organizational skill, mathematical aptitude and some programming expertise in any language is desired.

The proposed project is a continuation of this work.

The CMB blackbody temperature measured by various experiments at discrete frequencies. Between 20-200 MHz, the CMB temperature is expected to deviate from its blackbody temperature of 2.725K and take certain spectral shape known as the 21cm signal. This spectral shape depends on the evolution history of the Universe. A representative form of such deviation is shown in this figure.

The CMB blackbody temperature measured by various experiments – a precursor to the proposed work located at the Gouribidanur radio observatory, India: a single element radio telescope purpose developed to detect the redshifted 21cm signal by precision radio background measurements. Left: HYPERION – an interferometer designed and developed at the UC Berkeley and initially deployed at the Caltech’s Owen’s Valley Radio Observatory to detect the redshifted 21cm signal by precision radio background measurements. The proposed project is a continuation of this work.
Constraining the continuum background of extragalactic origin by precision radio background measurements.

Experiments that aim to detect the redshifted 21cm signal do so by making precision radio background measurements at low frequencies. These measurements also produce a volume of information on all-sky averaged galactic and extragalactic radio continuum which is yet not studied in detail. A purported detection of the redshifted 21cm signal in 2018 stirred in a controversy on whether there exist an excess radio background of extragalactic origin. This project will develop a method and corresponding algorithm to separate the isotropic and anisotropic components in the all-sky radio background data. The isotropic part, being of extragalactic origin, can provide an upper limit on the volume averaged emissivity of the extragalactic radio source population. This will be compared with the currently available radio source-counts from various radio surveys and estimates from the diffused all-sky maps and will address the question whether there exists an excess extragalactic isotropic radio background. The work would involve generating simulated dataset for testing the method as well as real data from earlier observations.

Following the development of the foreground separation method, we would study the effect of foreground modelling on the detectability of the redshifted 21cm global signal. As a result of foreground separation, a part of the 21cm signal is always lost. Such signal loss will not only reduce the chances of a 21cm detection but also can render a false detection and/or distorted cosmic history. We will investigate the possibility of detecting the redshifted 21cm global signal in the presence of signal loss due to radio background modelling. This project also has the potential to be converted into a Ph.D thesis.

This project is most suitable as a Master’s thesis with a solid background in Computer/Data Science, Telecommunication engineering, physics and astrophysics, maths. A good coding efficiency in any language, (preferably in python and/or in C) is needed. A part of this work may also be offered as a 6 month’s project for domestic or international students who wish to work as interns provided the student can make funding arrangements for themselves.

Left: A simulated data set showing the radio continuum background measured by a single element radio telescope over 24 hours. Right: The isotropic component isolated from the radio background data using the initial algorithm which will be developed further as a part of this project.
EoR foreground mitigation with the CRAM

Bright radio galaxies near to the horizon imprint contaminating structure in datasets for the Epoch of Reionisation experiment with the Murchison Widefield Array (MWA). The EoR experiment aims to measure fluctuations in the neutral hydrogen brightness temperature from the first billion years of the Universe. This exceptionally weak signal is masked by foreground radio galaxies and Milky Way Galaxy, which are orders of magnitude brighter.

The CRAM-tile (Central Redundant Array Mega-tile) is a new large MWA tile (8x8 dipoles) that sits within the centre of one of the redundant sub-arrays of the MWA (4x4 dipoles). Its size means that it measures the sky with a smaller primary beam size compared with the normal MWA tiles. This project will use data from the CRAM to help develop foreground removal techniques for the MWA EoR program, using simultaneous data acquisition on redundant MWA-MWA and MWA-CRAM baselines.

Aims of project (dependent on length of program)

(i) Characterise the CRAM tile primary beam response
(ii) Compare observations from redundant MWA-MWA and MWA-CRAM baselines
(iii) design and test methods for using the datasets to remove contaminating signal from the MWA EoR data.

This project can be tailored for single year (Honours) to three-year (PhD) programs, and would suit a student with interest in signal processing, data analysis and computing.

CRAM tile, installed in 2018-2019 at the Murchison Radio-astronomy Observatory (credit: A. McPhail)
Little is known observationally about the period in the early Universe between when the first stars formed and when the Universe was completely ionised by radiation from stars, galaxies and active black holes. Our group here at the Curtin Institute for Radio Astronomy is attempting to learn about this epoch by observing the 21-cm radiation emitted by neutral hydrogen, which has been redshifted by the expansion of the Universe to metre wavelengths. To achieve this, we use the Murchison Widefield Array (MWA) telescope - an interferometer consisting of 256 antenna tiles, tuned to low radio frequencies (including both the FM radio and digital TV bands), situated in the West Australian outback, about 800 km north-east of Perth.

In this project, we aim to measure the all-sky signal from neutral hydrogen, using the Moon as a thermal reference source. This is a novel technique that relies on imaging the Moon with the MWA across a wide band from 70 to 230 MHz. The thermal radiation from the Moon, however, is corrupted by reflections from radio transmitters on Earth and emission from relativistic electrons in our own Galaxy. Couple this with the fact that different radio wavelengths penetrate to different depths in the lunar regolith, and you have a very challenging experiment.

Depending upon the interests and skills of the student, the project could be tailored to include: interferometric calibration and imaging, computer modelling of reflected terrestrial transmissions (earthshine), separation of earthshine from the Moon's thermal emission, modelling and removal of Galactic foregrounds and extraction of the faint cosmological signal from multiple epochs of observations. There are a lot of data already collected and waiting to be processed, offering a great opportunity to learn how to do exciting science with a low-frequency radio interferometer.
Observing Cosmic Dawn with a closely-spaced radio array

The redshifted 21-cm signal from neutral hydrogen is the most promising opportunity to directly observe the Universe’s first billion years of evolution. The faint signal should be detectable at low radio frequencies (50 - 300 MHz), however, it is obscured by bright foregrounds sources and requires extreme precision in instrumental calibration. The EDGES experiment (Bowman et. al., 2018) has made the first claimed detection of the signal, and many experiments are attempting to verify their unexpected results. Most of these ‘global signal’ experiments make use of single dipole or monopole antennas, which can be prone to systematic effects that could cause a false detection.

In general, radio interferometers measure angular fluctuations in the sky brightness and are largely insensitive to the global average. However, interferometers with very short baselines (less than a wavelength) do have a significant global-signal response. While interferometers are not immune to effects that may corrupt measurements of the redshifted 21-cm signal, the systematics involved are quite different from single-dipole experiments and they therefore offer an independent means to verify the EDGES signal.

The Engineering Development Array - 2 (EDA-2) is a prototype instrument located at the future site of the Square Kilometre Array - Low (SKA-Low), which consists of 256 Murchison Widefield Array dipoles arranged in the proposed SKA-Low station layout. These antennas are packed tightly together in a roughly circular area with a diameter of just 35 m. This short spacing between antennas makes the EDA-2 an ideal test-bed instrument for observing a global redshifted 21-cm signal. In this project you will have the opportunity to analyse data from the EDA-2 and develop new calibration and observing strategies. You will also run simulations to test and verify methods for extracting the faint 21-cm signal from behind the veil of bright foreground emission from our own Galaxy. This is a great opportunity to join a growing team working on a common goal with far reaching implications for observational cosmology.
Extragalactic Radio Astronomy

**Project lead:** Dr Nick Seymour  
**Project members:** Prof Melanie Johnston-Hollitt, Dr Jess Broderick, Dr Guillaume Drouart, Dr Natasha Hurley-Walker, Dr John Morgan, Dr Amanda Wilber

**Student members:** Mr Stefan Duchesne, Mr Torrance Hodgson, Mr Ben Quici, Ms Kathryn Ross

This project seeks to leverage the wide field of view, broad frequency coverage, and excellent surface brightness sensitivity of the MWA to explore radio-emitting sources in the distant universe. It leverages state-of-the-art low-frequency radio sky surveys such as GLEAM (the GaLactic and Extragalactic All-sky MWA survey) and its ongoing higher angular resolution counterpart, GLEAM-X, together with supporting multi-wavelength data, to study some of the largest structures in the universe, such as giant radio galaxies, galaxy clusters, and the cosmic web.

As well as studies of structure on the largest astrophysical scales, the project uses the MWA to identify much smaller sources, including some of the most distant galaxies in the universe, detecting radio waves that they emitted when the universe was just a fraction of its current age. Furthermore, by using the twinkling of radio sources seen through the solar wind, we can use the MWA, spanning only a few kilometres, to mimic a telescope one hundred times the size, and thereby identify some of the most compact low-frequency radio sources known, which are typically young supermassive black holes that have only recently begun accreting matter.

Finally, within our own Galaxy, we can use the sensitivity of the MWA to old, diffuse radio emission to identify previously undiscovered supernova remnants – the few thousand year-old remains of stars that ended their lives in cataclysmic explosions known as supernovae.
A unique astrophysical laboratory in our extra-Galactic backyard: Centaurus A

Radio galaxies are characterised by extremely powerful radio jets emanating from the accretion disk of a supermassive black hole residing at the centre of the host galaxy. They are so luminous that radio telescopes can observe them out to the far reaches of the Universe. One radio galaxy, however, is unique in that it is far closer than any other. This radio galaxy, Centaurus A, is only 13 million light years away and due to this proximity, is extremely bright and extends across a large area of sky (about 7 degrees, which is 14 Moon diameters!).

Counter-intuitively, this brightness and size actually makes it difficult to observe, since most radio telescopes are designed to look much further afield. Radio imaging of Centaurus A is particularly challenging due to the large range in brightness and spatial scale that it spans. Instrumental effects have hampered previous efforts to reveal the complex feedback mechanisms that govern the evolution of the radio source as relativistic particles stream from the dense, bright core to form both large and small-scale structures in the faint radio lobes.

The Murchison Widefield Array (MWA) has recently undergone a significant upgrade, which has effectively doubled the angular resolution of the telescope. This provides an opportunity to examine extended sources in greater detail than ever before. Improvements to imaging algorithms have also enabled us to combine data from both the original MWA and the new phase 2-extended configuration. We have now produced what is arguably the best view of the entire radio source to date, with the potential to gain new insights into the physics at work in the lobes and the transition regions where energy is transferred between small and large scales.

In this project you will analyse these exciting new images of Centaurus A and compare the radio data to both archival and new observations covering almost the full electromagnetic spectrum. You will also have the opportunity to make new images and improve our calibration and imaging strategies. By observing our closest neighbouring radio galaxy in unprecedented detail, you will be able to unlock secrets that are hidden in more distant galaxies, but have far-reaching implications for our physical understanding of the Universe.
Absolute flux density measurements of southern sky calibrator sources

In order to fully exploit the scientific capabilities of the Murchison Widefield Array (MWA), and the upcoming low-frequency component of the Square Kilometre Array (SKA-Low), astronomers need a set of calibrator sources with accurately measured flux densities. The number of bright calibrator sources in the Southern Hemisphere is very limited. Therefore, sources of moderate flux densities have to be used in order to correctly calibrate flux density scale in sky images from the aforementioned low radio-frequency instruments. Perley & Butler 2017 extended their flux-density scale down to approximately 50 MHz based on their recent measurements with the Karl G. Jansky Very Large Array (VLA). Their flux scale includes several primary calibrator sources for the MWA and SKA-Low. However, there is a need for more accurately measured flux density calibrators measured over the entire frequency band 50 - 350 MHz of the SKA-Low telescope. Moreover, we would like to develop a method to measure flux density of any source in an absolute way (without the need to calibrate/bootstrap using earlier measurements).

The absolute flux scale measurements are critical for future instruments such as the SKA-Low in order to be able to accurately measure flux densities of the observed sources. This project aims in developing a technique of performing absolute flux-scale measurements by using the Engineering Development Array (EDA; Wayth et al. 2017) and absolutely calibrated total power radiometer such as BIGHORNS (Sokolowski et al. 2015). We would like to apply this technique to measure flux-densities of multiple low-frequency Southern Sky calibrators over the entire frequency range of the SKA-Low (50 - 350 MHz). As the first step flux-densities of the calibrator sources measured by Perley & Butler (2017) would be performed to verify the method and compare the newly measured flux-densities with the existing flux scale. The method would then be applied to a larger set of sources. Finally, we would like to extend the method to be applicable to the upcoming SKA-Low telescope.

Research Field
Radio Astronomy/Engineering

Project Suitability
PhD, Honours / Masters

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The Murchison Widefield Array (MWA) is a low frequency (80 — 300 MHz) radio telescope operating in Western Australia and the only SKA_Low precursor telescope. Its design has many small antennas rather than fewer larger antennas as is typical for radio telescopes working at higher frequencies.

Forming high-fidelity images with the MWA can be challenging. The issues include: the very wide field of view of the MWA, the large data volume due to having many antennas, the corrupting effect of the ionosphere, the unusual reception pattern of the antennas (they are fixed on the ground), among others. Processing MWA data can often violate assumptions inherent in conventional radio astronomy data processing software. More accurate techniques are available but often come at a huge computational cost. Because of this, supercomputers are required to process large quantities of MWA data.

To deal with these different effects, astronomers need computationally-efficient and clever algorithms to make better use of the large volumes of data. This project aims to investigate and develop novel techniques in radio astronomy data processing to improve the performance and/or fidelity of calibration and imaging algorithms, with a focus on MWA and future SKA_Low data. In particular, we can combine different observations together by taking into account their different instrumental effects, creating deeper images with more sensitivity to different angular scales.

Aims of project

i. Investigate and develop novel techniques in radio astronomy data processing
ii. Apply to real data for particularly challenging areas of the sky, e.g. the Galactic Plane
iii. (Masters, PhD): derive novel science from the new images, e.g. resolved spectral index maps

The application of these techniques has the potential to impact the Epoch of Reionisation (EoR) and GaLactic and Extragalactic All-sky MWA (GLEAM) survey science programs of the MWA, which have each collected several PB of raw data. These techniques will be vital for exploiting the full potential of the new long baselines of the MWA, installed in 2017. This project is suited to a student with a strong interest in the fundamentals of radio astronomy and a solid background in computer science, maths and/or physics.

Figure 1. Example MWA data combining large angular scales (left) with fine details (middle) to create a better image of the Vela supernova remnant
Radio galaxies occur when the central black hole in a galaxy produces powerful outflows of relativistic particles. These outflows produce synchrotron emission which we observed in the radio regime. This radio emission often outshines the host galaxy and these radio ‘jets’ are related to the accretion onto the black hole in a complex fashion. In the early stages these outflows are frustrated by the inter-galactic medium within the galaxy and struggle to break out. This frustration causes the radio emission to be absorbed at low-frequencies leading to an empirical relationship between the size of a radio source and the frequency it turns over at. Smaller and younger radio galaxies peak at higher frequencies.

Hence, searching for radio sources which peak at high frequencies can find some of the youngest radio galaxies, but very few of these high frequency peakers are known.

The aims of this project are:

(i) to use broad-band multi-wavelength radio surveys to create new sample high frequency peakers in both deep (e.g. GLASS) and wide surveys,
(ii) Conduct follow-up radio observations to enable modelling of the radio emission and low-frequency turn-over,
(iii) Using European Southern Observatory facilities measure the properties of the host galaxies including redshift and stellar mass,
(iv) Obtain and analysis VLBI observations of these galaxies to unravel their nature,
(v) Put these sources into the context of radio galaxy evolution to see what process trigger the formation of radio jets.

This project will uniquely exploit the frequency coverage of many Australian radio telescopes such as the ATCA, ASKAP and the Curtin-operated telescopes MWA.

Figure 1: VLBI observations of M 87 at 86 GHz (from Kim et al. 2016). The image was created after stacking 5 VLBI images taken during 2004–2015.
Finding Ultra-High-Redshift Radio Galaxies Using GLEAM

Understanding galaxy formation and evolution across cosmic time is both a fundamental topic in astrophysics and a key science driver for the forthcoming Square Kilometre Array (SKA). In the early Universe, high-redshift radio galaxies (HzRGs; e.g. review by Miley & De Breuck 2008, A&AR, 15, 67) are crucial beacons for investigating how the most massive galaxies form (e.g. left panel below), and their link to the massive ‘red and dead’ ellipticals that are the brightest cluster galaxies in the more local Universe.

We have developed a new selection technique to find HzRGs by using radio spectral curvature in the broadband 70–230 MHz GLEAM survey (Hurley-Walker et al. 2017, MNRAS, 464, 1146), conducted with the Murchison Widefield Array (MWA). From a pilot study of four sources (Drouart et al. 2020, PASA, in press) we uncovered the second-most distant radio galaxy currently known (right panel below), observed when the Universe was less than a tenth of its current age!

We are now building on the success of our pilot by investigating the properties of a further 100 HzRG candidates selected using the same technique. Our goal is to find the first massive galaxies that formed during the Epoch of Reionization (EoR; redshift \(z > 6\)), when the Universe was less than a billion years old, which would facilitate a number of exciting, cutting-edge scientific opportunities.

You will play a leading role reducing, analysing and interpreting the multi-wavelength data that we are currently acquiring for these targets from the following world-class telescopes: MWA, ATCA, ASKAP, ALMA, LOFAR and the VLT. Key investigations in the project will be (i) to locate the immediate descendants of the first supermassive black holes that formed in the Universe; (ii) build an orientation/obscuration-free sample of active galactic nuclei at \(z > 6\); (iii) study the co-evolution of the supermassive black hole and host galaxy during the first billion years of the Universe; (iv) characterise the intergalactic medium during the EoR via the observation of redshifted 21-cm neutral hydrogen absorption; and (v) better understand the accretion processes that power the radio jets in these sources, which in turn can affect the ambient environment (so-called ‘feedback’).

Left: The ‘spiderweb galaxy’ at redshift \(z = 2.2\): witnessing the formation of a dominant cluster galaxy in the early Universe. The grey-scale is a Hubble Space Telescope image, while Ly\(\alpha\) (blue) and radio contours (red) are also shown. Figure from Miley et al. 2006 (ApJ, 650, L29).
Right: A newly discovered, GLEAM-selected high-redshift radio galaxy at \(z = 5.55\) from Drouart et al. 2020 (PASA, in press). The top figure is a 30-GHz ALMA spectrum of the host galaxy, showing 5\(\sigma\) detections of two CO transitions (extracted over the blue aperture in the lower left figure). In the lower left figure, the grey-scale VLT HAWKI K-band (near-infrared) image has been overlaid with contours (red) from the collapsed ALMA continuum image (84–115 GHz), identifying the host of the radio emission. The extended, albeit asymmetric radio emission suggests it is powered by synchrotron processes. The lower right plot shows zoom-ins on the two CO detections.
GLEAM-X: Exploring the Universe in Radio Colour

The Murchison Widefield Array (MWA) is a low frequency (80 — 300 MHz) radio telescope operating in Western Australia and the only SKA_LOW precursor telescope. One of the largest science programs for the MWA is the GaLactic and Extragalactic All-sky MWA (GLEAM) survey, which has surveyed the entire visible sky for two years since the MWA commenced operations.

A large part of the 0.5 PB of GLEAM data has been published as an extragalactic source catalogue (see Figure 1), as well as observations of the Galactic Plane and the Magellanic Clouds. Observations of GLEAM-eXtended have commenced, using the newly-upgraded MWA, which now has double the resolution, allowing images 10x deeper to be created, potentially revealing millions of new radio sources over the next few years.

Combining the datasets will create the most sensitive survey output from the MWA ever. The wide bandwidth of the MWA makes possible in-band spectrum measurements of many objects, which directly informs us of their astrophysics.

Aims of the project:

i. Process GLEAM-X data to generate widely useful images and catalogues;
ii. Undertake a focused research project that utilizes the data. This could include (but is not limited to): transient/variable radio sources, scintillation, the ionosphere, and continuum studies on objects such as radio galaxies, galaxy clusters, supernova remnants, and pulsars;
iii. Publish the results, either as an outreach app or website (Honours) or as scientific papers (Honours, Masters, PhD).

This project is well suited to a student with strong computing skills, an interest in gaining a deep understanding of radio astronomy calibration and imaging, and an interest in a science area that can be addressed by data from the survey.

Figure 1  The first year of GLEAM observations, covering the whole Southern Sky. This is the first radio colour view of our universe: find out more via this TED talk: http://bit.ly/nhwted.
HI absorption in high-z radio galaxies

Before the very first galaxies formed, the Universe was a sea of hydrogen and helium, gently cooling and collapsing. When the first galaxies formed, they ionised the surrounding gas, turning it from an opaque absorbing cloud into the transparent, ionised plasma we see today: this time is called the Epoch of Reionisation.

This change will have occurred at different rates in different locations in the Universe (Figure 1). When we look at high-redshift galaxies which emit in the radio spectrum, any neutral hydrogen along the line-of-sight will absorb the characteristic HI line at that redshift. For the highest-redshift galaxies, this HI line is shifted from 1.4GHz down to ~200MHz. This is within the frequency range of the Murchison Widefield Array, a radio telescope operated by Curtin University and based in the Murchison Radio Observatory.

This project aims to detect HI absorption in high-redshift radio galaxies using the MWA. We have developed a pipeline to efficiently process data and search for lines. An example spectrum produced after running the pipeline is shown in Figure 2. There are hundreds of hours of data already taken on several targets and fields which would be suitable for this search. A detection would be a world-first and have huge scientific impact. Applying the pipeline to wide survey fields would pathfind toward similar studies with SKA_LOW.

Aims of the project:

i. Process existing data through the spectral line pipeline and search the resulting data cubes for HI absorption;
ii. Use detections or limits to understand the environment of the target radio galaxies;
iii. (Honours-only) Search fields for lines in survey fields to blindly detect high-z galaxies.

This project is well suited to a student with an interest in astrophysics and astronomy, and excellent computing and organisational skills.

Figure 1  The Universe ionises, transforming from a sea of opaque hydrogen into the complex structures we see today.

Figure 2  Spectrum produced for a high-redshift radio galaxy from several hours of data processed through the existing pipeline. The black lines indicate the value at the target, and the blue shading indicates 3x the noise level in each channel.
How Do Powerful Radio Galaxies Effect Their Environment?

Powerful radio galaxies in the distant Universe are unique beacons of massive black holes sitting in galaxy proto-clusters. These are dynamic environments with highly accretion black holes with powerful jets, as well as large amounts of star formation occurring in the proto-cluster members. These powerful radio galaxies have a direct impact on their environment, stimulating powerful outflows.

The aim of this project is to investigate this connection. How the powerful radio galaxy effects the proto-cluster it resides in and vice-versa. This project will take advantage of the new all-sky deep surveys from the Murchison Widefield Array and the Australian Square Kilometre Array Pathfinder to make unprecedented measurements of the radio jet. These will be supplemented by higher frequency observations from the Australian Telescope Compact Array and the Atacama Large Millimetre Telescope. We will also use X-ray observations from eROSITA.

The aims of this project are:

(i) measure and model the continuum and polarisation properties of a large sample of known powerful radio galaxies in the southern hemisphere in order to constrain their jet powers.

(ii) study how that jet power relates to the accretion onto the super-massive black hole.

(iii) compare the radio emission to the distribution of proto-cluster members to study their influence. Polarisation of the radio jet can reveal information about the intra-cluster medium.

(iv) use eROSITA X-ray observations to study the accretion and possible inverse Compton emission from these high redshift radio galaxies.

(v) search for other powerful radio galaxies in the early Universe to expand the sample.

This project will involve close collaboration with researchers at the European Southern Observatory with the potential to spend time at the headquarters in Munich.

Figure The Spiderweb Galaxy. Deep Hubble image of the core of the MRC 1138-262 protocluster at z = 2.2 obtained with the Advanced Camera for Surveys. [From Miley et al. (2006)]. Superimposed on the HST image are contours of Lyα (blue, resolution ~ 1") obtained with ESO's very Large Telescope (VLT), delineating the gaseous nebula and radio 8GHz contours (red, resolution 0.3") obtained with NRAO's VLA, delineating the non-thermal radio emission. The gaseous nebula extends for > 200 kpc.
The future of radio astronomy is on the Moon! For a long time, radio astronomers have dreamed of placing a low-frequency radio telescope on the far side of the Moon, where it would be completely shielded from earth-bound interference, and unaffected by the ionosphere. As a step toward this ambitious goal, several projects are now planning to send radio arrays into lunar orbit, where they would observe while on the far side and transmit data back to Earth while on the near side of their orbits. This potentially opens an entirely new parameter space of ultra-long wavelength, high angular resolution radio imaging that is impossible from the surface of the Earth.

To make such a mission a reality, detailed simulations of the orbiting array and new imaging and calibration strategies will be required. Researchers at the Curtin Institute of Radio Astronomy are collaborating with Chinese colleagues to produce such simulations and build software that can be used to produce images from lunar-array data. We are looking for students to join the project in order to:

(i) realistically simulate the science-data output of the satellites

(ii) develop and test new calibration strategies for the array

(iii) develop and test imaging algorithms that can be applied to this data set

This is a unique opportunity to become involved with a space mission and to collaborate with Chinese researchers on an ambitious project to observe the Universe like never before!
Opening a window on the ionized interstellar medium of nearby galaxies

The ionised Interstellar Medium (ISM) is an important component of our Galaxy, comprising as much as 50% by volume and 80% by mass of the total ISM. It traces many astrophysical processes, and yet, due to the difficulty of observing it directly (compared with the neutral component, which can be studied via the 21 cm line) it is poorly understood. Very Long Baseline Interferometry (VLBI) observations allow the turbulence in the ionised ISM to be probed along lines of sight by measuring the “scatter broadening” of intrinsically compact sources. However, there are great difficulties in determining the distribution of the ionised ISM from our position well within the plane: only within 1kpc of the Solar System can complex structure be mapped, allowing correlation with other astrophysical phenomena.

Applying this technique to other galaxies could produce significantly improved results since even a small inclination to the line of sight separates the components of the ISM, greatly increasing the observable information. A pilot study of M31 undertaken a few of years ago showed very promising results, with strong evidence of the detection of the ionised ISM of a nearby galaxy for the first time. Much deeper VLBI observations of M31 have now been undertaken and await analysis.

Beyond the main goal measuring the ISM of M31 there are further secondary goals that might be achieved with these data. The first is HI absorption towards the brighter background sources, one of which lies right on a neutral filament in the M31 galaxy. The second is determining accurately the brightness M31* across at least 3 epochs in 2012, when it is thought to be much dimmer than expected. Third, the possibility of detecting compact sources that are hosted within M31, such as X-ray binaries.

With future instruments, such as the SKA participating in observations, the number of lines of sight probing a galaxy such as M31 would be enormous. Planning for such observations could also form part of the project if the student is interested.

Fig: The angular size of sources (assumed to be intrinsically compact sources seen through the M31 galaxy as a function of angular distance from the core of M31. Those nearest to the centre appear to be larger. This is thought to be due to “scatter broadening” of the sources by the turbulent ISM of M31.
Searching for transients and variables in the GaLactic and Extragalactic All-Sky MWA (GLEAM) surveys

The Murchison Widefield Array (MWA) is a low frequency (80-300 MHz) radio telescope operating in Western Australia and the only SKA_Low precursor telescope. One of the largest science programs for the MWA is the GaLactic and Extragalactic All-sky MWA (GLEAM) survey, which has surveyed the entire visible sky for two years since the MWA commenced operations. The GLEAM-eXtended (GLEAM-X) survey expanded this with a further two years of observing at higher resolution.

GLEAM and GLEAM-X have collected vast quantities of data. A large part of the first year of this data has been published as an extragalactic source catalogue. However, to produce this catalogue, all of the data was averaged together in time. The original data in full time resolution, as well as newly processed GLEAM-X data, still remain to be investigated. Hidden in these images are possible transient events, such as: flaring M-dwarf stars, reflective space junk, and potentially other undiscovered sources. There are also many astrophysical reasons for sources to change in brightness with time, such as scintillation from intervening plasma, and the flaring and dimming of distant black holes.

The project involves careful analysis of the GLEAM and GLEAM-X data, using the combined catalogue as a reliable reference source. The student will search for objects which do not appear in the combined catalogue (transients), and identify their nature. There is also the potential to monitor the brightness of sources over time (variables). Recently a new method of transient source detection has been developed via visibility differencing, and this project can extend that search to the entire GLEAM and GLEAM-X sky, as well as other public MWA data sets.

Aims of the project:

i. Search GLEAM and GLEAM-X data for transient events, either by computational searches of existing images, or visibility differencing;

ii. (Masters, PhD-only): Determine the variability of large numbers of objects over time and frequency through the GLEAM and GLEAM-X data, and use this to constrain the physics causing the variability from intrinsic or extrinsic causes.

This project would suit a student with good programming skills who is willing to learn more and search a large dataset for potentially interesting events. With approximately 7 million source measurements to search and correlate, organisation and clear thinking are crucial skills.

![Figure 1](image)

Figure 1 Above: An example set of images, demonstrating a variable source. The source is detected only in the 2nd and 4th images. Left: The degree (V) and significance (eta) of variability for a subset of sources that will be used in this work.
Simulating all-sky MWA observations using WODEN

The Murchison Widefield Array (MWA) is a low frequency radio (think FM radio waves) interferometer consisting of 2048 dipole antennas, spread over 5km out in the WA outback. The MWA is indirectly capable of imaging the radio sky by correlating and processing the signals captured by each antenna, rather than immediately making an image like a traditional optical telescope. The data collected by the telescope is affected by a slew of instrumental effects such as receiver noise and reflections within cables connecting antennas. All these effects must be understood and mitigated to enable science. Real data contains unknown astrophysical and atmospheric effects as well as these instrumental effects, making it hard to isolate and understand each effect. Furthermore, the MWA has an extremely large field-of-view, being able to see essentially all the way down to the horizon.

Realistically simulating observations gives us a path to individually investigate each effect and test our calibration and imaging software. Simulating interferometric data is computationally expensive however and is further compounded by the field-of-view of the MWA, as one must simulate essentially the entire sky. One solution is to implement parallel code on GPUs, to which end we have begun developing a software package dubbed WODEN.

The goal of this project would be to develop a fast but accurate way of simulating all-sky emission through WODEN. One could simply split the sky into pixels, but at the required resolutions, this will require > 100 million pixels. As an interferometer records data in the Fourier transform space of an image, an alternative is to take an all-sky image, Fourier transform, and sample using a suitable kernel, to generate simulated interferometric data. This process is known as ‘degridding’. The aims of this project would then be:

- Implement GPU-based degridding in WODEN and compare to pixel-based methods
- Compare to real data from the MWA
- Depending on the scope of the project, think about adding atmospheric effects from the ionosphere into the OSKAR simulation package, or other instrumental effects

This project would suit computationally minded physics majors, or comp-sci students with a strong interest in astrophysics.
Testing Cosmology with Next Generation Radio Surveys

Extra-galactic radio surveys are dominated by luminous radio sources powered by super-massive back holes. These outshine their host galaxies by orders of magnitude hence can be detected at extreme distances (much further than surveys at other wavelengths). The mean distance of these radio sources is about halfway back to the Big Bang. With large numbers of radio sources constraints can be made on various aspects of cosmology. Such cosmological studies are a key science goal of the Square Kilometre Array (SKA) and with continuum surveys from the Australian SKA Pathfinder.

This project will use the next-generation all-sky survey from the Murchison Widefield Array, GLEAM-X, to perform cosmological studies. This project would include some hands processing to contribute to the production of GLEAM-X, but would mostly be focusing on the cosmological projects described below:

(i) use the all-sky and deep MWA surveys to determine the source counts as a function of frequency and use these to constrain models of radio galaxy evolution and the measurement of the extragalactic background light,

(ii) use the all-sky distribution of GLEAM-X sources to independent measure the dipole of the cosmic microwave background due to our galaxies movement relative to the absolute frame of reference,

(iii) study the cross-correlation of the distribution of radio sources in the all-sky image to constrain the bias factor of these powerful radio galaxies,

(iv) cross-correlate this survey at different frequencies to infer the redshift distribution of the whole sample.

Fig 1: sky distribution of radio sources which are part of the GLEAM-X pipeline with a shading related to their space density.
The formation and evolution of the super-massive black holes which reside in the centres of most galaxies remains one of the principle mysteries of astrophysics. We know that they evolve via two processes: merging (along with their host galaxies) and accretion. Their merging history would have to be consistent with models and observations of galaxy evolution, as well as future gravitational wave results (e.g. from LISA). Their accretion history can be constrained by X-ray and mid-IR surveys (for high accretion rates) and by radio surveys probing the relativistic jets emitted at low accretions rates. Hence it is possible to determine how the distribution of black holes masses evolves from the present day to the early Universe.

This project aims to:

(i) develop models to relate accretion rates and the states of the accretion disk with observables such as X-ray, mid-IR and radio luminosities from surveys. In particular, this work would focus on using multi-frequency radio surveys (e.g. the Murchison Widefield Array and the Australian SKA Pathfinder) to constrain the power of radio jets and therefore the accretion related to the radio emission. This work would also build upon our knowledge of galactic black holes,

(ii) use these models to determine the backward evolution of the black hole mass function consistent with observables,

(iii) examine the processes which could lead to the rapid formation of black holes in the early Universe and the effect they have on their environment,

(iv) make predictions of observables from accreting black holes at high redshift taking into account factors such as inverse Compton scattering of the CMB by relativistic electrons from the radio jets and the increased density of the interstellar, circum-galactic and intergalactic media.

This project will uniquely exploit the broad frequency coverage of many Australian radio telescopes such to constraint the evolution of super-massive black holes across cosmic time.

Fig 1: Model of the distortion of an accretion disk by a black hole as used in the film Interstellar (James et al. 2015).
The far-infrared to radio correlation of star forming galaxies at low frequencies

How stars formed in the early Universe is one of the major questions to be answered by the Square Kilometer Array (SKA) and its pathfinder instruments. Radio emission is impervious to the effects of dust obscuration, making it the most robust measure of star formation for the most distant galaxies. Our current recipes to estimate star formation based on radio emission are calibrated against the far-infrared to radio correlation (FRC) – a tight relationship between radio and infrared luminosities spanning many orders of magnitude. In the local Universe (z < 0.1) the physics that drive the FRC are thought to be well understood. What remains to be seen is how it behaves with increasing redshift, as in the literature there has been both evidence for and against its evolution. Understanding how the FRC may evolve, if it indeed does, is a crucial step towards interpreting star formation in the earliest epochs of the Universe.

This project would focus on exploiting the broadband radio data that is beginning to become available from SKA-precursor instruments, including data from the GaLactic and Extragalactic All-sky Murchison Widefield Array eXtended (GLEAM-X) survey, and the Evolutionary Map of the Universe (EMU), to characterize the spectral properties of star forming galaxies. At low frequencies there is an exciting opportunity to investigate the radio turnovers introduce by free-free absorption, and how these may evolve across the FRC. Combining these data with higher frequency data from existing projects (including the GALaxy and Mass Assembly Legacy ATCA Southern Sky project) and targeted follow up observations could produce a set of radio templates to be used to provide a reference of the behaviour to be expected from star forming galaxies at higher redshifts.

Aims of the project:

i. Use new GLEAM-X and EMU data to examine the radio spectra of star-forming galaxies;

ii. Search for free-free absorption and examine potential correlation with infrared emission;

iii. Propagate the behavior found to predict the FRC at high redshifts.

This project is well suited to a student with a strong interest in astrophysics and astronomy, and good computing and organisational skills.

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**Figure 1** An example of the spectral shape of a star forming galaxy at radio wavelengths from Galvin et al. (2018). MWA GLEAM data constrained a turnover that was modelled as free-free absorption.
Tracing past radio AGN activity in the BASS sample

The growth of central supermassive black holes (also known as Active Galactic Nuclei, AGN) is episodic and not well understood. The Swift BAT AGN Spectroscopic Survey (BASS) is a very large survey (>1000) of hard X-ray selected AGN with complementary optical spectroscopy observations aimed at furthering our understanding of growth and structure around nearby supermassive black holes. A significant recent BASS discovery is the significant excess of late-stage nuclear mergers – a result that is consistent with theoretical simulations which find a strongest excess of nuclear mergers in gas-rich major-merger host galaxies of obscured luminous black holes (Koss et al 2018). The prevalence of mergers suggests that these galaxies do not reside in isolation. High angular resolution is required to pinpoint the origin of the emission.

Current radio continuum studies of this sample have found that while these black holes are accreting very efficiently, at higher radio frequencies they are not radio-silent but typically classed as radio-quiet (Wong et al 2016; Smith et al 2016) and that likely to not be dominated by a jet origin but related to outflow winds (Baek et al 2019; Smith et al 2020 submitted). Low radio frequency observations are currently missing but crucial for tracing past jet episodes and for estimating the mechanical energy that would be injected into the ISM and IGM of the host galaxy. Studying these galaxies with the Murchison Widefield Array will enable the modelling of the radio emission and potentially the age of the jet emission. The GaLactic and Extragalactic All-sky MWA – eXtended (GLEAM-X) survey can be used for this work.

Aims of the project:

i. Examine and characterise the low-frequency radio spectral energy distribution from GLEAM-X observations of a sample of nearby galaxies where AGN activity has restarted (selected via their hard X-ray emission);

ii. (Masters) Estimate contribution of jet emission to observed radio emission across the band.

This project uniquely exploits the frequency coverage of the MWA over 20 bands and the Phase 2 long-baseline observations which provide sufficient resolution for pinpointing the source of the observed low-frequency emission. It allows us to look back into the past of supermassive black holes and examine how they feed and grow. This project suits a student with a strong interest in astrophysics and astronomy.
Radio emission is a superb tracer of star formation across the Universe. As such measuring the star formation history of the Universe is a key science goal of the Square Kilometre Array (SKA). To prepare for the SKA surveys we need to obtain a better understanding of distant star-forming galaxies which exist in surveys with the SKA precursors.

The Evolutionary Map of the Universe (EMU) survey conducted by the Australian SKA Pathfinder (ASKAP) will detect powerful star-forming galaxies out to when the Universe was a quarter of its current age. However, to detect less powerful star-forming galaxies at high redshift we will have to take advantage of gravitational lensing. This phenomenon occurs when a massive galaxy along the line of sight magnifies and distorts the light from a background galaxy. Several lensed star-forming galaxies are known, but are poorly studied in the radio.

The aims of this project are:

(i) using the GAMA survey fields with broad and deep radio coverage (from EMU and MWA), establish the radio properties of highly luminous star forming galaxies at high redshift. Determine how similar or different they are local star forming galaxies,

(ii) from the wide area radio surveys determine the radio properties of known lensed high redshift star forming galaxies and model this radio emission,

(iii) using our knowledge of known lensed star forming galaxies search for new candidates, obtain their redshifts and determine their properties. This part of the project will leverage Australia's partnership with the European Southern Observatory and their telescopes in Chile.

This project will uniquely exploit the frequency coverage and wide survey area of many Australian radio telescopes such as the ATCA, ASKAP and the Curtin-operated telescopes MWA.

Figure 1: A schematic representing how light from a distant galaxy is distorted by the gravitational effects of a nearer foreground galaxy known as Einstein rings. This project will study known lensed distant star-forming galaxies as well as searching for more candidates.

(Image: © ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.)
Transient and variable AGN from the ASKAP VAST Survey

ASKAP, the Australian Square Kilometre Array (SKA) Pathfinder, has now started science operations. VAST, an ASKAP survey for variables and ‘slow’ transients (Murphy et al. 2013, PASA, 30, e006), will offer new insights into the dynamic radio sky at mid frequencies (about 1 GHz). This will be possible because ASKAP has a very competitive combination of a wide field of view and exquisite sensitivity.

In this project, you will conduct some of the first ASKAP searches for variable and transient flaring activity – hallmarks of extreme physics (e.g. Pietka et al. 2015, MNRAS, 446, 3687) – from the active galactic nuclei (AGN) at the hearts of massive elliptical galaxies, as well as Seyfert galaxies. In particular, you will shed further light on the physical mechanisms responsible for (i) intrinsic variability in the central engines of powerful radio sources, and (ii) extrinsic variability due to interstellar scintillation in our Galaxy. You will also investigate whether there are correlations between the variability statistics and other radio / multi-wavelength properties.

The end goal is to conduct a thorough census of the variability properties of many hundreds of AGN within the areas of sky that VAST is currently surveying. This in turn will enhance our knowledge on the duty cycles of activity and quiescence, the link between black hole accretion and jet formation, and how the jets influence the ambient environment (e.g. see review by Bignall et al. 2015, PoS(AASKA14)058).

Left: A view of the ASKAP telescope, located at the Murchison Radio-astronomy Observatory in Western Australia. Image credit: CSIRO; https://www.scienceimage.csiro.au. Right: Multi-year radio light curve monitoring of the blazar J0721+7120. These data were obtained with the Effelsberg Radio Telescope in Germany. Figure from Angelakis et al. 2019 (A&A, 626, A60).
Unravelling the Nature of Local Starburst Galaxies

Radio emission is a superb tracer of star formation across the Universe. As such measuring the star formation history of the Universe is a key science goal of the Square Kilometre Array. Local starburst galaxies have extreme star formation rates (forming thousands of solar masses per year of new stars), but are representative of typical galaxies when the Universe was half its age. Hence to understand these distant galaxies we must obtain a better understanding of their local analogues.

This project will use the deep surveys from the Murchison Widefield Array to build up catalogues of local star-forming galaxies with wide coverage across the electromagnetic spectrum. In the radio, the MWA observations plus complimentary radio surveys will provide measurements across radio spectrum (~0.1 to 10 GHz). The GAMA survey will provide the infrared to optical data. X-ray observations will be available from the eROSITA instrument.

The aims of this project:

(i) create a sample of local starburst galaxies with broad wavelength coverage, in particular model their synchrotron and free-free emission. This catalogue will provide a benchmark for studies of starbursts in the high-redshift Universe and allow us to better understand the origin of radio emission in such sources,

(ii) develop novel models for the broad-band radio data based on the geometry of the galaxy,

(iii) match this sample to eROSITA observations which can be used to constrain the X-ray luminosity/star formation rate relation. Possibly also extend this to higher energies too,

(iv) perform detailed modelling of the subset of starbursts with observations in the infrared from the Herschel Space Observatory which will provide a more accurate interpretation of the astrophysics behind the radio emission.

This project will uniquely exploit the frequency coverage of many Australian radio telescopes such as the ATCA and the Curtin-operated MWA.

Figure 1. This composite image of starburst galaxy M82 shows the distribution of dense molecular gas as seen by the GBT (yellow and red) and the background stars and dust as seen by Hubble (blue). The yellow areas correspond to regions of intense star formation. The red areas trace outflows of gas from the disk of the galaxy. This project will study such galaxies to understand their complex radio emission and its association with the relativistic particle created by star formation.

Credit: Bill Saxton (NRAO/AUI/NSF); Hubble/NASA.
Unsupervised clustering of the Extra-galactic Universe

Modern all-sky radio surveys represent a big data challenge, one where traditional approaches informed by physical expectations may no longer be the most appropriate. The GaLactic and Extragalactic All-sky MWA eXtended (GLEAM-X) project has observed the sky south of Dec +30 across a frequency range of 72 – 230 MHz. When finished it is expected to detect in excess of a million objects across twenty intermediary frequencies. Collectively, these objects and their properties represent a massive multi-dimensional dataset that is difficult to interact with and efficiently mine for meaningful scientific outcomes. This is especially true for rare or previously unseen objects that are buried beneath the more typical sources.

This project will explore how unsupervised clustering methods may best be applied and exploited to create a structured framework to allow objects detected by GLEAM-X to be categorised and explored efficiently. Methods regularly applied in the machine learning community (including auto-encoders, generative adversarial networks, t-SNE etc.) will attempt to organize the contents of the GLEAM-X outputs into a scheme that neatly separates objects into fundamental or regressed classes. These methods are especially powerful as they do not necessarily have to incorporate expectations specified by assumed physical models, thereby avoiding potential bias or constraints inadvertently introduced. When finished, the applied approach would be capable of compressing all object properties into a simple two- or three-dimensional embedding to be made available for exploration. A major outcome of this data-driven approach to modelling is the ability to identify outliers, which in this scenario could be a set of exceptionally rare or previously unseen objects.

Aims of the project:

i. Develop appropriate clustering methods using existing public catalogues (e.g. GLEAM);
ii. Expand the method to the new GLEAM-X data;
iii. Search for and characterize reference objects such as radio galaxies;
iv. Explore outlying populations to discover new populations of sources.

This project is well suited to a student with a good programming background, an interest in developing new computational techniques, and good organisational skills.

Figure 1 A naïve example of 30,000 GLEAM sources (21 input features) being projected to a lower dimensional embedding (3 dimensions) using t-SNE. Potential interesting populations are highlighted with red circles.
Variability of Radio Galaxies at Low Radio Frequencies

Radio galaxies are powered by accretion onto the super-massive black holes they host at their centres. Variation of the accretion rate is reflected in variation of the radio emission over time. Monitoring these variations can tell us about the accretion process onto the central black hole. The timescales are long (many years) as these black holes are millions to billions solar masses, so they require a long-term monitoring and/or dedicated observations. The wide-field of view of the Murchison Widefield Array and its frequent observations of calibrators over the last seven years provides an exciting, yet untapped data set with which to investigate radio galaxy variability at low radio frequencies of many thousand radio sources. These calibration observations continue today and allow us to catch exciting variations when they happen (e.g. Fig 1).

The aims of this project are:

(i) produce images of calibrator fields over the last seven years to determine light curves of thousands of radio sources. This initial work will provide the best measure of variability for this population to date.

(ii) develop novel methods to classify the varying sources into different classes (e.g. are the changes periodic, the same at all frequencies or fall into rate classes such as in Fig. 1)? Are they intrinsic to the source or due to foreground material (scintillation and micro-lensing),

(iii) follow-up exciting rare sources of variability such as binary black holes and micro-lensing events with VLBI observations,

(iv) use the long-term monitoring of the radio galaxies to quantify the timescales on which AGN accretion rates can change.

This project will uniquely exploit the frequency coverage of many Australian radio telescopes such as the ATCA, ASKAP and the Curtin-operated telescopes MWA.

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Research Field
Radio Astronomy

Project Suitability
PhD
Masters/Honours

Project Supervisor
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Co-Supervisors
Dr Jess Broderick
Dr Marcin Sokolowski

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Fig 1. Example of a long-term light curve of a radio galaxy from Vedantham et al. (2017). In this case the authors ascribed the variations due to micro-lensing from a foreground object, possibly a free-floating black hole.
Pulsars and Fast Transients

**Project lead:** Dr Ramesh Bhat, Dr Clancy James, Dr Esha Kundu, Dr Sam McSweeney

**Student members:** Mr Wayne Arcus, Ms Dilpreet Kaur, Ms Freya North-Hickey, Mr Mawson Sammons, Mr David Scott, Ms Susmita Sett, Mr Keegan Smith, Mr Nick Swainston, Mr Alexander Williamson

This project explores the universe at the highest time resolution, studying compact sources of radio emission that produce bursts or pulses of radio waves that can last for less than a millisecond. Having developed the capability of the MWA to study radio sources at a time resolution of less than one ten thousandth of a second, we can use this to study the properties of pulsars – rapidly spinning neutron stars that emit regular pulses of radiation, with a stability better than the earth’s best atomic clocks. We are conducting an MWA survey of the entire southern sky to detect new pulsars, and to study known systems, aiming to better understand how these exotic objects produce their radio emission.

This project also uses the ASKAP radio telescope at the Murchison Radioastronomy Observatory to detect new fast radio bursts (FRBs), and to ascertain which galaxies they come from. FRBs are energetic, short-duration single bursts of radio emission coming from distant galaxies, whose origin is as yet unknown. By studying how the different radio frequencies within a burst are slowed down as they travel through the tenuous gas between galaxies, we can determine the density of that gas, providing one of the few methods of probing this matter, which has hitherto remained virtually undetected. This allows us not only to weigh the universe, but also to perform key cosmological measurements. Finally, by measuring precisely where the bursts appear to come from within their galaxies, we can try to pin down what gives rise to these new and unexplained phenomena.
A census of bright southern sky pulsars with the Engineering Development Array

Since their discovery over 50 years ago, pulsars have been amongst the most fascinating astrophysical objects. They are extremely dense objects, built primarily of neutrons (and hence called neutron stars), rotating at rates of up to several hundreds of times per second and emitting beacons of radio emission. These radio pulses are extremely regular in their arrival times and therefore pulsars (especially those with spin periods of the order of a few milliseconds) can be used for high-precision timing applications, such as searches for low-frequency gravitational waves that are produced by super-massive black-hole mergers. Their timing properties can also be exploited in the commissioning phases of new radio telescopes and instrumentation.

The Engineering Development Array 2 (EDA2; Wayth et al. in preparation) is one of the precursor stations of the low-frequency component of the Square Kilometre Array (SKA-Low), which will be built at the Murchison Radio-astronomy Observatory in the next decade. It consists of 256 MWA dipole antennas, the analogue signals from which can be digitised and processed. The current software and firmware enable electronic steering of the beam in arbitrary direction in the sky and the forming of station beam in real-time. This allows us to relatively easily observe and verify the detections of many known, bright pulsars and we expect to detect at least 100 with the EDA2.

The main goal of this project is to perform a series of short observations of a modest sample of southern-sky pulsars with the EDA2 or other SKA-Low precursor stations and verify their detections. This will be a useful exercise in ascertaining the sensitivity and polarimetric characteristics of prototype SKA-Low station telescopes. The results of this shallow all-sky survey will be compared with the number of detections expected according to the mean flux densities of these pulsars, the sensitivity of the SKA-Low station at the observing frequencies and toward the sky positions of pulsars during the observations. The characteristics of the detected pulsars, such as polarimetric pulse profiles, will be compared with those obtained with the Murchison Widefield Array and other published results.
Catching Fast Radio Bursts with the MWA

Since the landmark discovery of Fast Radio Bursts (FRBs) by the Parkes radio telescope (Thornton et al. 2013), this new field of radio transients has flourished to the extent that astronomers are now beginning to use them for science. The discovery also triggered a world-wide hunt to find many more, with the recent breakthrough by the Canadian CHIME telescope marking another major milestone, i.e. hundreds of bursts detected down to ~400 MHz. These intense bursts are thought to originate from cosmological distances, and they are potential new probes for cosmology; e.g., to measure the baryonic content of the Universe (Macquart et al. 2020), and the magnetic field of the Intergalactic Medium (Caleb et al. 2019).

Yet, the physics governing the origin of these energetic bursts still remains a mystery, despite a continuing flurry of theoretical ideas, including exotic possibilities including dark matter, and even cosmic strings; and even after their interferometric localisations at sub-arcsecond resolution. The plot further thickens with no burst emission seen to date at frequencies below ~300 MHz.

Prompt follow-up of FRBs is technically challenging due to their extremely short time durations (of the order of a few milliseconds). The co-location of the Australian SKA Pathfinder (ASKAP) telescope and the Murchison Widefield Array (MWA) was exploited extensive shadowing campaigns (Sokolowski et al. 2018), placing the most stringent constraints on the low-frequency emission from these enigmatic bursts. Over the past year, the high-time resolution capabilities of the MWA have been pushed to enable voltage trigger and buffer modes. Along with the rapid-response observing mode now possible with the MWA, this is now allowing receiving and responding to the trigger alerts from facilities such as the ASKAP and the Five-hundred metre Aperture Spherical Telescope (FAST) in China.

This project will exploit these new and advanced capabilities of the MWA to undertake some exciting science relating to FRB emission physics, as well as their propagation and progenitor models, which will contribute to advancing our understanding of these mysterious bursts.

Figure 1: FRB 110220 – one of the brightest FRBs discovered in the Parkes high time resolution Universe survey (Thornton et al. 2013). The burst’s dispersion measure of 945 pc cm\(^{-3}\) results in an arrival time spread of approximately 1100 milliseconds across the 400 MHz observing band of Parkes survey observations. The burst would have arrived at the MWA 185 MHz band approximately 112 seconds after its time of detection at Parkes. The inset shows the shape of the pulse, where an exponential tail resulting from multi-path scattering through the intergalactic medium is clearly visible, and follows the expectations based on a Kolmogorov-type turbulence.
Chasing Fast-spinning Pulsars with the First SKA-Low Precursor

Pulsars are proven laboratories for advancing fundamental physics; those with spin periods of the order of a few to several milliseconds – the so-called millisecond pulsars – are particularly promising for a wide variety of science. Their clock-like stability can be exploited for applications ranging from detecting gravitational waves to probing the state of ultra-dense matter. As such, doing fundamental physics with pulsars is a headline science theme for the Square Kilometre Array (SKA) telescope, e.g. making a direct detection of nanoHertz gravitational waves is a key science driver for the Phase 1 SKA.

Pulsars are generally brighter at low radio frequencies (i.e. below 300 MHz), in which Australia’s Murchison Widefield Array (MWA) operates. The MWA is a next-generation telescope, and an official Precursor for SKA-Low, i.e. the low-frequency component of the SKA. However, finding fast-spinning pulsars at low frequencies poses several major technical and computational challenges. In particular, traditional approaches involving tiling large areas of the sky and searching through thousands of pencil beams become computationally prohibitive. The superbly large field-of-view (500 sq. deg.) and interferometric advantages of the MWA, along with its unique capability to record high-time resolution voltage data from large parts of the skies at once, bring some exciting prospects to circumvent these formidable challenges.

This project will leverage a number of recent advances uniquely applicable to low-frequency wide-field interferometric arrays like the MWA. For example, implementing the hybrid approach of semi-coherent de-dispersion (cf. Bassa et al. 2017) to process high-time resolution voltage time series data from the MWA will enable achieving optimal detection sensitivity to short-period pulsars. The interferometric advantages of the MWA can be exploited for efficient identification of promising pulsar candidates. These strategies will help accelerate the process of discovery and confirmation of pulsars, their rapid sky localisation as well as detailed characterisation. A demonstrable success in this area will bolster the prospects of SKA-Low to emerge as an efficient pulsar discovery machine.

Left: an artist’s impression of a fast-spinning (millisecond) radio-emitting pulsar, in binary orbit with a white-dwarf companion star. Right: MWA detection of a pulsar that spins at a rate of 456 times per second.
From Low-frequency Pulsar Observations to Interstellar Holography

Pulsars make fabulous tools as probes of the interstellar medium (ISM) of our Galaxy. Their radiation is pulsed, spatially coherent and highly polarised – an ideal combination that enables their signals to carry imprints of the ionised, turbulent and magnetico-ionic properties of the media through which they propagate. At low radio frequencies (i.e. longer wavelengths), these effects are significantly magnified as a result of their strong dependencies with the observing frequency.

Multipath propagation through the ISM gives rise to a wealth of observable phenomena, many of which can be meaningfully used to study the small-scale structures in the ISM. For decades, possible investigations were limited to the use of more traditional scattering and scintillation techniques, which are generally useful for a statistical characterisation of the ISM along the pulsar’s sight line. Deflected parts of the radiation may also occasionally give rise to subtle features in the secondary spectra of pulsar scintillation (e.g. parabolic arcs; Figure 1), and these can be exploited to pinpoint the location of turbulent plasma or probe any anisotropy that may be present (e.g. Bhat et al. 2016, 2018). The physical origin of these arcs is an active area of research, with a multitude of recent interpretations involving hot stars or plasma sheets (Walker et al. 2017; Simard & Pen 2018; Gwinn 2019). Another notable development is the application of cyclic spectroscopy (Demorest 2011), and phase-retrieval algorithms that enable coherent de-scattering; i.e. simultaneous recovery of the pulsar’s intrinsic signal and the ISM delay structure (Walker et al. 2013).

This project will capitalise on new instrumentation and capabilities that are now routinely available for pulsar observations with the Murchison Widefield Array (MWA), which enable signal reconstruction at a microsecond time resolution. Developing the related software instrumentation and signal processing techniques, and exploiting them for novel pulsar science will form the central theme of the project. This includes, for example, an accurate characterisation of the signal distortion caused by the ISM (important for high-precision timing applications such as pulsar timing arrays) and the holographic reconstruction of the interstellar microstructure at resolutions unattainable by other techniques. The project involves close collaboration with the University of Auckland and Manly Astrophysics.

Fig 1: Dynamic scintillation spectrum of the millisecond pulsar J0437-4715 (left) and its secondary spectrum (right), from MWA observations (Bhat et al. 2018). Faint parabolic arc-like features arise from the deflected parts of pulsar’s scattered radiation. The indicated delays (~microseconds) will be directly measurable using the new capabilities and the advanced techniques that will be realised through this project.
Pulsar Science with the FAST and the First SKA-Low Precursor Telescopes

Pulsars – i.e., rapidly-spinning neutron stars, produced by massive stellar explosions – are proven laboratories of nature for advancing fundamental physics. Those with spin periods of the order of a few milliseconds, or in compact orbits with another star, are highly promising for wide-ranging physics and astrophysics. For example, the clock-like stability of their pulse arrival times can be exploited for applications ranging from searching for ultra-low frequency gravitational waves to probing the state of ultra-dense matter. This array of exciting science is enabled by discoveries of exotic pulsars that allow us to probe new physics, in particular physics under extreme conditions, such as strong-field gravity, or matter at nuclear densities. Indeed, fundamental physics with pulsars is a recognised headline science theme for the upcoming Square Kilometre Array (SKA) telescope.

The unprecedented collecting area of the newly-built Five-hundred metre Aperture Spherical Telescope (FAST) in China makes it the most sensitive instrument to search for pulsars. This is vividly demonstrated by a growing number of new discoveries and candidates that are emerging from pulsar search program under way the FAST. On the other hand, the massively large field of view of the Australian Murchison Widefield Array (MWA) – hundreds of square degrees at frequencies 100-200 MHz – makes it an excellent survey instrument at low radio frequencies. High time resolution digital archives of the full southern sky will be produced by an all-sky survey program under way at the MWA, and these data can be mined for important confirmation and/or follow-up observations of new pulsar discoveries and candidates from the FAST. Similarly, potential pulsar candidates and discoveries from the MWA can be efficiently followed up using the high-frequency capabilities of the FAST telescope.

This project will capitalise on the unique, and highly complementary, capabilities of the two major radio telescopes – the FAST and MWA, to undertake rapid follow-up and confirmation of promising pulsar candidates. Besides the prospects of discovering exotic pulsars in the large swathes of the common skies of these two major facilities, this will constrain the spectral, scattering and emission of properties of numerous pulsars, which will be valuable to forecast pulsar survey yields expected with SKA1-Mid and SKA1-Low.

Research Field
Observational Pulsar Astronomy

Project Suitability
PhD
Masters

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Co-Supervisors
Di Li (NAOC)

The Five-hundred metre Aperture Spherical Telescope (FAST) in China (left) and Australia’s Murchison Widefield Array (MWA; right) have substantial common skies and contemporaneous sky visibilities, to enable some unique pulsar science.
Resolving Pico-arcsecond Structures in Relativistic Plasmas Around Pulsars

Pulsars, or neutron stars, are exquisite laboratories for studying extreme, high-energy physics. Their super strong gravitational and magnetic fields cannot be replicated on Earth, making the environments of pulsars the only places in the Universe in which ultra-relativistic plasmas can be studied. Pulsars emit highly coherent beams of radio waves, which are detected as a series of pulses as the neutron stars rotate and the beams sweep by the Earth. The physics that underlie the emission mechanism is not well understood and is one of the most celebrated unsolved problems in modern astrophysics.

Because neutron stars are so small (~25 km in diameter) and distant (thousands of light years), they cannot be resolved by conventional imaging techniques. However, thanks to their rotation, pulse-to-pulse variations in the observed time series contain information about the spatial structure and dynamics of the emitting relativistic plasma. Pulsar signals are known to exhibit structure on a wide range of timescales, from milliseconds and microseconds down to nanoseconds (cf. Hankins 1971, Cordes 1981, Hankins et al. 2003), with the finest time structures corresponding to physical structures on the order of metres!

Owing to the technical challenges of obtaining high-quality, ultra-high-time resolution recordings of pulsars, the smallest timescales (~microseconds to nanoseconds) are rarely studied in detail. However, recent advances in instrumentation and software have now made this possible with the Murchison Widefield Array (MWA), Australia’s premier pathfinder telescope for the Square Kilometer Array (SKA) project. As a well-established instrument for pulsar studies, the MWA is uniquely positioned to become a leader in ultra-high time resolution studies of pulsar emission mechanism.

This project will exploit the MWA’s new high-time resolution capabilities to study several bright pulsars in the southern sky, whose micropulses (i.e. microsecond structures) have not previously been observed. The primary focus will be to uncover the physics that governs the dynamics of the relativistic plasma by mapping out the locations of the emitting blobs as they change over time. The frequency structure of “micropulses” will be studied over the full frequency band of the MWA (~ 80 to 300 MHz), yielding further insights into the underlying plasma physics as well as enabling unprecedented studies of the dispersive properties of the interstellar medium through which these micro pulses propagate.

**Research Field**
Pulsar Astrophysics

**Project Suitability**
PhD
Masters

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*Left:* A cartoon diagram showing a pulsar’s polar cap, depicting a carousel arrangement of sparks made up of individual microbursts.  
*Right:* A time series showing “nanoshots” in a giant pulse from the Crab pulsar. These structures reveal the presence of emitting regions on the order of metres (from Hankins et al. 2003).
Uncovering Southern-sky Pulsars with a Next-generation Low-frequency Radio Telescope

Pulsars – rapidly-rotating, highly-magnetized neutron stars that emit beams of radiation like cosmic light houses – are nature’s premier laboratories for advancing fundamental physics. With applications ranging from testing strong-field gravity to probing the state of ultra-dense matter, they enable us to push the boundaries of physics. While > 2500 pulsars are currently known, a vast majority were found in surveys using large single-dish telescopes such as the Parkes and Green Bank telescopes. Historically, pulsar surveys are proven to be highly rewarding, with a multitude of science enabled by the discoveries of exotic objects and specialised targets, including pulsars in relativistic binary systems, millisecond pulsars, and those with extreme magnetic fields. Not surprisingly, fundamental physics with pulsars is a headline science theme for the Square Kilometre Array (SKA), and conducting a full cosmic census of the Galactic pulsar population is a high-profile key science driver for the SKA.

However, finding pulsars with SKA precursor and pathfinder telescopes pose numerous challenges. The computational costs involved in beamforming and signal processing with these next-generation facilities are prohibitive, besides the inherent complexity in realising their full potential given the large field of view and attainable survey efficiency. Australia’s Murchison Widefield Array (MWA) – a low-frequency (80-300 MHz) telescope in Western Australia, and official precursor for the low-frequency SKA – is no exception. Fortunately, with a major recent upgrade (the Phase 2 MWA), it has become possible to conduct sensitive pulsar searches with the MWA, reaching a survey efficiency ~2-3 orders magnitude higher than that possible with any other currently operational facilities around the world.

This project will involve processing large volumes of (~Petabyte scale) high time resolution data from an all-sky pulsar survey under way at the MWA – the Southern-sky MWA Rapid Two-metre (SMART) pulsar survey. It is an ambitious program to search the vast southern skies with a high sensitivity at low radio frequencies. The survey is expected to discover hundreds of pulsars including dozens of millisecond pulsars (Figure 1), and will serve as an important reference for future surveys planned with the upcoming SKA. The MWA’s unique access to the southern sky provides the opportunities to explore a new parameter space, and thence potential for making exciting discoveries, and prospects for high impact science.

Figure 1: The pulsar population detectable with the SMART pulsar survey under way at the MWA. The filled circles in grey are long-period pulsars (i.e. spin periods ~ seconds) whereas those in colour represent millisecond pulsars.
Stars & Stellar Evolution

In addition to our four priority research areas, our staff also work on a variety of other projects, many of which relate to stars and stellar evolution. Topics of interest range from coronal mass ejections from our Sun to white dwarfs, supernova remnants, and maser emission from evolved stars.
Interplanetary Weather Forecasting with the Murchison Widefield Array

Our society is heavily reliant on infrastructure such as power grids and Satellite Navigation Systems. However a major Space Weather event such as those that occurred in the 19th century and the first half of the 20th century could place these technologies at risk. In fact it has been estimated that the cost of a Carrington-like event could be 1 trillion USD. Consequently, predicting the severity of such events in advance is a hugely important topic.

Just as stars twinkle in the night sky, compact radio sources twinkle due to turbulence in the solar wind, a phenomenon known as interplanetary scintillation (IPS). This technique is useful both for studying compact radio sources, and for making measurements of the solar wind. The latter will be the focus for this project, with a particular focus on using MWA IPS observations to detect Coronal Mass Ejections (CMEs).

We have a quarter of a Petabyte(!) of observational data consisting of ~1000 observations taken in the first half of 2016 when the Sun was relatively active. We believe that there should be 185 Coronal Mass Ejections detectable within this data.

The initial phase of the project will be to reduce this huge amount of data (or a large subset of it), and determine what major events are detected within it. The next phase will to connect as many events as possible to Coronal Mass Ejections detected by other instruments (primarily LASCO), and also detected via in-situ measurements in Earth Orbit and elsewhere. The expectation is that not all MWA events will have been detected previously, and that the MWA measurements will be able to significantly refine our understanding of how the ejections evolved as they moved away from the Sun.

As well as working with the huge archive of existing data there will also be the opportunity to make new observations with the MWA, and developing creative ways to use the instrument to detect and track space weather.

You will also have the opportunity to work with an international network of collaborators across East Asia, India, the US and Europe, as well as more locally with CSIRO.

Research Field
Radio Astronomy

Project Suitability
PhD/Masters
Honours

Project Supervisor
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Co-Supervisors

1 A CME detected by the MWA. Each point is a scintillating source and stronger scintillation indicates denser solar wind. The CME can be seen as an increase in scintillation equidistant from the Sun.
Mapping the magnetic field structure of white dwarfs

White dwarfs represent the final stage of stellar evolution for the majority of stars and they provide one of the most sensitive probes into the history of stellar formation in the Milky Way due to their predictable cooling rates. A significant fraction of these stellar remnants harbours a magnetic field ranging from a few 100 G up to several 100 MG and it can affect the evolution and atmosphere structure of the white dwarf, as well processes such as accretion flows. The origin of magnetic fields in white dwarf stars remains unknown. Currently two leading theories have been proposed to explain the presence of magnetic fields in white dwarfs. The first is the fossil field origin, which means that the white dwarf has inherited the magnetic field from its progenitor, which is usually assumed to be a magnetic peculiar A and B star (Ap and Bp star). However, this scenario fails to explain the paucity of magnetic white dwarfs in close but non-interacting orbit with low-mass main-sequence stars. This leaves magnetic cataclysmic variables without direct progenitors, and as a result, a second origin was proposed. In this second scenario, a magnetic field is created within binary systems, either during a common envelope phase or in the merger of two white dwarfs. The two theories predict different magnetic field structures and rotational velocities. A study of the strength of the magnetic field, its surface structure and whether it is correlated with the white dwarf mass and/or cooling age will provide clues to the origin of the magnetic field. To understand the origin of magnetic fields and the role it plays in white dwarf atmospheres and evolution, we must first know the field strength and structure.

The European Southern Observatory (ESO) operates several 4m to 8m optical telescopes in the Chilean Atacama Desert which provides the best observing conditions on Earth. These telescopes are equipped with state-of-the-art instruments covering a vast range of the electromagnetic spectrum from the near ultraviolet and optical to the infrared. Therefore, ESO provides the ideal tools that are needed to carry out detailed studies of white dwarf stars.

The aim of this project will be to study the magnetic field structure of white dwarfs known to show variability in photometry, spectroscopy or spectropolarimetry. You will calculate magnetic model spectra and develop fitting programmes to find a unique solution to the field structure through mapping the magnetic field on the surface of the white dwarf. The model spectra will be compared to photometric, spectroscopic and spectropolarimetric data. Since Australia has access to 8m class telescopes of the ESO and its vast range of instruments, this project will primarily use data obtained with ESO.

Research Field
Stellar Astrophysics

Project Suitability
PhD
Honours

Project Supervisor
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Co-Supervisors
A/Prof James Miller-Jones

Figure 1: Artist’s impression of stellar magnetic field lines (Credit: ESO/L. Calcada)
Radio Recombination Lines with the MWA

Radio recombination lines (RRL) are produced when atoms cascade into a series of successively lower ionisation states. In particular, the RRLs found at low frequencies are highly sensitive probes of the environment where the atoms are found, making them useful diagnostics of temperature, density and pressure.

RRLs at low frequencies were first discovered in 1980 and have since been discovered at frequencies from 10 to 1420MHz. However, the region between 70 — 200MHz is not well-studied. Early studies suggest that somewhere between 100 and 200MHz the RRLs transition from emission lines to absorption lines. Recent constraints from studies by LOFAR have suggested that this transition may be around 130MHz, but it is highly dependent on the environment in which they are detected.

This project will use a new spectral line pipeline to process Galactic plane observations taken with the Murchison Widefield Array (MWA). While the pipeline is faster than previous pipelines, it has not yet been used on very large fields-of-view in the Galactic plane, and this project can test the utility over wide fields. The resulting spectra will be searched for RRLs, with a particular focus on carbon recombination lines, which are detectable at low radio frequencies, because the signal is boosted by collisional excitation.

Aims of the project:

i. Use the new pipeline to process MWA data and compare with previous results;
ii. Search for carbon RRLs across wide bandwidths, and search for the transition point between absorption and emission;
iii. Use these results to probe the environments of the regions in which they are found.

This project is suited to a student with a good grounding in astrophysics, willingness to learn supercomputing, and a good understanding or willingness to learn statistics so that these sensitive measurements may be made in a robust and quantitative way.

Figure 1  The Orion Nebula in optical light (left) and radio (right), the latter as observed by the MWA GLEAM survey. This project would involve using the fine frequency resolution of the MWA to search for radio recombination lines in star-forming regions like Orion.
Searching for bound supernova remnants

When a white dwarf explodes in a supernova, it may leave behind a bound remnant that is expelled with a large velocity. Supernovae that involve white dwarfs are classified as Type Ia supernovae. These cataclysmic events are standard candles used to measure cosmological distances and measure the age of the universe. We know that these types of supernovae are caused by the thermonuclear disruption of a white dwarf whose mass has reached the Chandrasekhar limit of 1.4 solar masses, the maximum mass of a white dwarf star. However, we know very little of the evolutionary paths leading to these explosions. A subclass of Type Ia supernovae are the subluminous Type Ia supernovae and these are predicted to leave behind a remnant of the exploding white dwarf. Only a handful of these remnants have been found.

The aim of this project will be to search for bound remnants and to study the properties of these stars. These surviving stars can be identified first by their peculiar Galactic motion and also their unusual physical characteristics, such a very low mass and an atmosphere without hydrogen or helium. As part of this project you will measure the stars’ motion through the Milky Way and retrace its past motion to identify the position of the supernova event. You will also analyse spectroscopic and photometric data to determine the bound remnants’ properties such as the temperature, mass and atmospheric composition using the latest model atmosphere and spectral synthesis codes.

This project will exploit the data from the orbital observatory Gaia that is measuring accurate positions, distances and velocities of over a 100 million stars in the Milky Way. The project will also involve observations obtained using the 4m to 8m optical telescopes of the European Southern Observatory (ESO) that is located in the Chilean Atacama desert and which provides the best observing conditions on Earth. These telescopes are equipped with state-of-the-art instruments covering a vast range of the electromagnetic spectrum from the near ultraviolet and optical to the infrared. Therefore, ESO and Gaia provide the ideal tools that are needed to carry out detailed studies of white dwarf stars, including bound remnants of supernova explosions.

Figure 1: Artistic view of the remnant of a supernova explosion (Copyright Russell Kightley (http://scientific.pictures), used with permission.)
Searching for merged stars in the white dwarf population

White dwarfs that underwent a merger event will have distinctive properties. The most notable of these are the acquisition of a magnetic field and fast rotation. One group of white dwarfs, the rare hot, carbon-rich white dwarfs (hot DQs), has an exceptionally high incidence of magnetism and fast rotation as compared to the general white dwarf population. These stars with their unusual atmospheric composition are also more massive than average white dwarfs, and all these properties suggest that they are products of merger events. Currently, only a small number of these stars are known, and they all have similarly hot effective temperatures. We do not know what their descendants are. Since white dwarfs are no longer burning any fuel, they are simply radiating out their internal heat and therefore they become cooler with age. Descendants of hot DQ stars will therefore have similar properties to hot DQs but will be much cooler.

The aim of this project will be to identify candidate white dwarfs that have carbon in their atmosphere but have lower temperatures. Such white dwarfs exist, but their properties such as mass and rotation are largely unknown and therefore, they cannot be evolutionarily linked to hot DQs. As part of this project you will analyse spectroscopic, spectropolarimetric and photometric data of these candidate descendants and determine their stellar properties such as their temperature, mass and atmospheric composition using the latest model atmosphere and spectral syntheses codes.

The European Southern Observatory (ESO) operates several 4m to 8m optical telescopes in the Chilean Atacama Desert which provides the best observing conditions on Earth. These telescopes are equipped with state-of-the-art instruments covering a vast range of the electromagnetic spectrum from the near ultraviolet and optical to the infrared. This project will also exploit data from the orbital observatory Gaia that is measuring accurate positions, distances and velocities of over 100 million stars in the Milky Way. Therefore, ESO and Gaia will provide the ideal tools to carry out detailed studies of these hot DQs and their descendants.

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**Research Field**
Stellar Astrophysics

**Project Suitability**
PhD
Honours

**Project Supervisor**
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**Co-Supervisors**
A/Prof James Miller-Jones

**Figure 1**: A spectrum of a carbon-rich white dwarf showing Zeeman broadened carbon lines representative of a magnetic field of 0.6 MG (top) and a circular polarization spectrum showing the characteristic choppy pattern of the Zeeman components of the carbon lines (bottom).
Searching the Skies for Supernova Remnants

When a massive star reaches the end of its life, it explodes in a supernova, ejecting an enormous amount of energy and some of its mass into the surrounding interstellar medium. This fast-moving spherical shockwave expands and emits radiation, glowing brightly in the optical, radio, and X-ray parts of the electromagnetic spectrum; astronomers detect this as a supernova remnant (SNR), and it can last 10 – 100,000 years. Given what we know about star formation in our Milky Way galaxy, we would expect to find about 3,000 of these remnants, but only about 300 are known. This is due to several factors: the older SNRs are very large and faint; the younger SNRs are compact and can be mistaken for other objects without detailed observations; the spectra of SNRs are distinctive, but existing radio surveys often do not have the required frequency coverage to discriminate between SNRs and other Galactic objects.

Fortunately, the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey is sensitive to these objects. Early searches have detected 26 new SNRs, an increase of nearly 10% in known SNR from just half of the GLEAM data. The new Galactic Plane data from the higher-resolution GLEAM-eXtended survey will be particularly rich for finding younger, more compact SNRs. Not only will the project use these novel radio data, it will also use data from the eROSITA X-ray satellite, which will confirm GLEAM-X detections, and enable study of the internal physics of the SNRs, and probe their interactions with their environments.

Aims of the project:

i. Process GLEAM and GLEAM-X Galactic Plane data to produce wideband images of regions of the Galactic plane (at PhD level, the entire visible Galactic Plane);

ii. Jointly search the radio and X-ray data for new supernova candidates;

iii. (Masters, PhD-only) Select interesting subsamples of SNRs to follow up with further observations, to probe the physics of the SNR interactions with their environments.

This project is well suited to a student with a strong interest in astrophysics and astronomy, willingness to learn low-frequency radio astronomy, and good computing and organisational skills. The project is part of a collaboration with X-ray astronomers at the Max-Planck Institute for Extraterrestrial Physics in Munich (Germany), and short-term visits to MPI may be possible for Masters and PhD students. This project is available as a Curtin-funded PhD position in support of Dr Hurley-Walker’s ARC Future Fellowship.
Silicon monoxide masers towards evolved stars

Asymptotic giant branch stars and red super-giant stars are common sources to power silicon monoxide (SiO) masers. Masers can be thought of as naturally-occurring radio-wavelength lasers, and are powered by energetic and exotic conditions in space. In this study, the SiO masers are powered by in-falling and out-flowing motions of gas surrounding an evolved star, most of which are called hydroxyl (OH) or infrared (IR) stars.

As not much is known about these masers, this project presents an opportunity to advance the "big picture" science of evolved stars. The student will process and analyse data collected with the Australia Telescope Compact Array, a radio telescope in northern New South Wales, with approximately 60 targets. Each of the target observations contains multiple spectral line transitions, including each of the v=1, 2 and 3 maser line transitions; any discovery of relationships between the different spectral lines will be an important contribution to the understanding of evolved OH/IR stars.

In extremely rare cases, SiO masers can be excited by star-forming regions. A detection of this kind would be very important and have a high impact in the community, warranting further investigations.

In the course of this work, the student will develop a good understanding of interferometry and data processing. The results from this work could easily be formatted into a publication, which would be of huge benefit to a student pursuing research into the future with a PhD or masters project. The project is suitable as either a third year or an honours project.

Aims of project

(i) Identify maser locations in high-resolution data;
(ii) Associate maser parameters with physical conditions;
(iii) Constrain the physical conditions required to exhibit different types of masing conditions, and identify the properties of the v=3 maser line.

Figure: A three-colour image of different infrared maps overlaid with the locations of detected SiO masers. All masers appear to be associated with an OH/IR star. The data associated with this project are high-resolution follow-up observations of each of these locations to learn more of these environments.
The focus of the engineering program is research and development in radio astronomy engineering. Key areas of research will focus on high impact contributions to the SKA, and in particular, SKA-LOW. The SKA and its precursors and prototypes provide the overarching context for the engineering program.

Many of the projects address electronic engineering topics which have broad application in the telecommunications, defence and space sectors, and graduates in this field work across a wide range of institutions and industries.

Two Primary Engineering Themes are as follows:

- Astronomical instrumentation and signal processing
- Radio frequency front-ends
Astronomical instrumentation and signal processing

This project builds on existing success in the development of hardware and software systems for astrophysics-focused radio astronomy systems, and adds new scope with support for an EoR Global Signal science program, and RFI mitigation program.

This project continues support SKA1-Low verification and commissioning by contributing to data collection, analysis and interpretation from the SKA-Low prototypes as part of the larger international consortium. This activity is working in closely with the E2 program, which includes detailed understanding of the antenna systems. This project will continue to make use of the CIRA Engineering laboratory.
A 4x4 phased-array transmitter for bistatic radar

Phased-array antenna systems have widespread use in diverse areas such as radar, radio astronomy and 5G telecommunications.

This project will build upon existing work to design, build and commission a 4x4 phased-array transmitter for use in communications and bistatic radar experiments.

The overarching goal of this project is for the transmitter to be used as part of the Space Debris Illuminator bistatic radar system, with the low frequency radio telescopes at the Murchison Radio-astronomy Observatory to be used as the receiving elements.

**Aims of project**

(i) expand upon an existing 4x1 phased-array system to complete the design and construction of a 4x4 phased array transmitter

(ii) design and build control software for the phased array

(iii) deploy the system and perform performance characterisation experiments.

**Figure 1:** This is an MWA tile, which is a 4x4 phased array receiver.
Radio propagation in the LF and HF bands using modern digital communications.

Intercontinental radio communications has long used the Low Frequency (LF) and High Frequency (HF) radio bands, where the Earth’s ionosphere reflects radio waves, enabling communication far beyond the horizon.

Modern hardware and signal processing techniques allow new experimentation and development for radio communication hardware and experiments in these bands.

This project aims to measure the properties of the ionosphere using modern wideband software radio systems and utilising digital radio transmitters as active high-power probes of the ionosphere.

Aims of project

(i) Long-term observation and monitoring of international digital radio broadcasts

(ii) derivation of the propagation and signal scattering environment

(iii) Improved models of the large-scale density and turbulent structure of the ionosphere.

Figure 1: Schematic of radio propagation. https://www.spaceacademy.net.au/library/notes/rviono.htm
A Lego Radio Telescope Simulator

This project will design and build the hardware aspects of a “Lego Radio Telescope” simulator, which is intended as an outreach and education tool to help people understand how array configuration affects the performance of radio telescopes.

The project is intended to work in tandem with a software system that will simulate the performance of a telescope and display the results on a screen.

The goal of the project is to allow people to re-arrange the locations of lego telescope antennas. The system detects the locations of the antennas and transmits that to the accompanying software system.

This project would suit a student with an interest in radio astronomy, electronics and microcontrollers.

Aims of project

(i) Design system for detecting location of antennas

(ii) Design system for communicating the locations of antennas between hardware and software display system

(iii) work with outreach team to maximise education and outreach potential of the system as well as practical aspects for portability etc.

Research Field
Radio Astronomy/Engineering

Project Suitability
Masters, Final year Engineering
Honours (as appropriate)

Project Supervisor
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Co-Supervisors
Dr George Heald (CSIRO)
Active Radio Frequency Interference cancellation with advanced signal processing

Human generated Radio Frequency Interference (RFI) from terrestrial and orbiting transmitters is an ever-increasing challenge for radio astronomy. Strong RFI signals can completely swamp the faint signals from astronomical radio sources, rendering data partially or completely corrupt.

There are many approaches to dealing with RFI in radio astronomy data, but most of them involve identifying and discarding affected data. Ideally, we would like to use sophisticated signal processing techniques to reduce or remove the RFI entirely, thus restoring parts of the radio spectrum that are otherwise corrupted due to RFI.

A promising method of dealing with RFI is to use additional reference antennas to create a high-quality copy of the interfering signal, which can be cross-correlated with the radio astronomy data. In principle, this can completely remove the interference.

Aims of project
(i) Build on existing work using a reference antenna at the MWA site
(ii) Incorporate real-time data stream from the reference antennas into the MWA and/or SKA-Low prototype systems.
(iii) Quantify the level of interference cancellation achievable in the context of MWA and SKA key science programs.

This project will make use of the Curtin-operated telescopes MWA and potentially the SKA-Low prototype arrays.

The ideal student will have a strong interest in radio astronomy, computing and signal processing.

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Figure 1: The SKA-Low prototype Engineering Development Array
Performance characterization of the Space Debris Illuminator

The “Space Debris Illuminator” is a dedicated steerable radio transmitter array intended for “illuminating” the low earth orbit area above the MWA radio telescope. The system transmits at 144 MHz.

The Space Debris Illuminator forms the transmitter part of a bistatic radar system with telescopes at the Murchison Radio-Astronomy Observatory forming the receiving part.

This project will finalise the signal chain and undertake a detailed characterisation of the performance of the system, in particular comparing against passive radar techniques that have been used with the MWA radio telescope.

Aims of project

(i) Complete the commissioning of the signal chain
(ii) perform test observations in conjunction with receiving arrays at the MRO
(iii) characterise the sensitivity and performance of the telescope.

This project will uniquely exploit the frequency coverage of many Australian radio telescopes such as the Curtin-operated telescopes MWA and EDA at the MRO.

The image on the right shows the dedicated antennas for the Space Debris Illuminator, which transmits at 144 MHz.
Signal Server – a real-time software radio data server

Modern software defined radio (SDR) systems stand in stark contrast to traditional hardware radios in their ability to deal with very large bandwidths, both in receiving and transmitting. A single device often has sufficient bandwidth (MHz or more) to “listen” to an entire radio frequency band simultaneously.

This project aims to build an open-source “radio data server” which will allow clients to connect to it and listen to relatively small chunks of radio spectrum, streamed as data over the internet.

Aims of project

(i) Survey of existing closed-source radio data server APIs
(ii) Design of system
(iii) Implementation and testing in the CIRA lab

This project would suit a student interested in radio engineering and signal processing, with good computing skills.

Figure 1: Screenshot of software radio system “gqrx” based on a software radio interface
Search for Terrestrial and Extraterrestrial Technosignatures with the MWA

The radio Search for Extraterrestrial Intelligence (SETI) is a worldwide effort aiming at detecting artificial radio transmissions from intelligent and communicative civilizations throughout the Universe, and demonstrate the non-uniqueness of life across the Universe. Many SETI programs have been conducted over the last decades, searching for narrowband features of non-human origin. Most of these ran on commensally collected data from world-class radio telescopes, with limited flexibility in sky, time, and frequency coverage.

The Murchison Widefield Array is (MWA), operated by the Curtin Institute of Radio Astronomy, is a low-frequency radio interferometer unparalleled in its wide field-of-view and the flexibility it offers to implement state-of-the-art signal processing methods to detect unknown artificial transmissions. The project offered here involves the development of an imaging pipeline - called Cyclone - enhancing active information-bearing radio transmissions through the exploitation of their non-stationary features, to distinguish them from natural astronomical transmissions. Figure 1 shows a comparison between the classic astronomical imaging pipeline and the Cyclone pipeline with a simulated data set featuring a natural astronomical source and an artificial transmission. The detected transmitters will then be classified into terrestrial or non-terrestrial sources after a thorough analysis of their locations and trajectory. This imaging system will be the first high-sensitivity wide-field SETI pipeline, releasing spatial constraints in the search parameter space. The detection of terrestrial transmitters will also support the creation of a Radio Frequency Interference database, providing an accurate assessment of the radio quietness and possible observational threats to the MWA telescope.

This project is suitable for students with Instrumental astronomy / Signal processing / Computer science backgrounds. Good programming skills required (C/CUDA/Python).

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**Research Field**
Radio Astronomy/Engineering

**Project Suitability**
PhD
Honours

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Figure 1. Simulated comparison between the classic astronomical imaging pipeline and the Cyclone imaging pipeline

a. Simulated result of classic all-sky energy-based imaging, featuring both an astronomical source (SNR = +5dB, highlighted in red) and an artificial transmitter (SNR = 0dB, highlighted in green)

b. Simulated result of the Cyclone imaging pipeline run on the same dataset as shown in figure (a). The natural source is this time not detected, whereas the artificial transmission has been enhanced.
A database for monitoring radio-frequency interference at the Murchison Radio-astronomy Observatory

The Murchison Radio-astronomy Observatory (MRO) is located in a remote area of Western Australia where a Radio Quiet Zone (RQZ) has been established in order to ensure high quality astronomical data. The MRO currently hosts several low-frequency (50 – 350 MHz) radio-telescopes including the Murchison Widefield Array (MWA; Tingay et al 2013), precursor stations of the low-frequency component of the Square Kilometre Array (SKA-Low) amongst the other instruments. The SKA-Low is a huge international endeavour to be built at the MRO in the next decade. Although the MRO is located at a designated RQZ with significant regulatory protections, radio-frequency interference (RFI) from aircraft and satellite (for example ORBCOMM communication satellites) is often observed as well as occasional interference from distant FM radio and digital TV transmitters.

In order to monitor and characterise the RFI environment at the MRO several RFI surveys have already been conducted in the recent years. Two of them used BIGHORNS broadband system (Sokolowski et al, 2015) in order to characterise RFI occupancy of the observing band between 50 – 350 MHz (Sokolowski et al., 2016) and frequency of occurrence of long-distance propagation events, so called tropospheric ducting (Sokolowski et al., 2017).

The goal of the this project is to create a database of RFI using the archival and new data from BIGHORNS and other instruments operating at the MRO. The database will be updated as new data are being collected and will be used in order to enable daily monitoring of the RFI quality of the future site of the SKA-Low telescope and provide information to astronomers using data from radio-telescopes already operating at the MRO. The RFI database will also enable software programs to verify quality of the data from these instruments (for example the MWA) by flagging particular time intervals where in-band or out-of-band (especially strong) RFI was observed.

Occupy of the 70 – 350 MHz band over a couple of months in 2014 and 2015 obtained from analysis of BIGHORNS data

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**Research Field**
Engineering

**Project Suitability**
Masters / Honours / potentially expandable to a PhD level

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The BIGHORNS broadband antenna at the MRO
Radio Frequency front-ends

This project builds on existing success in the prototyping, validation and verification of SKA-Low demonstrator arrays. The highest priority of this project is to support SKA1-Low by providing simulation, measurement, analysis and by developing tools to characterise key performance parameters of a low-frequency aperture array. The project collaborates closely with E1 in ensuring that radio astronomy instrumentation effects are well understood and the results and tools are clearly documented and efficiently implemented.

The radio-frequency laboratory has been an integral part of SKA precursor and prototyping verification since the start of CIRA. This project will continue to ensure that the laboratory capabilities are well-maintained and stand ready to perform critical measurements for SKA1-Low. The combination of experience, skill set and equipment will continue to develop to meet the demands of SKA1-Low as well as to position CIRA to capture new opportunities in space science, satellite communications, space situational awareness and defence.
The Square Kilometre Array (SKA) project is an international effort to build the world’s largest radio telescope, with eventually over a square kilometre (one million square metres) of collecting area. SKA-LOW, the low frequency component of the Square Kilometre Array radio telescopes, will be deployed on the Murchison Radio-astronomy Observatory (MRO) in Western Australia. Our engineering team is currently working on the analysis and simulation of this pioneering system. It will consist of a large array of essentially dipole-like radiators, clustered into “stations” of 256 antennas.

Contemporary array theory leverages computational electromagnetic simulation, in particular generating embedded element patterns, from which key system parameters can be evaluated, determining the efficacy of the system. Additionally, these patterns may be required for regular system calibration. The accuracy of the computation of these patterns has never been comprehensively investigated, and this is a key component of this research project, with a particular focus on the impact thereof on radio telescopes comprising aperture arrays.

The key aim of this project is to advance methods for evaluating and ensuring the accuracy and reliability of CEM simulations, in particular for array simulations and SKA-Low. This will be achieved through a combination of numerical experimentation, mathematical analysis and experimental validation.

Figure 1: The AAVS1 prototype on the MRO. (Photo: DB Davidson).
Intentional high-power microwave (HPM) interference poses a serious threat to electronic, communication and computer systems worldwide. HPM sources are able to reach radiated power levels in excess of hundreds on megawatts and even reaching gigawatt levels. These intensely powerful sources coupled with high-gain antennas are capable of delivering sufficient radiation to cause system upset and permanent failure from kilometre distances.

Given the reliance of our modern world on proper functioning of such systems, it is rather surprising that no standard has been fully developed that governs the susceptibility and immunity of electronic products against the HPM interference. This project seeks to contribute to further understanding of the interaction of HPM radiation with electronic devices through analysis, modelling and measurement that are key to the development of such standards. The analysis entails identifying the most susceptible coupling path from the incident electromagnetic wave to the target device. This involves modelling the electromagnetics of the target device as well as modelling the response of the circuit to the interference. These modelling and calculate results are validated against prototype measurements.

This project builds on the existing collaboration between the Curtin Institute of Radio Astronomy (CIRA) and the Defence Science Technology (DST) group in understanding the interaction of HPM with electronic devices. The student has the opportunity to perform experiments at the radio frequency instrumentation laboratory at CIRA and Curtin as well as interact with DST subject matter experts.

**Research Field**
- Electronic Engineering
- Electromagnetic Compatibility
- Computational Physics

**Project Suitability**
- PhD/MPhil

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**Co-Supervisors**
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Drones for antenna pattern measurements

This project will investigate the use of drones for measuring antenna patterns, in particular those of the Square Kilometre Array radio telescope “station” (an array of 256 dual-polarised log-periodic antennas, laid out in a semi-random fashion on an approximately 40m diameter ground plane). This project will in particular focus on using near-field to far-field (NF-FF) transformation methods over the operating band (50-350 MHz), as it is difficult to fly high enough to be fully in the far-field. The project has quite a wide scope, and grows on a current project which is building a drone. The student undertaking it could focus on theoretical aspects of NF-FF transformation, or on practical aspects of instrumenting the drone, or a combination of these.

Figure 1: A UAV team working on the MRO site. Credits INAF & ICRAR.
Metamaterials for radio astronomy engineering

Metamaterials are artificially engineered materials with electrical and magnetic properties not occurring in nature at radio frequencies – examples include “double negative” materials, with negative permittivity and permeability. These have been used in the theoretical development of transformation optics for electromagnetic cloaking, which has been demonstrated experimentally for some special geometries.

The aim of this project is to investigate the use of metamaterials for realizing new concepts in antenna elements for low-frequency radio telescopes, such as SKA-Low and other concepts. One line of investigation will focus on dense, regular arrays where strong mutual coupling complicates the design of wideband antenna arrays.

The application of metamaterials is an important topic in contemporary antenna engineering in general and this project overlaps strongly with many other applications of antennas in telecommunications, defence etc.

Figure 1: A split-ring resonator, part of a metamaterial array. Credits: NASA, public domain.
Sensitivity of Low-Frequency Polarimetric Phased Array Radio Telescope

The Low-Frequency Square Kilometre Array (SKA-Low) is the next-generation radio telescope that spans the frequency band from 50 MHz to 350 MHz. The SKA-Low has the characteristics of consisting of over a hundred thousand dual-polarized antennas. These antennas are fixed to the ground and are grouped into 256 stations in which the antennas are closely coupled. Telescope pointing is achieved electronically—without mechanical pointing—and the field-of-view (FoV) is wide. These features differentiate the SKA-Low from the more traditional dish-based telescopes which are mechanically pointed, have narrower FoV and in which the dish antennas that do not couple with one another. As a result, many of the key assumptions, equations and figure-of-merit (FoM) that apply to dish-based observation need review.

One of the most essential FoMs is the sensitivity of the telescope. This is a measure of the standard deviation of the estimate of the power of a target source under observation relative to the power of that source. Because the FoV is wide and the antennas point electronically, the target sources are always observed at oblique angles relative to the central axis of the antenna (z-axis in the diagram on the right). Consequently, the conventional formula that states the sensitivity of the telescope at the centre of the beam need to be generalized.

In this project the correct expression for the sensitivity of the polarimetric phased array radio telescope will be formulated. The aim to achieve an expression that is succinct, computable from basic antenna and radiometric parameters, and measurable through observation. It will treat the wide FoV and the antenna coupling, while establishing limits and careful approximations where appropriate.