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A Search for Pulsars Towards the Galactic Center

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Abstract

We present observations from two separate methods for observing the Galactic Center in an attempt to characterize its pulsar and neutron star populations. A persistent puzzle of the past 20 years has been the lack of pulsar detections towards the Galactic Center, specifically within a few parsecs of the central supermassive black hole Sgr A*. This object is bright in the total intensity of its polarized emission, but is very weakly linearly polarized. We take advantage of these circumstances in an experimental search technique where we utilize the Faraday effect in an attempt to detect high rotation measure (RM) point sources towards the Galactic Center, as the few pulsars that have been detected in this region have all been measured at a high RM. We also conduct a wide-field search of the 5° area around the Galactic Center at low frequencies (230-470MHz) and at multiple epochs in an attempt to detect transient sources and other significant emitters of synchrotron radiation.

Keywords

pulsar, neutron star, Galactic Center

A SEARCH FOR PULSARS TOWARDS THE GALACTIC CENTER

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August 2019

Abstract

We present observations from two separate methods for observing the Galactic Center in an attempt to characterize its pulsar and neutron star populations. A persistent puzzle of the past 20 years has been the lack of pulsar detections towards the Galactic Center, specifically within a few parsecs of the central supermassive black hole Sgr A*. This object is bright in the total intensity of its polarized emission, but is very weakly linearly polarized. We take advantage of these circumstances in an experimental search technique where we utilize the Faraday effect in an attempt to detect high rotation measure (RM) point sources towards the Galactic Center, as the few pulsars that have been detected in this region have all been measured at a high RM. We also conduct a wide-field search of the 5°area around the Galactic Center at low frequencies (230-470 MHz) and at multiple epochs in an attempt to detect transient sources and other significant emitters of synchrotron radiation.

1 Introduction

The Galactic Center is a region of particular astronomical interest as it contains environments unlike most any other within our galaxy. The density of material towards the Galactic Center gives rise to many different types of stars and star forming conditions that contribute to the diversity of objects that have been discovered in this region (Bower et al. 2014, Mauerhan et al. 2010). For example, the central few hundred parsecs of our galaxy contain approximately 10% of the molecular gas content distributed throughout the disk, giving rise to blindingly strong emission in the radio, as seen in Figure 2. While conditions like increased temperature and pressure in this region suggest a high probability of star formation, they also introduce a host of other conditions (i.e. tidal forces and magnetic fields) that suppress star formation conditions (Morris et al. 1996). Instead, star formation is primarily driven through shocks near the Galactic Center - violent compactions of the interstellar medium generated by supernovae, stellar winds, gas cloud collisions, and a host of other turbulent events (Morris et al. 1996, Draine 1993). As a result of this mechanism, the Galactic Center hosts primarily massive stars, with the central 30 pc comprising over 10% of the massive star population in the Milky Way (Figer 2002). It's quite clear that the Galactic Center continues to act as a source of new information and potential discovery as more is discerned about the nature of its inner regions, especially near the supermassive black hole Sgr A*.

The neutron star population within the Galactic Center is of particular interest, given that they have remarkably stable periods ranging from a few milliseconds to as long as minutes (Wielebinski 2002). Given their high rotational velocities, neutron stars generate very strong magnetic fields. Electrons are accelerated along the magnetic axes at relativistic speeds, generating synchrotron emission that can travel along our line of sight if the magnetic axis is offset from the spin axis - a process aptly named The Lighthouse Effect. The precision of their periodicity make pulsars the best cosmic timekeeping mechanism in existence. As those axes rotate through our line of sight we can measure the emission from the star, and then wait for the event to repeat, establishing the pulsar's rotational period.

Given their precise timing, even minor perturbations of a pulsar's rotation period would provide a means of analyzing the environment surrounding the star, as any notable disturbance comes as a result of the interaction between the pulsar's emission with the surrounding environment, as well as the environments encountered along the path to the observer (Carroll and Ostlie 2017). Consequently, even the detection of a single pulsar towards the Galactic Center would provide a means of precisely probing its environment, enable tests of General Relativity in the strong field regime (e.g. measuring the mass of Sgr A* to within 1 $M_{\odot}$), allow for the characterization of the formation history of neutron stars in this region, and provide a probe of the magneto-ionic environment around Sgr A* (Eatough et al. 2013).

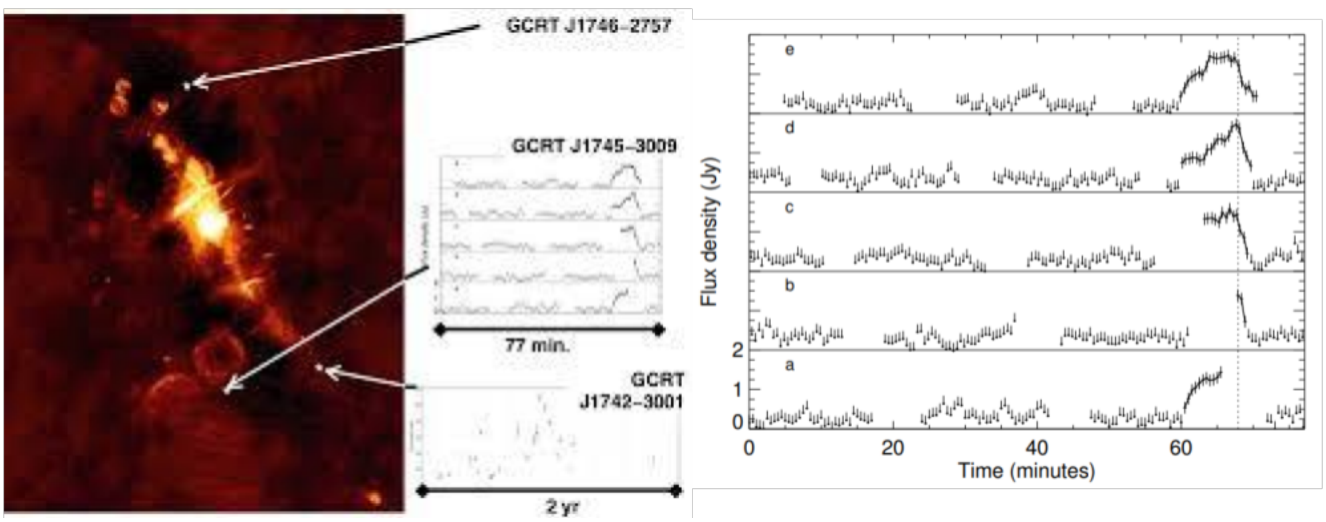

Figure 1: *Demonstration of light curves for Galactic Center transients. During a single 6 hour observation, GCRT J1745-3009 burst several times with a duration of roughly 10 minutes. At a frequency of 330 MHz, the background image demonstrates a sample of the transient objects that may exist towards the Galactic Center. Figure taken from Lazio et al. (2009).*

The Galactic Center also continues to present objects that are somewhat unknown in the context of established literature. The object GCRT J1745-3009 [Fig. 1], was discovered in a Very Large Array (VLA) blind search program, and was found near the Galactic Center with emission inconsistent with any known radio source (Hyman et al. 2005). This object, and others like it, was measured at different epochs and found to be transient - a source whose emission changes over time. This demonstrates that the Galactic Center is not of interest simply for what it contains, but also for how it changes with time. Additionally, GCRT J1745-3009 was found to emit coherent emission - a mechanism best measured at low frequencies (Hyman et al. 2005). Given that many classifications of objects tend to emit at low frequencies, it is clear that many properties should be accounted for in Galactic Center searches. Findings such as these therefore motivate nonspecific searches of the Galactic Center over multiple epochs in order to determine the manner of objects that populate this region.

2 Observations

While the Galactic Center presents unique potential for discovery, it also brings with it unique challenges. One of the most abiding issues over the past several decades has been the lack of pulsar detections around the Galactic Center, despite estimations that hundreds of pulsars may populate this region (Bower et al. 2018, Wharton et al. 2012). The typical theory for such non-detections is that hyper-strong interstellar scattering occurs towards Sgr A*, causing temporal smearing of pulsations - taken to be some distribution of signal over time. If scattering is great enough along the line of sight, the peaks of pulsar emission signals can be lowered to levels comparable to that of background noise, masking them almost entirely. While such a theory would generally make sense given the significant amount of material towards the Galactic Center, the detection of the magnetar PSR J1745-2900 at a projected separation of 0.1 pc from Sgr A* complicates such reasoning [Fig 2.]. The broadening of the magnetars pulse profile reveals that the pulsation was likely scattered far from the Galactic Center, further mystifying the missing pulsar problem.

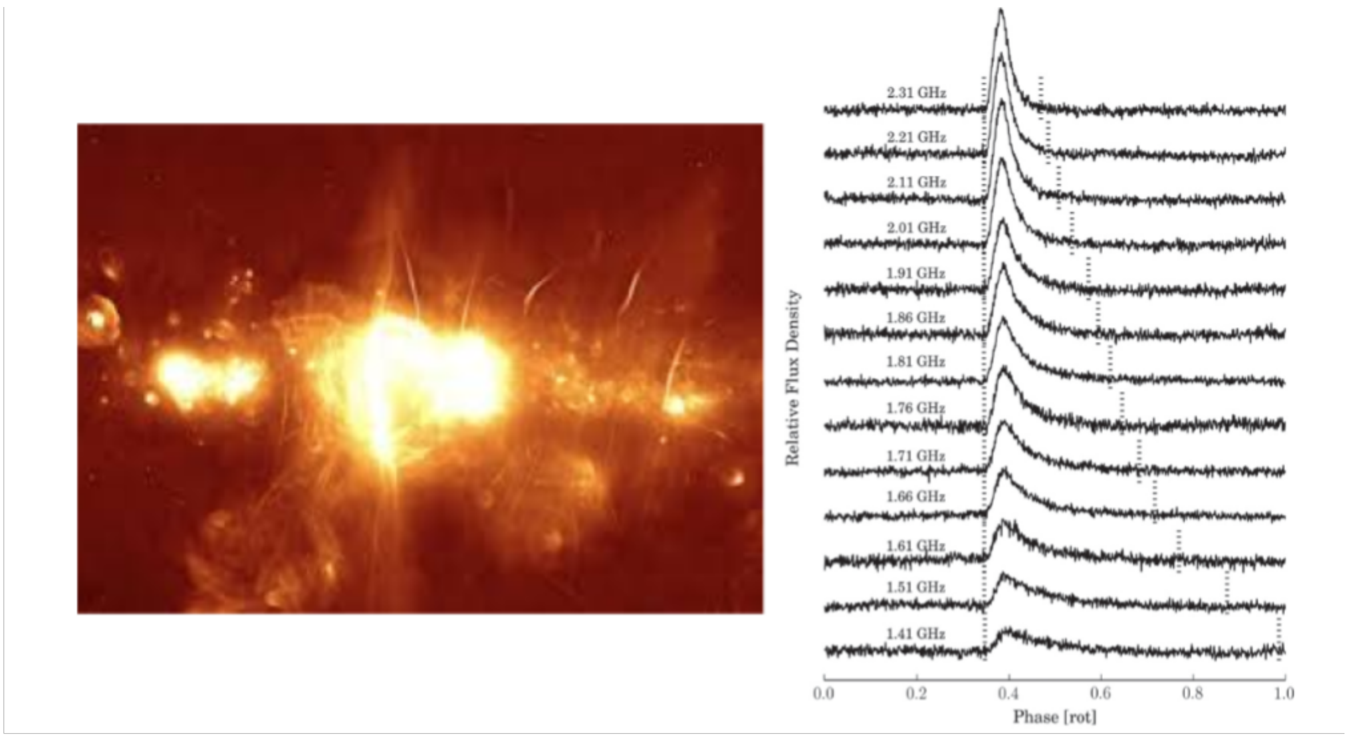

Figure 2: *The left image is a MeerKAT radio image of the Galactic Center, with the exceptional intensity of the region on full display (Image Credit: SARAO). The image is demonstrative of the extreme density of material towards the Galactic Center. Nonetheless, the magnetar PSR J1745-2900 was detected proximal to Sgr A* and its pulse profile is displayed (right). Pulse profile from Pennucci et al. (2015).*

While the dearth of pulsars towards the Galactic Center has yet to be explained, traditional pulsation searches still constitute a means of exploring this region. Modern pulsar searches typically take advantage of the inverse relationship between frequency and scattering by using higher frequencies to avoid scattering effects:

$$\tau_{scat} \propto \nu^{-4} \tag{1}$$

However, these measurements consequently suffer from reduced sensitivity to pulsations from pulsars towards the Galactic Center:

$$S_\nu \propto \nu^{-1.8} \tag{2}$$

This tells us that lower frequency searches are more sensitive to pulsation detections. However, care must be taken with such observations in order to avoid the interference of scattering and radio frequency interference (RFI). As equation (1) demonstrates, the scattering effects of significantly lower observations have the potential to be prodigious. Thus, the groundwork is laid for a careful, low frequency search of the Galactic Center for pulsar detections. This method can be successively iterated across multiple epochs in order to highlight both transient sources and potential pulsar locations.

3 P-band Wide-Field Search of the Galactic Center

3.1 Method

In order to execute an effective general search of the Galactic Center, one of the VLA's lowest frequency operating ranges, P band (230-470 MHz), is utilized. The software used to process all VLA data throughout this project is the Common Astronomy Software Applications package, but unfortunately the VLA CASA pipeline does not support observations as low as P-band. As a result, the initial flagging and calibration of the raw data is done manually. In doing so, we utilize the VLA P-band Continuum Tutorial, executing manual flags and generating and applying calibration tables to the raw data. The flagging includes corrections for dead/malfunctioning antenna, periods of poor weather, and RFI. In addition, ionospheric corrections must be made for these observations, given that low-frequency nature of these observations leaves them susceptible to interaction with the ionosphere.

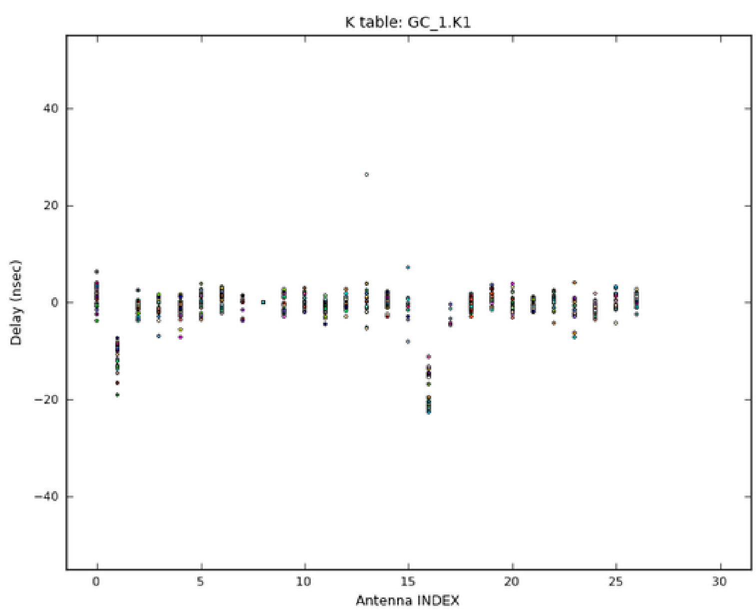

Figure 3: *A plot of the time delay from signals received at each of the antenna of the VLA. The time-of-arrival of each signal is plotted in relation to antenna ea09, and demonstrates the need for time delay corrections in order to ensure proper treatment of measurements from each individual antenna.*

For this data set, we make use of the source 3C295 as our flux calibrator and J1714-2514 as our phase calibrator. In order to ensure that the raw data is manipulated accurately, the phase and amplitude calibrations were performed such that measurements from the calibrator sources were stable. These provide a good means of determining the intensity and morphology of our source. Time delay corrections [Fig 3.] and bandpass calibrations were also executed in order to provide a good comparison of measurements between antenna and correct for nonuniform sensitivity across the frequency range.

3.2 Discussion

After all calibrations and corrections were applied to the data, preliminary imaging was performed in order to determine the effectiveness of these processes. The next step was to image our target field, focusing on Sgr A*. In order to do so, deconvolutions were necessary, and were executed using CASA's CLEAN algorithm through the tclean command. These tasks formed images from the received visibility's, and an image [Figure 4] was produced.

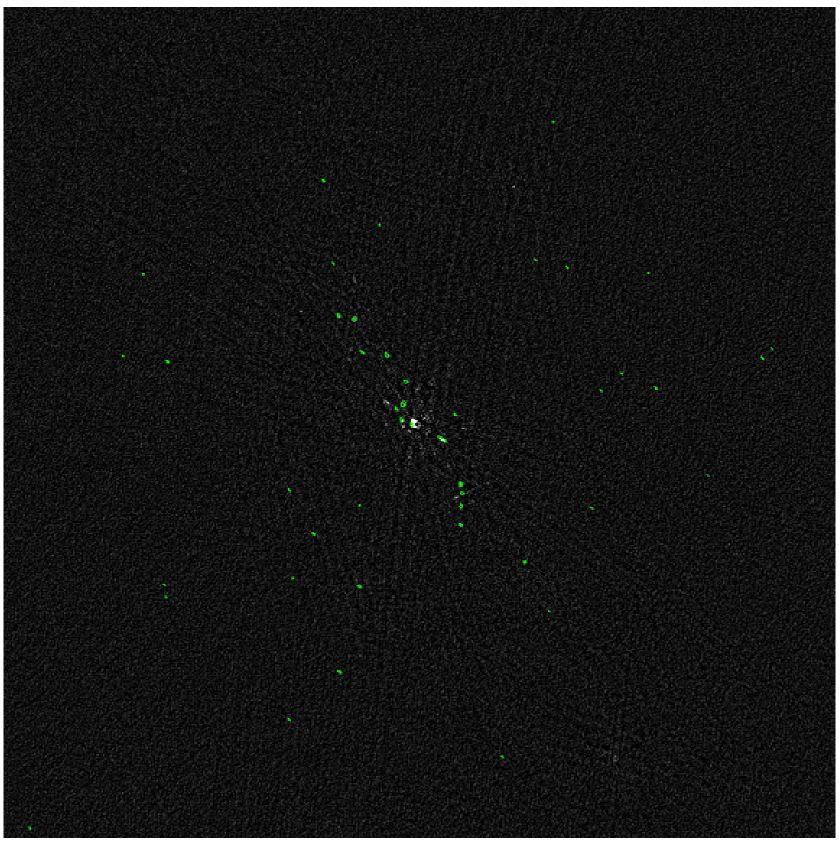

Figure 4: *A wide-field image of a 5° area near the Galactic Center. Regions of high emissivity relative to residual background noise are highlighted in green, and constitute both potential transient sources as well as locations suitable for pulsar analysis.*

The green regions on this image represent notable denotations of high emission relative to the residual background noise. While these regions do not constitute any specific classification of object, they highlight regions of interest for further study. In future work, imaging of the same location from different epochs can be compared to the presented image in order to identify transient sources. Since the highlighted regions here are part of a roughly 5°search area, the detections here would need more precise measurement in order to determine their exact nature. However, this provides adequate groundwork for pulsar detections near the Galactic Center, as the highlighted regions could be investigated at higher frequencies, and with a smaller field of view, for pulsation detections. Additionally, a similar technique can be applied to measurements of other portions of the Galactic Center, such as the GMRTAS150M project, in order to further characterize the populations of objects in those regions.

4 Rotation Measure Synthesis of the Galactic Center

4.1 Method

In an attempt to bypass some of the limitations of traditional pulsar searches towards the Galactic Center, we attempt to determine the rotation measure of Galactic Center objects by implementing the Faraday rotation effect. The Faraday effect incorporates the interaction between the plane of polarization of an electromagnetic wave and the magnetic field within a medium, as seen in Figure 5.

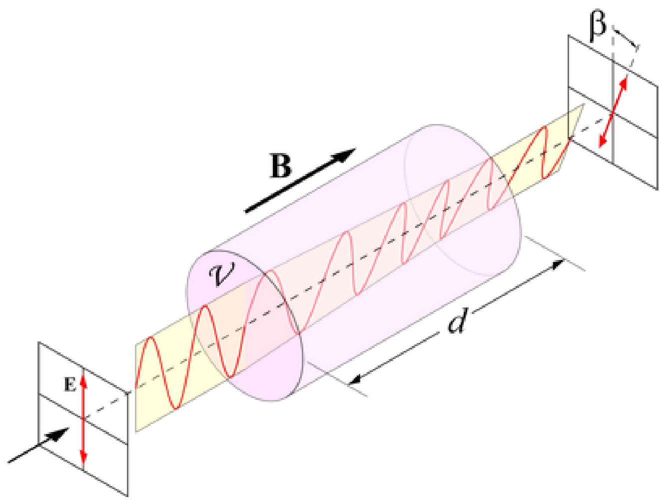

Figure 5: *A depiction of polarization rotation due to the Farday effect. The image incorporates the vector of the magnetic field strength, the distance that the magnetic medium occupies along the line of sight, and the rotation angle of the EM wave.*

As an EM wave propagates through a magnetically charged medium, the degree of rotation of the plane of propagation follows a simple dependence on wavelength:

$$\beta = RM \cdot \lambda^2 \tag{3}$$

As an end result, there is an achieved rotation of an EM wave's linear polarization. The rotation measure (RM) value that is incorporated in this effect pertains to the path along the observer's line of sight:

$$RM = 0.81 \int_{source}^{observer} n_e B \cdot dl \tag{4}$$

This effectively describes the magnitude of the interaction between the free electron content and the projection of magnetic fields along the line of sight to the source. In this project our path length towards the Galactic Center is extensive, and includes many extraneous sources that contribute to the measured RM. In order to address this, we utilize an RM synthesizer in order to step through RM space, identifying contributors to the measured RM at different Faraday depths.

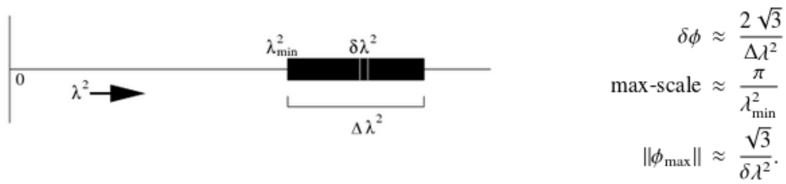

Figure 6: *A demonstration of Faraday depth along an observed line of sight. The resolution, max-scale, and maximum Faraday depth all have their wavelength dependencies listed as well. These parameters are instrumental in determining the output of a Faraday rotation measure synthesis. Taken from Brentjens et al. (2005).*

The Faraday depth corresponds to the interaction of free electrons solely through the magnetic mediums that they encounter along the path to the source [Fig 6]. In this project, we utilize data from the VLA's L and S band (combined 1-4 GHz) in order to achieve a good resolution ($\delta\phi$=50 rad/m^2) as well as a maximum measurable Faraday depth of ϕ_{max}=500,000 rad/m^2. Given that the RM of the magnetar J1745-2900 is -67,000 rad/m^2 and the RM of Sgr A* is approximately 500,000 rad/m^2, these limits give ample room for standard pulsar detections (Schnitzeler et al. 2016).

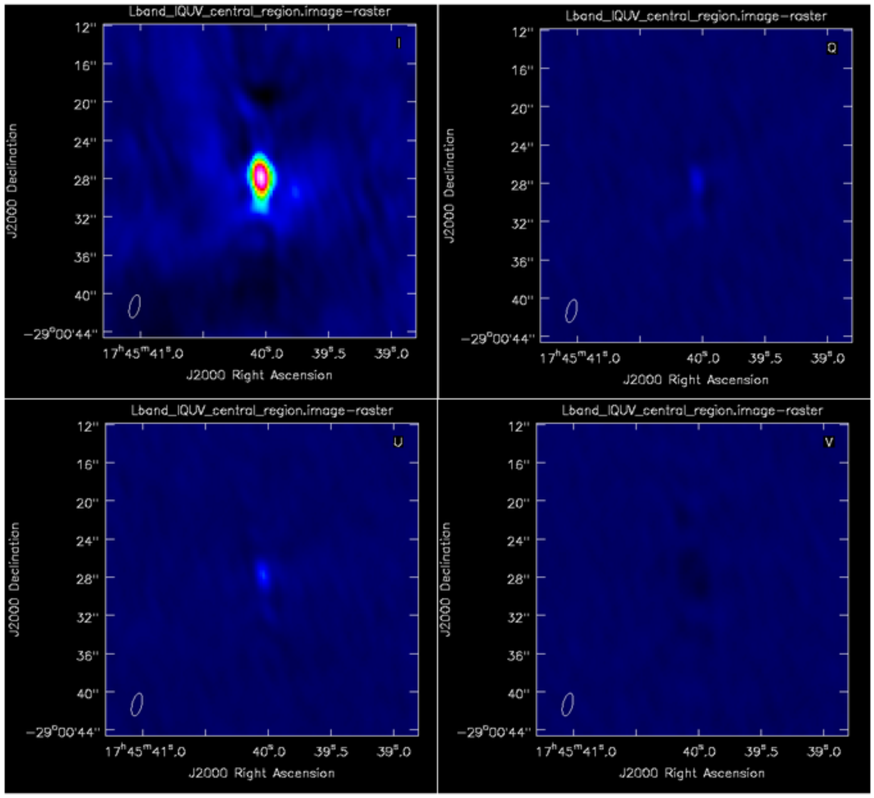

Figure 7: *Galactic Center images of Sgr A* in Stokes I,Q,U, and V polarizations. The high emission of Sgr A* in total intensity is evident in the I panel, while linear polarization measurements prove to be substantially reduced in the Q and U frames by comparison.*

In order to carry out these processes, we calibrate the L and S band data sets of Sgr A* through the CASA pipeline, bypassing manual calibrations. In order to achieve the polarization calibrations necessary for RM synthesis, we make use of a polarization script provided through the work of Indu Korambath. We then image the data sets in Stokes I,Q,U, and V polarization - exemplifying the magnitude of Sgr A* in total intensity, and the lack thereof in linear polarization [Fig 7.]. These parameters are effectively measures of the polarization state for electromagnetic radiation. Stokes I represents the total intensity of the measured radiation, while Q and U measure the linear polarizations. Comparably unimportant in the context of this project, Stokes V constitutes the circularly polarized radiation. The next step is to generate cubes of these regions, and identify specific regions within our search area where known pulsars are located so that RM synthesis can be performed. This is necessary in order to test that RM synthesis is effective when searching for high RM point sources such as the pulsars towards the Galactic Center.

4.2 Discussion

This proves to be an effective technique for measuring pulsations towards the Galactic Center, as Sgr A* is bright in Stokes I (1 Jy total intensity) and hampers the effectiveness of noise-limited imaging. In order to avoid such complications we instead utilize the linear polarization of a wave's propagation, as Sgr A* is below 0.1% linearly polarized (Bower et al. 1999). Given the significant Faraday depth that can be synthesized with this technique, it could very well prove to be an effective means of finding new pulsars towards Sgr A*. Additionally, the few pulsars that have been detected in this region have all been measured at high RM values.

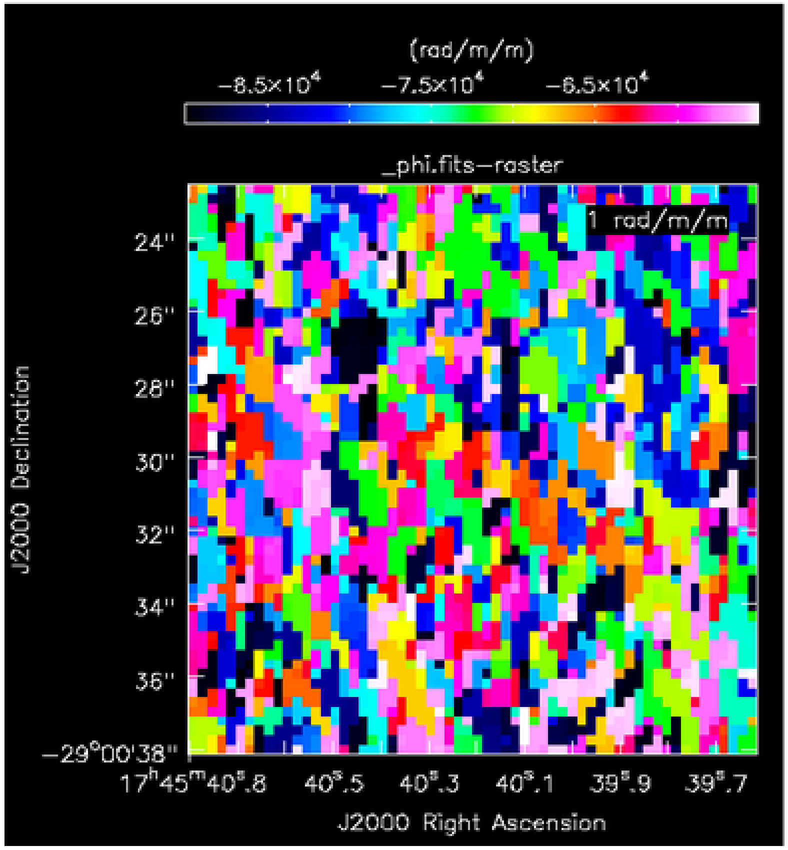

Figure 8: *The result of rotation measure synthesis of a previously identified Galactic Center pulsar. Its location is plotted directly at the center of the plot. The varying color scheme identifies different rotation measure values at a given location (right ascension and declination). Without any notable structure the figure effectively displays residual noise, but with enough sensitivity correction coherent structure could be resolved.*

Unfortunately, the data sets provided were not quite on source (Sgr A*), and were instead centered on Sgr B. As a result, the sensitivity of our measurements, and resulting images, were below what was anticipated. Consequently, the resulting pulsar RM synthesis did not generate anything above residual noise, despite having known pulsar locations within our field of view [Fig 8.]. In future work, a more precise observation of Sgr A* in a similar frequency range would likely provide better results. If high RM point sources are detected through this approach, a deeper search of the region could be performed in order to detect pulsations without the necessity of a wider-field search.

At this point, proposals for further observations of Sgr A* are scheduled to be tendered for the next rotation of the VLA through its B-North-A (BnA) configuration. This configuration is of particular relevance to this project simply given the location of the VLA. Given that the Galactic Disk is relatively low on the sky for the VLA, the BnA configuration allows for better observations towards the Galactic Center. The remaining primary objective for this project is to attempt to precisely determine the locations of known Galactic Center pulsars as well as the magnetar SR J1745-2900. If the experimental techniques presented in this report can be validated through these means, then further work can begin to finely comb through regions in proximity to Sgr A*.

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