South African Radio Astronomy Observatory

Research Project Proposals for Masters and Doctoral Research in 2020

1. All research project proposals must be submitted by a primary supervisor (see the definition of a primary supervisor in Section 1 of the Application Guide). In the case where the primary supervisor is not the research supervisor, the details of the co-supervisor, who will be responsible for supervising the research, must also be provided (as requested below).

2. Please provide the information requested below, in the order requested, and please use the same numbering, and "headings", as below.

3. As requested in the online application form, upload the research project proposal as a PDF document.

Information Required

Section A: Overview of the Research Project Proposal

1. Academic level of research project: Masters

2. Broad field of research: Astrophysics

3. Title of the research project: *Studying giant pulses in eclipsing binaries of Southerly millisecond pulsars using MeerKAT.*

4. Research project abstract/summary (max 250 words)

Project Abstract

Millisecond pulsars (MSPs) are rapidly spinning neutron stars that emit beams of radio emission from their magnetic poles. With the correct alignment, these radio beams will cross our line of sight periodically as the pulsar spins around its own axis. Sensitive radio telescopes, such as MeerKAT, can pick up pulses from MSPs and measure their time of arrival at the telescope with incredible precision.

Of the several hundred MSPs discovered to date, the majority of them are found in binary systems, orbiting a companion such as a main sequence star, a white dwarf or even another pulsar. Such binary systems can appear as eclipsing systems from our vantage point: as the pulsar moves behind its companion its emission disappears.

Some of these eclipsing systems, the so-called 'spider binaries', are in such tight binaries that the surface of the companion star is eroded into a surrounding stellar wind through the blast of the pulsar emission. This typically leads to extended observed eclipse durations, as the pulsar passes behind the outflow of material.

In 2018 Main et al. found that the pulses of PSR B1957+20 as it passed into and out of the eclipsing material, were greatly amplified through the lensing properties of these stellar winds. Researchers have since been monitoring the lensing and eclipse characteristics of spider binary systems keenly, and through pulsar flux variation measurements, dispersion measurement (DM) and rotation measurement (RM) changes are probing the eclipsing mechanism in detail.

Until recently the Southern hemisphere did not have a telescope sensitive enough to detect many of these lensed flux changes well. The MeerKAT telescope changes this. For the first time there is a telescope with enough sensitivity to detect single lensed pulses from the eclipsing pulsars in the Southern hemisphere.

This MSc project will use data from the MeerTIME MSP census to search for and analyse lensed pulses in eclipsing pulsar systems. Ideal targets to study with MeerKAT include the Southerly eclipsing systems, PSR J2051-0827 and PSR J1748-2246A.

PSR J1748-2246A located in the Globular Cluster, Terzan 5, has already been shown to exhibit brightly lensed single pulses during the eclipse ingress and egress (Bilous et al. 2019). Using Parkes data, the emission averaged over 3 minutes is seen to depolarize surrounding its eclipses (You et al. 2018); and estimates of RM changes from single magnified pulses point to over 100 rad m^{-2} per minute during the eclipse (private comm. Main 2021). With MeerKAT's improved sensitivity over Parkes, probing more deeply into the eclipsing region, accurate estimates on such RM changes will become possible.

Effects of lensing on longer timescales have also been observed in the eclipsing binary PSR J2051-0827, enabling precise measurements of the pulse flux variations as well as the changes in the DM throughout the eclipse (Lin et. al 2021). It is likely that this system will also show extreme lensing events and even caustics, as observed in PSR B1957+20 (Main et al. 2018), but the most recent study was limited by 10 sec time integrated data taken at Effelsberg (Lin et. al 2021). Using MeerKAT we will be able to analyse lensing at the level of single pulses, as well as compute single pulse RM values to estimate its changes accurately.

This improved MeerKAT's view on eclipsing mechanisms of binary pulsars systems and their defining characteristics (lens magnification, DM and RM), will ultimately contribute to our understanding of the interactions between the pulsar wind and the companion's outflow, and lead to estimates of the magnetic fields and mass-loss within the system. Moreover in such systems where the pulsar emission is amplified, the lensing nature of the stellar wind allows us to probe the magnetosphere and emission mechanisms of the MSP itself in more detail.

Team Information

Our partners at Swinburne University of Technology developed the pulsar processor for the MeerKAT

telescope and have created a “search mode” that can create high time resolution data for giant pulse detection. Professor Bailes leads the MeerTime collaboration (http://www.meertime.org).

Professor Karastergiou is an expert on the pulsar emission mechanism and can help in the interpretation of the data. Dr. Robert Main is a leading expert in eclipsing millisecond pulsars. Dr. Marisa Geyer is a South African pulsar astronomer working in the MeerKAT Commissioning team at SARAO with experience in pulsar data analysis and the MeerKAT telescope operations.

As a permanent staff member of UCT/SAAO Dr. Shazrene Mohamed will be the university supervisor, offering pastoral support and general master studies guidance to the student.

Section B: Supervisor(s) Details

1. Primary university supervisor’s details

a. Title and full name: Dr. Shazrene Mohamed

b. Name of South African or SKA Partner Country university at which the primary supervisor is a permanent academic staff member:

University of Cape Town/ South African Astronomy Observatory

c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

shazrene@saao.ac.za

d. Supervision of postgraduate students – please provide the details of all the previous and current postgraduate students supervised. Please provide the information in table format, as shown below.

2. Research supervisor 1 details

a. Title and full name: Dr. Aris Karastergiou

b. Name of South African or SKA Partner Country university at which the primary supervisor is a permanent academic staff member:

Dr Karastergiou is has a part time appointment at University of Western Cape/ Rhodes University

c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

aris.karastergiou@physics.ox.ac.uk

d. Supervision of postgraduate students – please provide the details of all the previous and current

postgraduate students supervised. Please provide the information in table format, as shown below.

i. Doctoral Students

Name of student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Lucy Oswald	UK	October 2017	September 2020	Polarized radio emission from pulsars	
Marisa Geyer	South African	October 2014	December 2017	Pulsar Scattering and the Ionized Interstellar Medium	
Elmarie van Heerden	South African	October 2014	December 2017	Data Challenges in Pulsar Searches	Prof Steve Roberts
Paul Brook	UK	October 2011	May 2015	Variability in Radio Pulsars	

ii. Masters Students

Name of student	Nationality	Date started Doctoral Degree (Month and Year)	Date completed / will complete Doctoral Degree (Month and Year)	Title of Research Project / Thesis	Co-Supervisor (if relevant)
Isabella Rammala	South African	January 2016	July 2018	The dispersion measure in broadband data from radio pulsars	Prof Oleg Smirnov Dr Griffin Foster

3. Research supervisor 2 details

a. Title and full name: Dr. Marisa Geyer

b. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member: SARAO

c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

mgeyer@ska.ac.za

d. Supervision of postgraduate students – please provide the details of all the previous and current postgraduate students supervised. Please provide the information in table format, as shown below.

Dr. Geyer is a full time member of the SARAO beamformer commissioning team.

She recently supervised Jones Chilufya's Hons project on searching for giant pulses in PSR J0540-6919. She has not formally supervised any Master's or PhD students. During her studies at Stellenbosch University she acted as chief study mentor of her residence and tutored in both mathematics and physics at first and second year level. At Oxford University (where she completed her DPhil in Dec 2017) she was an instructor in the computational physics lab. Being a co-supervisor to this project, and working with the student as well as Prof. Bailes, Dr. Karastergiou and Dr. Main, will enable her to develop her supervision skills and allow her to contribute to the development of the young African and South African pulsar community in the future.

4. Research supervisor 3 details

a. Title and full name: Dr. Robert Main

b. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member: Max Planck Institut fur Radio Astronomie (MPIfR), Bonn, Germany.

c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

ramain@mpifr-bonn.mpg.de

d. Supervision of postgraduate students – please provide the details of all the previous and current postgraduate students supervised. Please provide the information in table format, as shown below.

Dr. Main is a domain expert in eclipsing MSPs and the associated lensing that can be observed in such systems. See e.g. for reference his Nature publication at

https://www.nature.com/articles/s41586-018-0133-z

4.. Research supervisor 4 details

a. Title and full name: Prof. Matthew Bailes

b. Name of the university/institute, at which the co-supervisor/research supervisor is a permanent academic/research staff member: Swinburne University of Technology and the the Director of ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)

c. Email address and/or contact telephone number (please note that in the event this project is approved, these contact details will be made available to students awarded SARAO postgraduate bursaries)

mbailes@swin.edu.au, +61 414 324 677

d. Supervision of postgraduate students – please provide the details of all the previous and current postgraduate students supervised. Please provide the information in table format, as shown below.

Professor Bailes has supervised over 25 PhD and Masters students, 22 of which have completed their studies. These include Ben Stappers (Manchester pulsar group leader), Duncan Lorimer (WVU group leader), Willem van Straten (AUT pulsar group leader), Thomas Tauris (Bonn), Aidan Hotan (CSIRO staff), Joris Verbiest (Bielefeld University), Sarah Burke-Spolaor (WVU Faculty), Adam Deller (Swinburne faculty), Emily Petroff (Veni Fellow), Stefan Oslowski (Laureate Postdoctoral Fellowship, Swinburne)

i. Doctoral Students

Name of student	**Nationality**	**Date started Doctoral Degree (Month and Year)**	**Date completed / will complete Doctoral Degree (Month and Year)**	**Title of Research Project / Thesis**	**Co-Supervisor (if relevant)**
Emily Petroff	USA	16-08-2012	17-02-2016	The Transient Radio Sky Observed with the Parkes Radio Telescope	Van Straten

Stefan Oslowski	Polish	17-02-2009	16-05-2013	The Highest Precision Pulsar timing	Van Straten
Benjamin Barsdell	Australian	08-12-2008	05-12-2012	Advanced Architectures for Astrophysical Supercomputing	Chris Fluke
Lina Levin	Swedish	02-10-2008	15-11-2012	A Search for Radio Pulsars: from Millisecond Pulsars to Magnetars	
Sarah Burke-Spolaor	USA	26-03-2007	14-04-2011	Supermassive Black Hole Binaries and Transient Radio Events: Studies in Pulsar Astronomy	
Heather Ford	Canadian	22-10-2004	22-07-2010	The HI Cloud Population in the Lower Halo of the Milky Way.	
Paul Kiel	Australian	21-03-2005	16-07-2009	Populating the Galaxy with Pulsars	
Joris Verbiest	Belgian	11-07-2005	27-05-2009	Long-Term Timing of Millisecond Pulsars and Gravitational Wave Detection	
Emil Lenc	Australian	19-05-2004	05-02-2009	Studies of Radio Galaxies and Starburst Galaxies using Wide-field, High Spatial Resolution Radio Imaging	Steven Tingay (99% of supervision)
Adam Deller	Australian	02-02-2005	22-01-2009	Precision VLBI astrometry: Instrumentation, algorithms and pulsar	Steven Tingay

				parallax determination	
Haydon Knight	New Zealand	07-01-2002	23-08-2007	Pulsar Applications of Baseband Recording	Dick Manchester
Aidan Hotan	Australian	25-02-2002	18-05-2006	High-Precision Observations of Relativistic Binary and Millisecond Pulsars	Dick Manchester
Willem Van Straten	Canadian	01-02-1998	07-08-2003	High Precision Timing and Polarimetry of PSR J0437-4715	
Russell Edwards	Australian	05-01-1998	18-10-2001	Pulsar Searching	

ii. Masters Students

Name of student	**Nationality**	**Date started Doctoral Degree (Month and Year)**	**Date completed / will complete Doctoral Degree (Month and Year)**	**Title of Research Project / Thesis**	**Co-Supervisor (if relevant)**
Duncan Lorimer	British	1991	1993	Pulsar Statistics	Andrew Lyne
Craig West	Australian	1999	2003	Software Correlators for Radio Astronomy	Steven Tingay

Section C: Full Research Project Proposal

Maximum of three A4 pages, written for a professional who is not necessarily an expert in the relevant subfield

1. Scientific merit: describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.

It is arguable that no other astrophysical object addresses so many diverse areas of physics and astrophysics as radio pulsars. The science derived from radio pulsar observations almost always stems from the pulsar timing methodology that uses the pulsar's inherent stability to deduce remarkable facts about the pulsar's environment, their orbital companions, gravitational forces and even internal composition.

The first discovered pulsar binary system, for example, led to the confirmation of the theory of General Relativity through evidence of the system's emission of gravitational waves (Taylor et al. 1975); and the first extrasolar planet was discovered in orbit around a pulsar (Wolszczan & Frail 1992).
Pulsar astronomy also continues to push the boundaries of our understanding of nuclear theory through its discoveries of ever more massive neutron stars (Champion et al. 2008 and Cromatie et al. 2019).
Following our understanding that the astonishing clock precision of millisecond pulsars will enable the search for a nano-hertz gravitational waves (e.g. van Straten et al. 2001), the community is currently eagerly working towards detecting such low frequency gravitational waves with the first hints of viable detection recently published (Arzoumain et al. 2021).

The MeerKAT telescope has the opportunity to become the dominant radio pulsar timing instrument in the world with its ideal combination of geographical location, high gain, large bandwidths, digital beamforming, low system temperature and rapid slew rates. Indeed, if one was to design the ideal pulsar timing instrument from scratch, the system would closely resemble MeerKAT. Before the completion of MeerKAT, the largest radio telescope in the southern hemisphere was the Parkes 64m telescope in Australia. By comparison the MeerKAT has 8 to 10 times the sensitivity, which opens up many new areas of pulsar science. And since the detected pulsar signal-to-noise ratio scales as the square root of the integration time, a minute with MeerKAT is worth a whole hour on the Parkes telescope!

Our team is involved in commissioning the MeerKAT as a pulsar telescope and the results have been extremely exciting. The Meertime programme has been collecting high quality pulsar data at L-band frequencies on MeerKAT since February 2019, observing over 1600 known pulsars to date. The highlights of these observations already include eight newly discovered pulsars in well-studied Globular Clusters (Ridolfi et al. 2021); the lowest jitter noise recorded for any millisecond pulsar (Parthasarathy et al. 2021); the first rotation measurement estimate towards a distant pulsar in the Large Magellanic Cloud (Geyer et

al. 2021), and data of unmatched quality of the double pulsar system (Lower et al. in prep).

An interesting subset of the pulsar population, yet to be studied using MeerKAT, belongs to the so-called "binary eclipsing pulsars". In these systems the pulsar wind ablates material from its companion star. The subsequent outflows cause us to lose sight of the pulsar radio emission for minutes to hours as it passes behind the ablated material. Such eclipses became particularly noteworthy when, Main et al. (Nature 557, 522; 2018) discovered that one of the eclipsing pulsars (B1957+20) causes very large amplification (up to 80 times) of the radio emission from the pulsar as it enters eclipse.

Remarkably one can then use these naturally-occurring plasma lenses to study the emission region of the millisecond pulsars themselves using planetary-sized lenses to differentiate the emission regions of the pulsar on 10s of km length-scales. The lensing phenomena also provides a new way of accurately computing the instantaneous velocities of these stellar wind outflows, allowing us to monitor changes in the wind velocities with time and to improve on the current evolutionary models of these pulsar binary systems - that can ultimately produce isolated millisecond pulsars.

Until recently the Southern hemisphere did not have a telescope sensitive enough to detect many of these lensed flux changes well. The MeerKAT telescope changes this. For the first time there is a telescope with enough sensitivity to detect single lensed pulses from the eclipsing pulsars in the Southern hemisphere. This master's project will observe and analyse such eclipsing systems.

The improved MeerKAT's view on eclipsing mechanisms of binary pulsars systems and their defining characteristics, including its lens magnification measurements, the observed pulsar dispersion measurements and rotation measure estimates, will ultimately contribute to our understanding of the interactions between the pulsar wind and the companion's outflow, and lead to estimates of the magnetic fields and mass-loss within the system.

Up to now, MeerKAT time domain data have lead to over 15 submitted journal publications, with many more in the pipeline. However, the South African and African community in this field remains small. This master's study provides an opportunity to help grow the local pulsar and time domain expertise in, while providing the student with access to an active and international research collaboration.

2. Feasibility: outline the methods that will be used to achieve the objectives. Provide details on the availability of required data / access to required equipment / availability of research facilities and other resources required. Include any relevant expected intermediate milestones and associated timeframes towards attaining the overall objectives of the project.

To start, pulsar timing data will be made available to the MSc student to familiarise themselves with both the MeerKAT telescope (sensitivity, bandwidth etc.) as well as to practise reducing and analysing pulsar

data. This includes learning how to use established pulsar software suites and computing accurate time of arrival (ToA) measurements from the data. Familiarity with MeerKAT pulsar data will therefore be an straightforward initial objective.

Thereafter, the student will use existing MeerTime pulsar census data to establish what the typical mean signal-to-noise ratios of a set of Southern eclipsing MSP systems are. Based on this analysis we will continue with dedicated observing campaigns of the relevant systems, observing them as they enter and exit their eclipsing states.

An intermediate goal will be to analyse data from eclipsing binary pulsar systems, and to write python scripts to pick out the brightest (giant) single pulses within a given dataset. Once brightly lensed pulses are identified, the student will work to compute their characteristics, including estimates on the lens magnification by the companion stellar wind, the pulse's dispersion measure (DM) and rotation measure (RM).

Ideal targets to study with MeerKAT include the Southerly eclipsing systems, PSR J2051-0827 and PSR J1748-2246A. PSR J1748-2246A located in the Globular Cluster, Terzan 5, has already been shown to exhibit brightly lensed single pulses during the eclipse ingress and egress (Bilous et al. 2019). Using Parkes data, the emission averaged over 3 minutes is seen to depolarize surrounding its eclipses (You et al. 2018); and estimates of RM changes from single magnified pulses point to over 100 rad m^{-2} per minute during the eclipse (private comm. Main 2021). With MeerKAT's improved sensitivity over Parkes, probing more deeply into the eclipsing region, accurate estimates on such RM changes will become possible.

Effects of lensing on longer timescales have also been observed in the eclipsing binary PSR J2051-0827, enabling precise measurements of the pulse flux variations as well as the changes in the DM throughout the eclipse (Lin et. al 2021). It is likely that this system will also show extreme lensing events and even caustics, as observed in PSR B1957+20 (Main et al. 2018), but the most recent study was limited by 10 sec time integrated data taken at Effelsberg (Lin et. al 2021). Using MeerKAT we will be able to analyse lensing at the level of single pulses, as well as compute single pulse RM values to estimate its changes accurately.

After bright single pulses of these systems have been found and characterised, in the final leg of this project the student will interpret the analysed datasets, and aim to draw conclusions and ask scientifically meaningful questions. This analysis will include investigating whether correlations exist between the cadence of giant pulse emission and the orbital phase. That is, are there more giant pulses as the pulsar enters into the eclipse, such that they are truly lensed by the stellar outflow? Or are the giant pulses distributed randomly throughout the orbital phase? As well as asking questions about the eclipsing material, including whether the single pulse DM and RM values are changing as the pulses enter or exit the eclipse, and what it implies when creating a basic model of the eclipsing processes involved.

Dr Geyer will work with the student on a day-by-day basis initially on data reduction and the use of the MeerKAT telescope, and later on the emission of the MSPs. Dr. Robert Main, as co-supervisor, is a leading expert in eclipsing millisecond pulsars and will assist with regular supervision and the analysis of the eclipses studied. Professor Karastergiou is an expert on pulsar emission and will work on the interpretation of the results.

Professor Bailes (leader of the MeerTime project) will help facilitate the observations into the MeerTime schedules, and (pandemic permitting) host the student for an intensive 8-week visit to Australia as an Ozgrav visitor (accommodation and living expenses to be provided by www.ozgrav.org) to learn how to perform giant pulse searching from baseband data.

3. Link the proposed project to at least one SARAO research priority areas (refer to Annexure 1 of the Application Guide), and explain in some detail how the proposed research will contribute to the priority area(s).

As described in the research statement above, this project will directly contribute to radio pulsar research and therefore addresses priority number one of the Annexure, namely

1. Radio Pulsar and Fast-Transient science, instrumentation and data analysis (including real-time RFI detection).

4. If relevant, describe any particular qualifications, academic abilities, skills and/or experience that a student should have in order to successfully deliver on the objectives of the research proposed.

This project will require high levels of analytical and computer programming skills. Students should have an undergraduate degree and/or honors degree in Physics, Mathematics, Astronomy, Engineering or Computer Science.

Students with a keen interest in systematic data analysis, data reduction and script writing are suited to the project. Students that apply are expected to show keen scientific interest in the world of astronomy at large, and are expected to develop a more detailed understanding of radio astronomy and particularly pulsar astronomy over the course of this project.

Section D: Signatures

1. Signature of the primary supervisor, with date

Shazrene Mohamed, Dated: 23 July 2021

2. Signature of the co-supervisor/research supervisor, with date

Marisa Geyer, Dated: 21 July 2021

Robert Main, Dated: 23 July 2021

3. Signature of the additional co-supervisor/research supervisor, with date

Aris Karastergiou, Dated: 23 July 2021

Matthew Bailes, Dated: 23 July 2021