South African Radio Astronomy Observatory
Research Project Proposals for Masters and Doctoral Research in 2019

Section A: Overview of the Research Project Proposal

1. Academic level: Masters

2. Field of research: Astronomy / Astrophysics

3. Title: The compact radio source population towards the Galactic Centre

4. Abstract:

This project will make use of the groundbreaking MeerKAT observations of the Galactic Centre. The radio waves penetrate the high levels of dust in this region, revealing many bright and mysterious radio structures, along with a large number of very compact features. Most stars are too faint at radio wavelengths to be routinely detected, so the true point-like sources (as opposed to things that are merely small in angular scale) will be a combination of external galaxies very distant from our own, as well as exotic objects in our own galaxy such as pulsars, and stellar-mass black holes in interacting binary pairs. Re-imaging of the MeerKAT Galactic Centre data in two frequency chunks will provide an initial classification for many of these object based on their spectral shape, and for this project additional radio observations using the Karl G. Jansky Very Large Array are also available. These are in the most extended A-configuration, so much of the diffuse emission seen in the MeerKAT image is resolved out, leaving only the compact features. Multi-wavelength data can also be used as a further discriminator, and potentially interesting objects, many of which will have never before been seen, can be identified for follow-up observations. The student undertaking this project will develop radio interferometry skills and knowledge of many different astrophysical phenomena, leading to the production the most comprehensive catalogue to-date describing the properties of compact sources towards the centre of the Milky Way.

Section B: Supervisor(s) Details

1. Primary supervisor

a. Name: Prof. Ian Heywood

b. Institution: Rhodes University

c. Contact: ianh@astro.ox.ac.uk

d. Postgraduate supervision:

PhD

Name	Nationality	Start	End	Title	Co-supervisor
Tariq Blecher	South African	2017	2020 (expected)	*Strongly Gravitationally-Lensed Neutral Hydrogen*	Prof. Roger Deane (UP)
Sphesihle Makhathini	South African	2013	2017	*Advanced Radio Interferometric Simulation and Data Reduction Techniques*	Prof. Oleg Smirnov (Rhodes)

MSc

Name	Nationality	Start	End	Title	Co-supervisor
Lerato Sebokolodi	South African	2015	2017	*Automation of source-artefact classification*	Prof. Oleg Smirnov & Dr. Sphesihle Makhathini (Rhodes)

1. Co-supervisor

a. Name: Prof. Oleg Smirnov

b. Institution: Rhodes University

c. Contact: o.smirnov@ru.ac.za

d. Postgraduate supervision:

PhD

Name	Nationality	Start	End	Title	Co-supervisor
Sphesihle Makhathini	South Africa	May 2013	June 2017	*Advanced Radio Interferometric Simulation and Data Reduction Techniques*	Ian Heywood
Marcellin Atemkeng	Cameroon (SA PRP)	Feb 2013	Feb 2017	*Data Compression, Field of Interest Shaping and Fast Algorithms for Direction Dependent Deconvolution in Radio Interferometry*	C. Tasse, G. Foster

Iniyan Natarajan	India	Feb 2013	Dec 2017	*Probabilistic Methods for Radio Interferometry Data Analysis*	K. van der Heyden, J. Zwart
Jonathan Kenyon	South Africa	Jan 2015	Dec 2018	*CubiCal: A fast radio interferometric calibration suite exploiting complex optimisation*	T. Grobler
Theo Ansah-Narh	Ghana	Jan 2015	Dec 2018	*Exploring intensity mapping techniques through simulations*	F. Abdalla, K. Asad
Etienne Bonnassieux	France	Sep 2015	Sep 2018	*Development and Application of New Algorithms for LOFAR & SKA Survey Images*	P. Zarka, C. Tasse
Lerato Sebokolodi	South Africa	Jan 2017	Dec 2019	*A new multiwavelength polarimetric study of Cygnus A*	R. Perley, C. Carilli
Ulrich Mbou Sob	Cameroon	Jan 2017	Dec 2019	*Robust calibration for radio interferometers*	L. Bester
Kelachukwu Iheanetu	Nigeria	Feb 2016	Dec 2019	*Primary beam modelling and holography for radio interferometers*	J. Girard, K. Thorat, S. Makhathini
Gijs Molenaar (part time)	NL	Jan 2017	Dec 2019	*Virtualized and containerized data reduction pipelines*	
Benjamin Hugo (part time)	South Africa	Jan 2017	Dec 2020	*Imaging and calibration for wide-field MeerKAT polarimetry*	G. Bernardi

MSc

Name	Nationality	Start	End	Title	Co-supervisor
Lerato Sebokolodi	South Africa	Jan 2015	Oct 2016	*Source-artefact classification in radio astronomical imaging*	S. Makhathini, I. Heywood
Jonathan Kenyon	South Africa	Jan 2014	Feb 2015	*PyMORESANE: A GPU-accelerated implementation of the MORESANE algorithm*	
Chuneeta Nunhokee	Mauritius	Jan 2013	Dec 2014	*Ghosts and source suppression in radio interferometry*	T. Grobler
Benjamin Hugo	South Africa	Jan 2014	Dec 2015	*Bullseye: GPU accelerated facet-based imager*	J. Gain, C. Tasse

Ulrich Mbou Sob	Cameroon	Jan 2015	Dec 2016	*Calibration and Imaging with Variable Radio Sources*	T. Grobler, S. Sirothia
Tariq Blecher	South Africa	Jan 2015	Mar 2017	*MeqSilhouette: a mm-VLBI simulator*	R. Deane
Alexander Akoto-Danso	Ghana	Jan 2015	Sep 2018	*Wide-field VLBI surveys: implementing efficient algorithms to open discovery space*	R. Deane, G. Bernardi
Cyndie Russeawon	Mauritius	Jan 2018	Dec 2019	*Parameterized solvers for pointing errors and ionospheric calibration*	F. Abdalla
Lexy Andati	Kenya	Jan 2018	Dec 2019	*Visualization frameworks for interferometric pipelines*	
Simphiwe Zitha (part time)	South Africa	Jan 2016	Dec 2018	*Machine learning methods for calibrating radio interferometric data*	Arun Aniyan
Antonio Peters	South Africa	May 2017	May 2019	*Primal-dual solvers and dimensionality reduction techniques for radio data*	L. Bester
Athanaseus Ramaila (part time)	South Africa	Jan 2016	Dec 2018	*A Practical Survey of Novel and Legacy Radio Interferometry Imaging Algorithms and Packages*	S. Makhathini
Sakhile Masoka (part time)	South Africa	Jun 2018	Jun 2021	*Distributed gridding and baseline-dependent averaging for radio interferometry data*	M. Atemkeng, S. Perkins

Section C: Full Research Project Proposal

1. Scientific merit

The centre of the Milky Way offers a unique opportunity to study many different branches of astrophysics. As the home of Sagittarius A* (Sgr A*), it contains the nearest supermassive black hole to Earth (by a factor of about a hundred), allowing highly detailed studies of how this object influences our galaxy. This can be observed via several mechanisms that are unique to radio, for example the mysterious linear filamentary structures seen exclusively in the Galactic Centre region. These are assumed to be synchrotron-emitting plasma bound to the large-scale magnetic field of the galaxy, the particle injection mechanism for which remains a mystery. In addition to (or possible due to) the presence of Sgr A*, the central molecular zone of the Milky Way, an area totalling approximately one square degree on the sky, alone accounts for about 10% of the star formation of the entire galaxy. This prodigious amount of previous and on-going star formation also gives rise to many of the famous and mysterious radio features in the region. These are either powered by strong outflows driven by the combined winds of many hot, massive stars, for example the Galactic Centre supershell, or are the result of the violent deaths of stars and the exotic objects that they leave behind, for example supernova remnants and pulsar wind nebulae.

Typical, main-sequence stars tend to emit radio emission that is comparatively very faint, and they do not routinely appear in radio continuum observations. The radio emission associated with stellar-mass objects tends to occur due to more exotic processes, and the interaction of stars with each other or with their environments. Examples include pulsar emission, and the on-going accretion processes in binary pairs, the latter producing both sustained and episodically enhanced bursts of radio emission.

MeerKAT has numerous advantages over any other radio observatory for observing the Galactic Centre. As an interferometer spanning 8 km it has the angular resolution required to detect and separate the compact features associated with these exotic stellar phenomena (as well as the inevitable background of extragalactic point sources). In addition to this, the distribution of its 2,016 individual antenna pairs gives MeerKAT unprecedented imaging capabilities at these radio frequencies. This affords high fidelity images of the complex features associated with this region, and the high dynamic range required such that the bright emission associated with Sgr A* does not dominate — the compact radio feature associated with the supermassive black hole peaks at about 1 Jy / beam, however the radio complex directly surrounding it has an integrated flux density of approximately 200 Jy. The final advantage is one of geographical location, with the Galactic Centre passing almost directly above the Karoo region, allowing long duration observations to be conducted, further enhancing the imaging fidelity.

SARAO has recently capitalised on the power of MeerKAT for observing this region by conducting a survey of the Galactic Centre region as part of the commissioning and verification of MeerKAT. The end result of this is an image covering several square degrees of the region, providing a spectacular radio view of unprecedented detail. Many known structures are seen with enhanced detail, and many new features are revealed.

This project will make use of these observations to study the compact source population within. As alluded to above, many of these sources are likely to be extragalactic background galaxies, however there will also be lurking within them many interesting stellar-mass objects in our own galaxy, such as pulsars and X-ray binaries. Many compact sources belonging to both of these objects will likely be being seen for the first time.

The student undertaking this project will identify and extract these compact features, and subsequently classify them. Classification can proceed in a variety of ways, using indicators in the radio (angular size, spectral index) as well as by employing data at other wavelengths (e.g. the presence or absence of an optical or high-energy counterpart). The use of radio continuum measurements as a cost-effective way of searching for new pulsars has been put forward, but not presently demonstrated, and this project will investigate this avenue. The end goal is a catalogue of categorised compact radio sources, identifying the ones which may be interesting candidates for follow-up observations, chiefly pulsars but also X-ray binaries, and any other objects that defy simple explanation. The identification of any pulsar candidates would be of particular interest, not only as a demonstration of the feasibility of using radio continuum imaging as a search method, but also since a population of young pulsars in the Galactic Centre are one possible explanation for (part of) the unexplained excess of gamma rays seen in this region by the Fermi satellite.

2. Feasibility

As previously mentioned the data for this project have already been taken, and SARAO has provided approval for their use within this project. However in order to develop skills in the technical aspects of radio interferometry, the student will be responsible for reprocessing the observations in order to produce images in two spectral channels, and perhaps with alternative weighting schemes that enhance the sensitivity to point-source emission. In addition to the MeerKAT data, we will use existing (unpublished) data from the Karl G. Jansky Very Large Array (Heywood is a co-I on this project, and the PI Dr. Matthew Kerr will collaborate, an expert on pulsars and high-energy astrophysics). The VLA observations cover approximately two square degrees of the same region, however they are made with the array in its most extended A-configuration. This provides very high angular resolution, and the absence of short spacings means that much of the large-scale diffuse emission in the image is resolved out by the interferometer. Combining this with the MeerKAT data will make for a very powerful diagnostic of radio morphology, allowing secure identification of sources that are truly point-like and not just merely 'compact'. The upper edge of the VLA L-band may also serve as an additional spectral index anchor point. The student will be responsible for the imaging of these observations, under the guidance of the supervisors, both of whom have extensive experience in this area. The Galactic Centre is one of the most well-studied regions of space, and the student will make use of existing infra-red and high energy X-ray and gamma-ray images of the region for this project.

The Radio Astronomy Technologies and Techniques (RATT) group established at Rhodes maintains a cluster consisting of 8 "fat" nodes (512GB RAM, 16-48 CPUs per node) with plenty of attached storage. The student will have access to this cluster. Access to the IDIA computing infrastructure will also be requested for the student in order to reprocess the Galactic Centre data. These combined computing resources are entirely adequate for the proposed project.

A plausible time-frame for the project is as follows:

Year 0 — 0.5: Literature review in the relevant scientific and technical areas. Familiarisation of the student with the hardware and software required to process the MeerKAT data. Commencement of data processing. Extraction of preliminary point-source candidate list from existing MeerKAT Galactic Centre image.

Year 0.5 — 1: Continuation of data processing. Cross-matching of candidate list with VLA and MeerKAT two-point spectral data sets. Cross-matching of candidate list with multi-wavelength data.

Year 1 — 1.5: Classification of sources in catalogue via radio / optical / IR / high-energy properties. Identification of candidate objects worthy of further investigation.

Year 1.5 — 2: Collation and finalisation of results, publication of thesis.

3. SARAO research priority areas

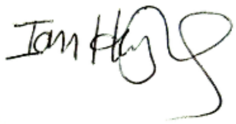
6. Science topics that involve the exploitation of MeerKAT data projected to be available by 2019- 2020.

8. Interferometric Data Processing and Analysis, including calibration and imaging.

4. Requirements of candidates

For this project a candidate would require an undergraduate degree in physics, engineering or similar discipline. A working knowledge of Linux operating systems and the Python language is desirable, and if not present the candidate must be capable of rapidly becoming familiar with both

Section D: Signatures



Ian Heywood
31 August 2018