Radio pulsars and transients in the Galactic center

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Abstract. Radio pulsars and transients provide powerful probes of the star formation history, interstellar medium, and gravitational potential of the Galactic center. Historical radio observations of the Galactic center have not emphasized the time domain aspect of observing this region. We summarize a series of recent searches for and observations of radio transients and pulsars that make use of two advances in technology. The first is the formation of large fields of view (≥ 1°) at relatively longer wavelengths (λ > 1 m), and the second is the construction of receivers and instruments capable of collecting data on microsecond time scales at relatively short wavelengths (≈ 3 cm).

1. Introduction

Transient emission—bursts, flares, and pulses—marks compact sources or the locations of explosive or dynamic events. The discovery of transient sources, most notably radio pulsars, can be used to probe a number of aspects of the Galactic center (GC):

- The spatial distribution of objects, as well as period and age distributions of pulsars, in the region, along with a careful tallying of selection effects, would help describe the stellar population in the region and discriminate between hypotheses attempting to explain the presence of the cluster of massive stars: stellar collisions and mergers, migration, and a past episode of intensive star formation.
- The density of the ionized medium can be inferred from its imprint on the radio signals, and potentially its structure, any turbulence within it, and any magnetic field threading it can also be determined.
- Pfahl & Loeb [1] argue that a population of stellar-mass black holes (BHs) exists in the GC due to tidally induced migration, e.g., 100 BHs within the central 1" alone. Pulsars discovered within this central field would be experiencing measurable gravitational
perturbations from the BHs and timing them would allow indirect study of this exotic population. The stellar density is probably sufficiently high that, by analogy with globular clusters, the region should be rich in pulsar binaries and millisecond pulsars.

- Orbits of pulsars close to Sgr A* will show many relativistic effects. Careful timing of pulsars would allow us to measure their Einstein delay, first and second order Shapiro delays, and frame-dragging effects. This in turn would provide methods for better constraining the mass of the central BH, and even estimating its spin. Combined with the effects of the proposed population of stellar-mass BHs, these measurements also would allow mapping out the shape of the central gravitational potential.

Generally, historical radio observations of the GC have not emphasized the time domain aspect of observing this region or, if so, have done so with only very infrequent observations (e.g., once per month). More recently, a variety of technological improvements and new recognition of the importance of these objects in the GC have spurred new observations. Though there can be common threads to the study of radio transients and pulsars (e.g., some classes of radio transients may be powered by neutron stars), the observational details are sufficiently different that we discuss the two kinds of objects separately.

2. Radio Transients
There have been a few historical radio transients detected toward the GC, though these typically have been discovered serendipitously in the process of other observations, typically Sgr A* itself. Examples of these historical transients include A1742−28 [2] and the Galactic Center Transient [3].

Effective searches for radio transients requires that the quantity \(A\Omega(T/\Delta t)\) be “large.” Here \(A\) is the collecting area or sensitivity of the telescope, \(\Omega\) is the solid angle coverage, and \(T/\Delta t\) is a measure of the cadence or time resolution achieved in the search. High-energy telescopes have been able to find many transients with relatively modest sensitivities by having a large field of view. Recent advances in both computing and imaging algorithms now make it practical to image relatively wide fields of view, of order 1°, on a regular basis at wavelengths \(\lambda \approx 1\) m [4]. Motivated by those successes, specific radio transient search campaigns have been conducted toward the GC with the Very Large Array, with recent observations also acquired at the Giant Metrewave Radio Telescope.

This transient campaign suggests that the duty cycle of radio-selected radio transients at \(1\) m with flux densities above approximately 0.1 Jy is about 10%. That is, in approximately 10% of the observing time, a radio transient has been detected (with one of the transients detected multiple times). Two specific transients that have been found include GCRT J1746−2757 [5] and GCRT J1745−3009 [6, 7]. Even these two objects hint at the potential diversity of radio transients. The former, GCRT J1746−2757, brightened and faded on a time scale longer than a day and potentially as long as a few months. In contrast to many radio transients that are found via their X-ray emission (e.g., microquasars and X-ray binaries), GCRT J1746−2757 did not appear to emit in the X-ray. Conversely, GCRT J1745−3009 showed rapid variability, bursting several times during the course of a 6-hr observation (Figure 1). If located in the GC, the brightness of this transient requires that it emit coherently, and it may represent the first in a new class of radio objects. Like GCRT J1746−2757, it was not detected in the X-ray.

Finally, another recent transient detected is CXOGC J174540.0−290031 [8]. It had the morphology of a classical Faranhoft-Riley Type II radio galaxy, namely two expanding lobes of radio-emitting plasma. Unlike a radio galaxy, however, the proper motion of one of the lobes could be measured. Midway between the two lobes was a central X-ray source, prompting the identification of this object as the result of a bipolar jet of relativistic plasma from a central engine powered by a low-mass X-ray binary. Intriguingly, this transient, or one like it, may be able to create a cavity of ionized gas, potentially explaining the nearby “mini-cavity” [9].
Figure 1. Light curves of GCRT J1745–3009 [7]. The top panel shows the single detected burst from 2003 September 28; the remaining panels show the bursts from 2002 September 30, arranged with the first burst shown in the bottom panel to the fifth burst shown in the second from the top panel. The ordinate ranges from 0 to 1 Jy in the top panel and 0 to 2 Jy in the other panels. For the 2002 September 30 bursts, the light curve has been folded at the apparent 77.1 minute periodicity. For the 2003 September 28 burst, the light curve has been aligned in time to be consistent with the decay portions of the 2002 bursts. In many cases, because the existence of GCRT J1745–3009 was not known at the time of the observation, the full burst is not captured as the observations were interrupted for calibration observations. The arrows represent 3σ upper limits for nondetections. The vertical dotted line is placed at the fitted position of the fourth 2004 burst for reference.

3. Radio Pulsars

Of the 1700 pulsars presently known, fewer than 1% are within 2° of the GC. This deficit of pulsars has long been attributed to the effects of radio wave propagation and scattering through the ionized interstellar medium. As scattering effects typically scale strongly with wavelength, “short wavelength” surveys (e.g., 20 cm) were initiated to mitigate the scattering effects [10].

Only more recently has the extent to which scattering vitiates pulsar searches toward the GC become apparent. Lazio & Cordes [11] (see also [12]) have shown, via observations of background sources and OH/IR stars, that the GC is either immersed in or surrounded by a region of intense scattering. Extrapolating their results to the impact on pulsar signals, Cordes & Lazio [13] estimated that the level of pulse broadening could be 2 milliseconds\(\lambda^4\) cm for the wavelength measured in centimeters. At the typical wavelength used for pulsar searches (\(\lambda > 20\) cm), this level of pulse broadening can exceed 2000 seconds, rendering pulsars undetectable as pulsed objects. The recent discovery of PSR J1745–2912 and PSR J1746–2856 from observations at 9.7 cm, and their non-detection at 3.6 cm, lead Johnston et al. [14] to suggest that the scattering may be even more intense than these models predict. Both of these pulsars are
within 0.3° of the GC and are likely located between 150 and 500 pc, but on the near side of the GC.

The typical pulsar search methodology, a periodicity search, is to survey the desired region, collecting long time series which are then Fourier transformed and searched for periodic signals (or multiple harmonics from periodic signals). This methodology fails completely if pulsars do not pulse, as they would not at typical search wavelengths. Searching at wavelengths short enough to mitigate the pulse broadening is difficult, both because of the resulting relatively small telescope beams as well as the typically steep pulsar spectra. Cordes & Lazio [13] and Lazio & Cordes [11] outlined an alternate search methodology in which pulsars might be detected as angularly broadened compact sources, analogous to how Sgr A* and the OH masers associated with various OH/IR stars have been detected. Angularly broadened compact objects with pulsar-like characteristics could then be targeted for more intensive at wavelengths short enough to mitigate the pulse broadening.

Two surveys of the GC using the Very Large Array have been carried out for compact radio sources. Lazio & Cordes [15] surveyed the central 1° at a wavelength of 20 cm and found 175 sources. Bower (2006, unpublished) surveyed the central 17′ at 3.6 cm, in an effort to match a field also surveyed with Chandra, and found 85 sources. Candidate lists from these surveys are now the subject of periodicity searches with the 100-m Green Bank Telescope at a wavelength of 3.3 cm. A blind survey of the central few arcminutes also has been conducted as part of these observations. Although a blind survey of the entire GC region is too expensive in terms of telescope time, a blind survey of the central 1° or so is justified given the presence of the central stellar cluster. In addition, a survey at 6 cm has been conducted with the 100-m Effelsberg telescope [16].

4. Future Observations

There are a number of radio telescopes, either under construction or in the design and development phase, for which searches for radio transients, radio pulsars in the GC, or both form an important part of the science case. We describe these briefly.

The Expanded VLA1 (EVLA) is a project designed to replace the (original) electronics in the VLA with more modern versions, including replacing the original analog correlator with a modern digital version. The result will be larger bandwidths and a greater access to the spectrum. The increased spectral access will be particularly important at wavelengths around 3 cm, at which it result in a considerable improvement in sensitivity, and the new correlator will enable efficient radio pulsar searches for the first. If the GC population is similar to the disk population of radio pulsars, the EVLA is likely to discover several (or more!) pulsars in the GC.

The Allen Telescope Array2 (ATA) is a telescope under construction with the aim of providing several new capabilities for observing in the 3–60 cm wavelength range. Composed of 6-m diameter parabolic antennas, the ATA will have a relatively large field of view (≈ 1° deg.2 at 30 cm) and the ability to access multiple regions within this field of view simultaneously. In addition, it is expected to be able to access its entire wavelength range instantaneously. Radio transients (potentially including transmissions from extraterrestrial transmitters) are among its key science goals.

The Long Wavelength Array3 (LWA) is a telescope designed to open for the first time long-wavelength regime of the spectrum (λ > 3 meters) to high resolution imaging. Radio transients form an explicit part of its science case. It will be constructed of “stations” of dual-polarization dipoles, each station performing equivalent to a more traditional parabolic antenna, and it

1 http://www.nrao.edu/
2 http://www.seti.org/
3 http://lwa.unm.edu/
will be located in the southwestern U.S. state of New Mexico. Pointing will be accomplished electronically. The LWA will be able to access the GC, though because of the GC’s elevation as seen from New Mexico, there will be some loss of sensitivity. Nonetheless, if there are other objects such as GCRT J1745−3009, and they emit at long wavelengths, the LWA should still have the sensitivity to detect them. Importantly, the LWA will also have multiple, independent fields of view, potentially allowing for considerably more search time, one of the major limitations with existing instrumentation.

The Low Frequency Demonstrator\(^4\) of the Mileura Wide-field Array (MWA-LFD) is a telescope in the design and development phase. Like the LWA it will be composed of dual-polarization dipoles phased into stations. Its design wavelength range range is approximately 1.25 m to 4 m. Located in Western Australia, where there are few anthropogenic emissions, it will be equisitely sensitive in the FM radio band (\(\nu \approx 100 \text{ MHz}\)). Radio transients form a key part of its science case, and the GC will pass directly overhead.

The Square Kilometre Array\(^5\) (SKA) is a telescope in the design and development phase. Intended to cover wavelengths from 1.25 cm to 3 m, the SKA will have a sensitivity some 50 times greater than that of the EVLA. Radio pulsars in the GC form an explicit part of its science case, and it will have the capability to search both in an imaging mode (as done with current VLA searches) as well as in a periodicity mode at high sensitivity and at short wavelength.

With this suite of telescopes becoming available over the next decade, we expect a considerable increase in the number of both radio transients and radio pulsars known toward the Galactic center.

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\(^4\) http://haystack.mit.edu/
\(^5\) http://www.skatelescope.org/