

Studying the mode-changing pulsar J1748-2021A using MeerKAT data

Section A: Overview of the Research Project

1. Title of the research project:

Studying the mode-changing radio pulsar, PSR J1748-2021A, using MeerKAT data

2. Broad area of research (Engineering or Science)

Science (Astrophysics)

3. Academic level of research project

Hons

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 stable “profile”, 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 subset of a unique and highly sensitive 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 set of pulses shapes into different modes (or categories) using a Machine Learning classifier, and use these obtained classifications to study the emission properties. The project will start by answering a few fundamental questions such as how many modes does this pulsar exhibit, how often does it switch between modes, and is there structure or quasi-periodicity in these modes. The findings will ultimately be tied back to our understanding of the underlying pulsar emission model and comparisons to other known mode-changing pulsars.

5. Primary supervisor's details

- a. Full name of primary supervisor: Dr. Marisa Geyer
- b. Primary supervisor's email address: marisa.geyer@uct.ac.za
(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:

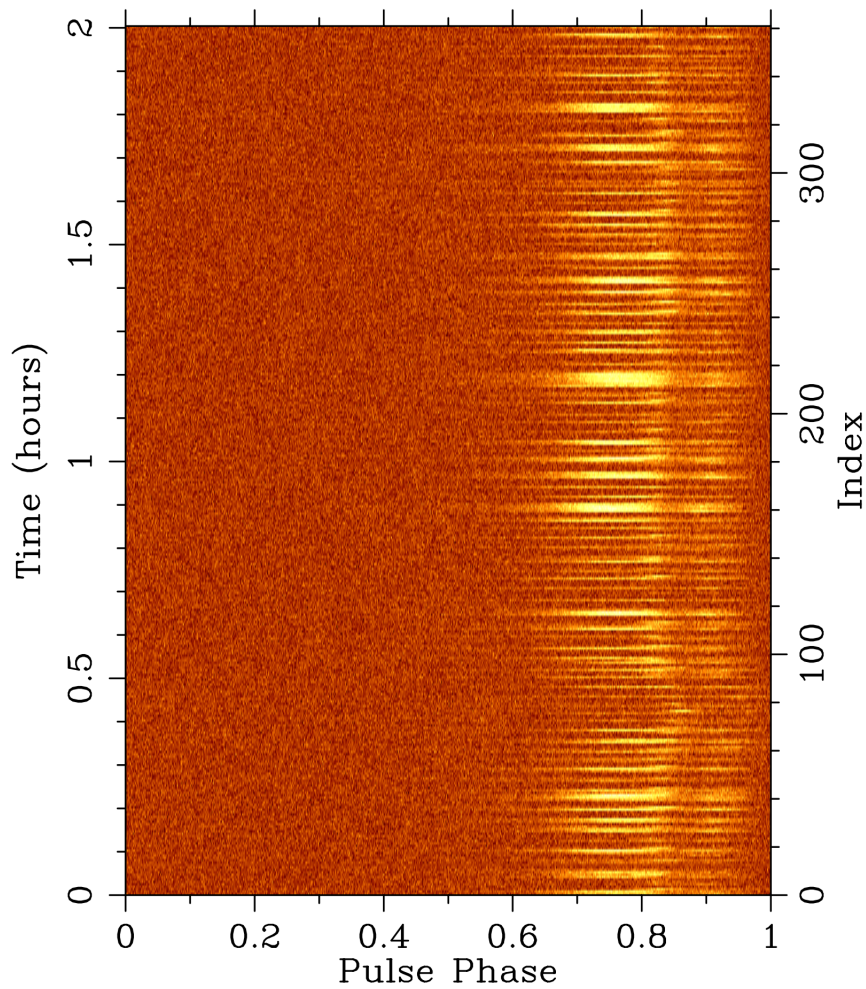
describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.

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, and what the statistics of these modes are (e.g. how often is the pulsar in which state). 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.

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.



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. As an Hons project the student would be expected to only analyse a subset of this data.

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.

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 Ilifu or the SARA0 science cluster. In particular a pulsar timing project environment is already set up on Ilifu for these types of analyses.

The Hons 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 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.

3. Link the proposed project to one or more of the SARA0 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 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 SARA0, principally involved in the beamforming commissioning of the MeerKAT telescope. Since the start of 2023 her affiliation with SARA0 has changed to that of an external visitor to the Radio Astronomy Research Group (RARG) at SARA0. 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 research involvements can be viewed on her website

www.marisageyer.co.za

Student Supervised	Student Affiliation	Project level	Project title	Date completed/ To be completed
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Jones Chilufya	UCT	NASSP Hons	<i>Studying giant pulses in the Large Magellanic Cloud pulsar PSR B0540-69 using MeerKAT</i>	Dec 2020
Venu Prayag	UCT	NASSP Hons	<i>Studying giant pulses in the Large Magellanic Cloud pulsar PSR B0540-69 using MeerKAT</i>	Dec 2021
Venu Prayag	UCT	NASSP Masters	<i>Searching for and characterizing pulsars in the Large Magellanic Cloud with MeerKAT</i>	July 2023
Senate Lekomola	UCT	NASSP Masters	<i>Studying giant pulses in eclipsing binaries of Southerly millisecond pulsars using MeerKAT.</i>	Dec 2023
Atiqur Rahman	UCT	UCT PhD	<i>Searching for nanoHz GWs in the MeerKAT PTA dataset</i>	Dec 2026

Section D: CV of Co-Supervisor/Research Supervisor

Dr Vivek Venkatraman Krishnan

Dr Vivek Venkatraman Krishnan is scientific staff at the *Max-Planck-Institut für 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