Understanding pulsar emission:
is pulsar J1748-2021A mode-changing or freely precessing?

Section A: Overview of the Research Project

1. Title of the research project:

Is PSR J1748-2021A mode-changing or freely precessing?

2. Broad area of research (Engineering or Science)

Science (Astrophysics)

3. Academic level of research project (Masters or Doctoral)

Masters

4. Abstract of research project

Pulsar emission at radio wavelengths is an open problem in astronomy and astrophysics. While the majority of pulsars are seen to emit a regular train of pulses that integrate to a standard "profile" that is stable for up to several decades, there are some pulsars that switch between distinct, countable modes of emission. These modes differ in their intensity and polarization properties of the associated integrated and single profiles. These so-called "mode changing" pulsars offer some of the best clues to understand radio pulsar emission.

The project will use a unique 77-hour MeerKAT dataset on a mode changing pulsar, PSR J1748-2021A, which resides in the globular cluster NGC6440, to investigate the quasi-periodicity and characteristics of its mode changes.

One of the aims of the project would be to classify this large set of pulses shapes into different modes (or categories) using a Machine Learning classifier, and use these obtained classifications to study underlying emission model configurations for mode changing pulsars.

5. Primary supervisor’s details

a. Full name of primary supervisor: Dr. Marisa Geyer

b. Primary supervisor’s email address: mgeyer.astro@gmail.com

(please note that if this project is approved, this email address will be

made available to students to contact the primary supervisor)

c. University where primary supervisor is employed: University of Cape Town (UCT)

6. Co-supervisor/Research supervisor’s details

Research Supervisor 1

a. Full name of co-supervisor/research supervisor: Dr Vivek Venkatraman Krishnan

b. University where co-supervisor/research supervisor is employed
Max Planck Institut fur Radioastronomie, Bonn, Germany

Section B: Details of Research Project

1. Scientific/Engineering merit:

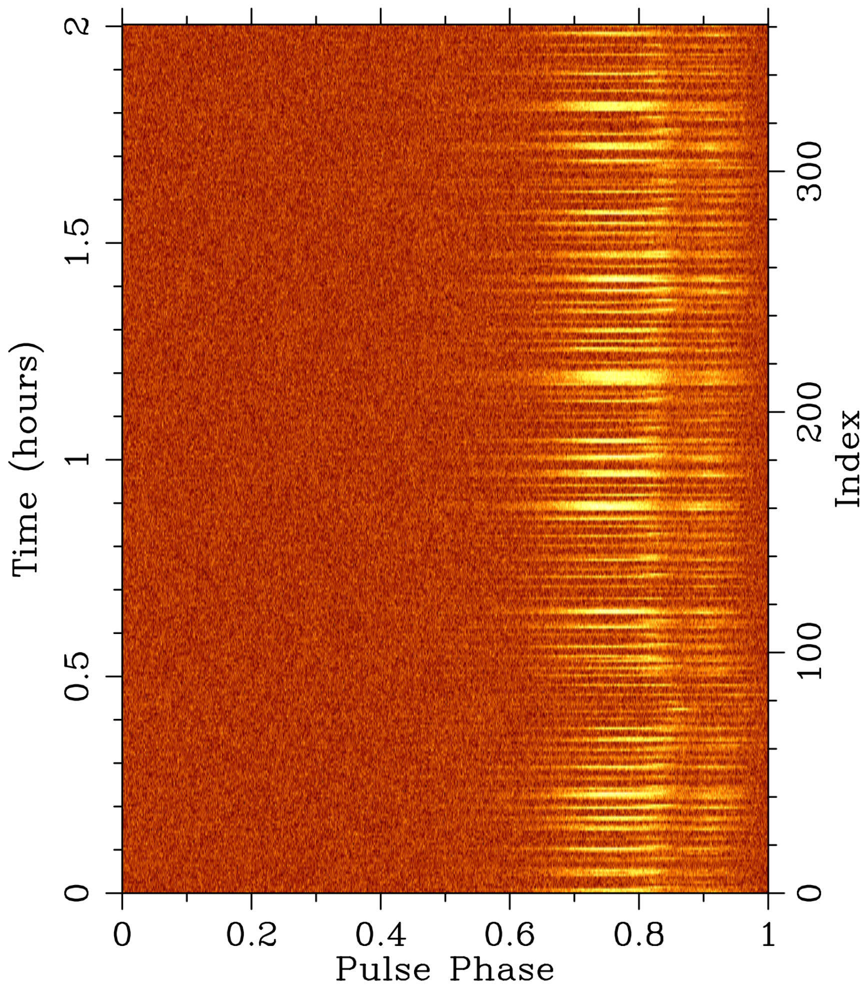
describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.

Radio pulsar emission is one of the least understood phenomena in Astrophysics. While the observed pulsar flux densities vary on many timescales due to scattering by the intervening medium, the intrinsic luminosity of most pulsars are very stable for up to several decades. However, there are some classes of pulsars where intensity modulations across a variety of timescales are observed. These primarily include the class of mode-changing pulsars, where the pulsar emission seems to switch between several distinct emission modes. In extreme cases, one or more of the modes can have the pulsar completely switch off, leading to “nulls” in the emission. These are called nulling pulsars, and the fraction of time that a pulsar is seen to vary from just a few pulses to a few years! Some pulsars also have been seen to exhibit drifting sub-pulses where the longitude of pulse emission is seen to drift predictably within the envelope of the integrated pulse profile. All the above mentioned intricacies make radio emission some of the most difficult phenomena to reliably explain, although there have been a number of theories explaining the different kinds of emission and also links between these types.

PSR J1748-2021A is a 288-ms spin period pulsar that resides in the globular cluster NGC6440A and exhibits quasi-periodic mode changes. It has at least two distinct modes of emission: A faint, narrow emission mode and a bright, broad emission mode as can be seen in the figure below. It also has random wanders of the profile at timescales of few tens of minutes to hours that can be evidenced from the same figure. It is presently unknown if there are only two modes in PSR J1748-2021A or if there are other modes that it switches to, with much lower signal to noise ratio. Such an analysis for this pulsar has been limited by the unavailability of a large dataset consistently probing its emission at timescales of minutes to weeks. These characters are also consistent with the pulsar undergoing free precession caused by an asymmetry in its shape. Such processions are thought to not exist because torque-free precession of a solitary pulsar should be damped out by the vortices in its superfluid interior.

One of the best ways to understand and differentiate free precession from mode changing is to analyse the position angle (P.A.) of the linear polarisation of the pulse profile. Under ideal conditions, the change in the P.A. across the pulsar longitude follows an "S"-type curve, that can be modeled using the Rotating Vector Model (RVM). RVM parameterises the changes in P.A. as a geometrical effect of changes in the viewing angle of the emission cone. Fitting an RVM model to our data allows the inference of the magnetic inclination angle (\alpha), i.e. the angle between the spin and magnetic axes, and the co-latitude of the line of sight vector with respect to the spin axis (\zeta).

As part of the MeerTime Relativistic Binary and Globular Cluster themes, we performed an orbital campaign on another pulsar that resides in the same globular cluster (J1748-2021B). This involved regular observations of the cluster for 2-4 hours every other day for about 35 days in 2019. During this campaign, we also recorded search mode (multi-frequency time series) data from which we could fold all other known pulsars in the cluster, including J1748-2021A. The versatility of the PTUSE backend allows for this data to be recorded with full polarisation information and a complete removal of the dispersive effects of the ionised interstellar medium (via coherent dedispersion). The unprecedented sensitivity of MeerKAT allowed us to detect single pulses from the pulsar for the bright emission and detections with integrations of just a few pulses for the faint emission modes. Thus we have a unique dataset where the pulsar's emission can be analysed in both total intensity and polarisation with high time resolution (to resolve single pulses) and over timescales of minutes to weeks. This is what we would like the master student to pursue for their thesis.



Caption: MeerKAT L-band data of PSR J1748-2021A across a 2hr observation, clearly showing the different emission modes present.

2. Feasibility

Radio pulsar data and analysis

We already have MeerKAT data for this pulsar ranging from 2019 to 2021, with more than 70 hours of data obtained over a ~35 day intense campaign.

These data are recorded in the so-called *search mode or single pulse mode* data using the PTUSE backend of the MeerKAT telescope. These search mode files can be folded using standard pulsar software tools such as *dspsr* to obtain *pulsar archives.* Pulsar archive files can be analysed using existing pulsar timing softwares and techniques.

In this project the student will therefore both learn techniques associated with pulsar searching (such as folding time series data using *dspsr*) and will learn how to work with *psrchive* to reduce the data and to form pulsar dynamic spectra. Using existing psrchive tools the student will be able to determine characteristics of the intervening ISM, including the dispersion measure and rotation measure and monitor these as a function of time.

As part of the analysis, the student will also aim to characterise flux changes in the pulsar emission between modes and with time, for which they will be required to learn how to use existing flux calibration techniques and softwares. Similarly the polarisation properties of the pulsar can only be well studied following a procedure of polarisation calibration. These techniques have all been proven to work well on MeerKAT data already.

The project analysis will include analysing a large number of single pulses, and aiming to classify them into different modes. This will best be done through a machine learning classification approach.

Compute resources, software and facilities access

The radio pulsar data can be analysed on the SARAO science cluster. In particular one machine is already set up to run an up-to-date singularity image with all the required pulsar software.

The MSc student affiliated with UCT will have access to office space at the campus. Students also will have access to the library and lecture room facilities at UCT.

Students will also be exposed to the research groups both in the Astronomy department at UCT and to the High Energy Physics, Cosmology and Astrophysics Theory (HEPCAT) group at the Mathematics and Applied Mathematics department via Monageng and Geyer's affiliations.

The student will also become an active research member to the Meertime collaboration, in particular the Globular Cluster working group, providing them with exposure to international communities and research experts.

Milestones and timeline of progress

Total duration: 1.5 to 2 years (dependent on whether it is taken up as a NASSP or full dissertation project); that is 18 to 24 months.

The first 5 months of the project will be spent reducing the search mode data to obtain single pulse archives. This includes getting comfortable with the software used and conducting initial literature reviews.

The next 4 months will be allocated to develop a machine learning based classification engine to classify the ~1 million single pulses into different “modes”. About 2 percent of this data needs to be manually classified to provide a training dataset to a machine learning model. The rest of the data can then be classified automatically.

By November 2024 (~ 9 months in) the student will be expected to present a poster of their project at the SARAO bursary conference; showcasing both a theoretical understanding of their project, and initial data analysis results.

In the second half of the project (10 - 18 months) the student will be expected to write software to understand short and long term quasi periodicities in the dataset, and to check if these periodicities have any relation to the properties of the pulsar. This will involve trying out different signal processing techniques to estimate the periodicities, and understand pulsar timing to tie this to any changes in the pulsar properties. The pulsar timing aspect will also involve generating times of arrivals of the pulses and studying them using standard pulsar timing software.

The last four months (14 -18 months) should be set aside for writing up the thesis. Longer projects (two years) will choose the most interesting research outcome within this project to focus on in more depth.

3. Link the proposed project to one or more of the SARAO research priority areas for 2023

Studying systems such as PSR J1748-2021A in NGC6440 using MeerKAT to analyse radio pulsar data and pulsar emission models ties in directly with the priority of exploiting data from existing South African based Radio Astronomy facilities, of which MeerKAT is ranked highest.

The current South African-based pulsar community remains small, especially relative to the fantastic science outputs of the MeerKAT LSPs Meertime and TRAPUM. This MSc research project will provide a South African based student the opportunity to take part in these high ranking programmes, and to form part of the efforts to grow a local pulsar research footprint.

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 data analysis and computer programming skills. In particular students keen on developing an improved understanding of pulsar astronomy, but also data analysis and machine learning techniques are encouraged to apply. Students should have an undergraduate degree and/or honors degree in Physics, Mathematics, Astronomy, Engineering or Computer Science.

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.

Section C: CV of Primary Supervisor

Dr Marisa Geyer is a lecturer at the Mathematics and Applied Mathematics Department at UCT and a Honorary Research Affiliate to the Department of Astronomy at UCT. From 2017 – 2022 she worked as a Commissioning and Operations Scientist at SARAO, principally involved in the beamforming commissioning of the MeerKAT telescope. Since the start of 2023 her affiliation with SARAO has changed to that of an external visitor to the Radio Astronomy Research Group (RARG) at SARAO. Dr. Geyer is an active research member of both the Meertime and TRAPUM research collaborations.

She completed her PhD in Astrophysics at Oxford University in Nov 2017; and an MSc in Theoretical Physics at Stellenbosch University in 2014.

Her publication records, and other reearch involvements can be viewed on her website www.marisageyer.co.za

Student Supervised	**Student Affiliation**	**Project level**	**Project title**	**Date completed/ To be completed**
Jones Chilufya	UCT	NASSP Hons	*Studying giant pulses in the Large Magellanic Cloud pulsar PSR B0540-69 using MeerKAT*	Dec 2020
Venu Prayag	UCT	NASSP Hons	*Studying giant pulses in the Large Magellanic Cloud pulsar PSR B0540-69 using MeerKAT*	Dec 2021
Venu Prayag	UCT	NASSP Masters	*Searching for and characterizing pulsars in the Large Magellanic Cloud with MeerKAT*	July 2023
Senate Lekomola	UCT	NASSP Masters	*Studying giant pulses in eclipsing binaries of Southerly millisecond pulsars using MeerKAT.*	Dec 2023

Section D: CV of Co-Supervisor/Research Supervisor

Dr Vivek Venkatraman Krishnan

Dr Vivek Venkatraman Krishnan is scientific staff at the *Max-Planck-Institut fur̈ Radioastronomie (MPIfR)*, Germany, where he acts as the co-lead of the programme timing relativistic binary pulsars with the MeerKAT telescope. He is also a research member of TRAPUM and MGPS pulsar search programmes with the MeerKAT telescope and the principal investigator on two projects on timing relativistic binaries with the Parkes telescope. He will soon start his own group funded by the European Research Council Starting Grant, where-in he will develop and employ novel signal processing techniques to discover pulsars in compact binary orbits.

Student Supervised	**Student Affiliation**	**Project level**	**Project title**	**Date completed/ To be completed**
Kathrin Grunthal	MPIfR	Masters (100%)	Mass measurements of PSR J1618-3921	Feb 2023
Jiwoong Jang	MPIfR	PhD (30%)	Mass measurements of PSR J1439-5501	Jan 2023
Miquel colom i Bernadich	MPIfR	PhD (30%)	Mass measurements of PSR J1227-6208	Oct 2023
Shalini Sengupta	MPIfR	PhD (50%)	Mass measurements of 4 Helium WD binaries	Dec 2023
Arunima Dutta	MPIfR	PhD (30%)	Timing and profile analysis of J0955-6150	Dec 2024
Denisha Pillay	MPIfR	PhD (50%)	Mass measurements of J1036-8317	June 2025
Alexander Batrakov	MPIfR	PhD (50%)	Testing scalar-tensor gravity theories with a new timing model using relativistic binary pulsars	Mar 2024