The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
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The Galactic center pulsar SGR J1745−29

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Abstract. The discovery of the Galactic center pulsar SGR J1745−29 has provided an important new window into plasma processes in the Galactic center (GC) interstellar medium, the population of compact objects in the GC, and the prospects for probing general relativistic effects through timing of a Sgr A* pulsar companion. We discuss here radio observations of the pulsar and how they are providing fresh insights. In particular, our results show that recent pulsar surveys had the sensitivity to detect many pulsars in the GC region without significant losses due to interstellar scattering. This raise the question of why only this pulsar close to Sgr A* has been detected.

1. Introduction

The discovery of a pulsar that is gravitationally bound to the Galactic center black hole, Sgr A*, would provide an extraordinary opportunity to explore general relativity and black hole properties with unprecedented precision. This has motivated numerous searches for pulsars in the GC, none of which have been successful in finding a pulsar companion to Sgr A*. This has primarily been attributed to the presence of very strong interstellar scattering along the line of sight. In the most developed model, the scattering screen is expected to smear pulsed signals over a timescale that is tens to hundreds of seconds at low frequencies (Lazio & Cordes 1998). The solution has been to exploit the steep spectrum dependence of the temporal broadening (ν^{-4}) and observe at higher frequencies. Unfortunately, typical pulsar spectra also decline steeply with increasing frequency, making observations less sensitive to the pulsar population. Nevertheless, while existing surveys at a range of frequencies have sensitivity to a fraction of the pulsar population, no pulsars have yet been discovered.

The pulsar SGR J1745−29 was discovered serendipitously through Swift X-ray observations that were carried out in search for flux variations associated with the G2 cloud impact on Sgr A*. It was quickly realized that the dramatic increase in X-ray luminosity in the central arcseconds of the GC were associated with a source separate from Sgr A*. *Chandra* observations localized the source to a separation of 2.4” from Sgr A*. *NuSTAR* observations discovered pulsed X-ray emission with a period of 3.76 s. The X-ray variability and timing inferred magnetic field identified the source as a magnetar.

Immediately following X-ray detection, bright radio emission from 1.3 to 18 GHz was detected by numerous radio telescopes including Effelsberg, Nancay, the GBT, and the phased Very Large Array (Bower *et al.* 2013, Eatough *et al.* 2013, Spitler *et al.* 2013). This identifies SGR J1745−29 as just one of a handful of known radio magnetars. The radio observations confirmed the X-ray period and period derivative. In addition, radio observations provided multiple probes of the plasma properties along the line of sight, including the dispersion measure (DM), the rotation measure (RM), angular broadening due to scattering, and temporal broadening due to scattering. This ensemble of measurements provides a powerful probe of the GC environment and the intervening medium along the line of sight.

2. Is SGR J1745−29 located in the Galactic center?

Several pieces of evidence demonstrate that SGR J1745−29 is located in the GC and most likely within parsecs of Sgr A*:

• The projected distance between SGR J1745−29 and Sgr A* is 0.1 pc at the distance of the GC. Given the rarity of magnetars in the Galaxy, it is reasonable to associate the pulsar with the region of highest stellar density, the Galactic center cluster.

• The X-ray absorption column is $\sim 10^{24}$ cm^{-2}, comparable to what is observed for Sgr A* and other GC sources.

• The DM$= 1778$ pc cm^{-3} is the largest measured for any pulsar. This value is within the range predicted for the integrated DM through the Galaxy by the NE 2001 electron density model. The pulsar must be in front of Sgr A West, which would lead to a significant additional contribution to the DM.

• The RM$= 6.7 \times 10^4$ rad m^{-2} is also the largest measured for any pulsar. It is an order of magnitude less than the RM for Sgr A* but much larger than seen in the diffuse gas and towards extragalactic background sources in the central degrees of the GC. This confirms the picture that the bulk of the RM for Sgr A* originates within the accretion region. But the pulsar RM must originate from magnetized plasma within 10 pc of Sgr A*, where constraints on the plasma density are set by diffuse X-ray emission.

• The angular broadening of the pulsar at 3.4 and 2 cm is in agreement in size and orientation with that of Sgr A*. This indicates that the two objects share the same scattering medium and are located at approximately the same distance from the scattering medium.

Together, these pieces of evidence indicate that SGR J1745−29 is neither very far in the foreground or very far in the background and most likely within a few parsecs of Sgr A*. Thus, SGR J1745−29 is truly a GC pulsar.

Proper motion measurements of the pulsar, which are underway with the VLBA+phased VLA, may be able to reveal the origin and fate of the pulsar. Provided that the pulsar remains radio bright for an extended period of time (~ 1 y), velocity resolution of $\sim$10 km s^{-1} is possible. The characteristic velocity for an object bound to Sgr A* at 0.1 pc is $\sim$400 km s^{-1}. This can demonstrate whether the pulsar is gravitationally bound to Sgr A* and possibly permit us to point backwards to the supernova remnant from which it originated.

3. Multiple line of sight plasma effects

As discussed in the previous two sections, four line of sight plasma effects have been observed towards SGR J1745−29. Each of these appears to originate from a different component of the ISM. The DM is the result of diffuse plasma that pervades the Galactic plane and that has been characterized primarily through observations of other pulsars and extragalactic background sources. The RM, which is the integral of the line of sight magnetic field weighted by the electron density, appears to originate from very close (within 10 pc) to Sgr A*, where the magnetic field is very large (> few mG). This magnetic field may power a jet originating near Sgr A*.

The scattering effects, angular and temporal broadening, can be used to uniquely determine a distance to the scattering medium under the assumption of a thin scattering screen. Together these measurements indicate a distance from the GC $\Delta = 5.8 \pm 0.3$ kpc, which is consistent with localization in the Scutum spiral arm (Figure 1). Alternatively, one can consider a uniform turbulent medium along the line of sight that can roughly reproduce the observed angular and temporal broadening. Such a model could also consist

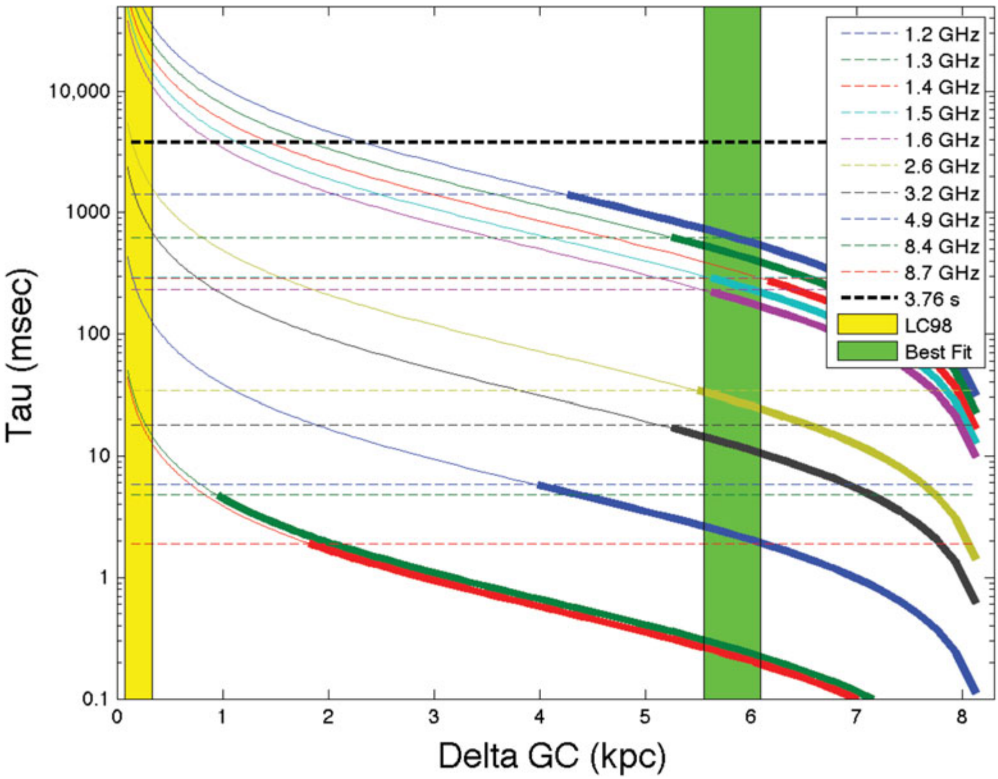

Figure 1. Temporal broadening of pulsed radio emission as a function of distance Δ from the GC. Horizontal dashed lines indicate the measured constraints from temporal broadening measurements. Solid lines are theoretical curves for a thin scattering screen. Permitted parameter space is at values of Δ where τ is less than the observed values; these are highlighted as thick solid lines. The dashed black line indicates the pulse period of 3.76 s. The solid yellow region is the solution for Δ from Lazio & Cordes 1998. The solid green region is the best-fit solution $\Delta = 5.8 \pm 0.3$ kpc. [A COLOR VERSION IS AVAILABLE ONLINE.]

of multiple thin scattering screens distributed over the line of sight from Sgr A* to the Sun. Both the single thin scattering medium and the extended distribution of scatters models are sharply different from the previously estimated model of a single thin scatterer close to Sgr A* with $\Delta \approx 0.1$ kpc.

In this new picture, the very strong scattering of Sgr A* and SGR J1745−29 are not the result of processes local to the GC but due to random superposition along the line of sight. In this way, the GC scattering resembles that seen towards the Cygnus region and NGC 6334B. The scattering medium may be HII regions or the ionized surfaces of molecular clouds along the line of sight.

Patchiness is observed in the angular broadening properties of OH/IR maser spots and of extragalactic background sources on scales of $\sim 1'$ to $\sim 10^{\circ}$. This patchiness demonstrates that a single thin scatterer cannot be responsible for all scattering in the direction of the GC (although a single screen may still be responsible for individual lines of sight). More exotic models for the scattering medium may be possible. For instance, one may be able to construct models in which additional temporal broadening occurs on some lines of sight without significantly affecting the angular broadening. There may also be scenarios in which a thick screen permits the scattering screen to be close to Sgr A*. But these models are *ad hoc* without further evidence.

High time resolution imaging observations of the pulsar may provide further insights into the scattering medium. If one could provide images as a function of pulse phase, then one could expect to see the angular broadening increase as the pulse evolves from the initial delta function into the exponential scattering tail. In the simplest case, this would lead to the image growing from a point source to a ring. The ability to measure this effect is complicated by the substantial jitter in the intrinsic pulse shape, the low SNR of high resolution imaging even with inclusion of a big aperture such as the phased VLA, and the challenges of imaging a faint source only arcseconds in separation from the very bright Sgr A*.

4. Pulsar detection in the Galactic center

The detection of SGR J1745−29 at radio frequencies as low as 1.3 GHz upends the conventional view of the limitations that scattering produces for GC pulsar detection. Clearly, some, if not all, pulsars close to Sgr A* can be detected at low radio frequencies. Further, the temporal broadening results demonstrate that most slow pulsars will not suffer substantial broadening with observations at frequencies $\sim$ a few GHz. Millisecond pulsar detection requires observations at frequencies $\sim$10 GHz.

Large pulsar populations are expected in the GC due to the presence of a massive star cluster and multiple supernova remnants. Dynamical friction is also expected to transport compact objects into the central parts of the GC. The overabundance relative to the increasing stellar density of X-ray transients detected by *Chandra* supports the conclusion that this dynamical friction process is at work. Thus, we have a strong expectation of a significant pulsar population in the central parsecs of the GC.

These arguments raise the question of why previous surveys, conducted at frequencies from 1.4 to 15 GHz, have not detected pulsars close to Sgr A*. SGR J1745−29 would have been easily detected by nearly all of the modern GC pulsar searches as would a fraction of the field pulsar population. This problem is further complicated by the fact that magnetars are rare in the field pulsar population, at a fraction of only 10^{-3} to 10^{-2}. There is no consensus explanation yet for the absence of GC pulsars and whether this requires rethinking our understanding of the GC pulsar population.

5. Summary

The serendipitous discovery of SGR J1745−29 has provided startling new insights into the GC and the GC pulsar population. The ability to detect this pulsar at low frequencies is both surprising and confounding: it is the proof of concept that pulsars very close to Sgr A* are detectable at low radio frequencies, yet it raises the question of why we have not seen other pulsars in past searches. The transient nature of the pulsar has opened up new windows for exploration and created many new questions. If the pulsar remains bright for an extended period of time, we may be able to address additional mysteries about the Galactic center, Sgr A*, and its pulsar population.

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