ELUSIVE NEUTRON STAR POPULATIONS: GALACTIC CENTER AND INTERMITTENT PULSARS

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by
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We present radio transient search algorithms and results from the ongoing Arecibo Pulsar ALFA (PALFA) survey of the Galactic plane. PALFA has discovered seven objects through a search for isolated dispersed pulses. All of these objects are Galactic and have periods between 0.4 and 4.7 s. One of the new discoveries, PSR J0627+16, has a duty cycle of 0.01%, the smallest among known radio pulsars. We discuss the impact of selection effects on the detectability and classification of intermittent sources, and compare the efficiencies of periodicity and single-pulse searches for various pulsar classes. We find that in some cases the apparent intermittency is likely to be caused by off-axis detection or a short time window that selects only a few bright pulses and favors detection with our single-pulse algorithm. In other cases, the intermittency appears to be intrinsic to the source. Accounting for the on-axis gain of the ALFA system, as well as the low gain but large solid-angle coverage of far-out sidelobes, we use the results of the survey so far to place limits on the amplitudes and event rates of transients of arbitrary origin.

While intermittent pulsars are hard to find because of their emission properties, pulsars orbiting near the massive black hole in the center of the Galaxy have eluded detection because of severe scattering by dense ionized gas. We report the results from three Galactic center pulsar surveys performed with the Green Bank telescope at 9, 5, and 2 GHz. The latter survey discovered three pul-
sars whose large dispersion measures and angular proximity to Sgr A* indicate the existence of a Galactic center population of neutron stars. PSR J1746–2850I has a characteristic spindown age of only 13 kyr along with a high surface magnetic field $\sim 4 \times 10^{13}$ G. It and a second object found in the same telescope pointing, PSR J1746–2850II, which has the highest known dispersion measure among pulsars, may have originated from recent star formation in the Arches or Quintuplet clusters given their angular locations. Along with a third object, PSR J1745–2910, and two pulsars with similarly high dispersion measures reported by Johnston et al. (2006), the five objects found so far are 10′ – 15′ from Sgr A*, consistent with a large pulsar population in the Galactic center, most of whose members are undetectable in relatively low-frequency surveys because of severe scattering broadening. Based on the properties of the new pulsars and the parameters of our surveys, we present a maximum likelihood estimation of the spatial distribution of the Galactic center pulsar population.
**BIOGRAPHICAL SKETCH**

Iulia (“Julia”) Deneva was born in Russe, Bulgaria, an ancient city on the Danube. Shortly after, she moved with her family to Bjala, a smaller town in the interior of Bulgaria, where she spent the next 14 years reading, dreaming, studying, and scheming how to some day get involved in space exploration or astrophysics. After the dissolution of the USSR and the suspension of its space program in the 1990s, the remaining way to space was West, and Julia decided to attend the English Language School “Geo Milev” in Russe.

While in high school, Julia took part in the annual science Olympiad, visited the Varna planetarium many times, learned English and Spanish, and acquired a small refracting telescope, a most prized possession. Her first introduction to radio astronomy was the movie “Contact” in 1997, featuring the Arecibo Observatory in Puerto Rico and the Very Large Array in New Mexico. She decided that if the Arecibo Observatory already existed, she would work there, and if it didn’t, she would help build it.

As the developed world was gradually opening its borders to Eastern Europeans who wanted to travel, work, and study abroad, Julia was accepted to Vassar College in Poughkeepsie, New York. She majored in Astronomy and Computer Science, observed supernovae at the college observatory under the guidance of Prof. Fred Chromey, and simulated merging neutron stars while working for Prof. James Lombardi. She circumvented the National Science Foundation’s bar on foreigners in its Research Experience for Undergraduates program, and in the summer of 2002 was a research assistant at the Arecibo Observatory thanks to a grant from Vassar and the Howard Hughes Medical Institute.
In 2003 Julia was accepted to the Ph.D. program at Cornell University, where she studied radio astronomy with a focus on pulsar searching under the guidance of Prof. Jim Cordes. During her years as a graduate student she frequently traveled to the Arecibo Observatory, where she was eventually offered a post-doctoral position. Julia is an aspiring neo-Renaissance person and her interests outside the physical sciences include poetry, globalization, psychology, and futurism. The most valuable lesson in her life has been that “impossible” is a subjective category.

When someone says her desire to be an astronaut is a hare-brained dream, she still does not listen.
Земя и небе

Върху земя човек роден е. Но той на нея е роден
небе да има и да стене, загуби ли го някой ден,
da чува в нежностите къси, в делата, в болката дошла
не ударите на кръвта си, а ударите на крила.

Върху земя човек роден е. Но той на нея се роди
над себе си, непокорени, да дири винаги звезди,
da ги достига и когато до тях е стигнал, да скърби,
pак взрян в небето непознато и смъртносно може би.

Върху земя човек роден е. Но той роден на нея бе
dori в пръстта, и на колене, да има пак едно небе,
небе да има и тогава, когато няма и очи,
sam в себе си да го създава, когато то се заличи.

Веселин Ханчев
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My parents, Stefan Denev and Bisserka Boneva-Kato, always encouraged my dreams of space exploration and astronomy, as far-fetched and unachievable they seemed in the economic and political chaos of post-Socialism Eastern Europe.

For sharing the ups and downs of grad school life, laughs and rants, good times and sleepless nights, thanks go to Dave Volpe, Marc Berthoud, Ryan Yamada, Tim McConnochie, Dave Rothstein, Lynn Carter, Ryan Shannon, Laura Spitler, Sabrina Stierwalt, Patrick Taylor, Yanling Wu. I am also grateful to my friends from college, Brandon Camarillo and Noah Alberts-Grill, who have been the closest I have to a family in the US for the decade that I have lived here.
Finally, to Ben Arthur for his unwavering support over the past three years,

Dear playmate, in your hand
Is mine, the Universe is stretching
To run along, and in the etchings
Around our eyes hides promised lands.
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As astrophysicists, in the broadest sense we aim to describe and explain the interactions between matter, energy, space, and time in the Universe. General Relativity Theory has provided a framework to relate these four categories and since the early 20th century many observations have verified its predictions. But dealing with time has been tricky. An introduction to General Relativity typically includes *gedanken experiments* placing accurate clocks at such unlikely places as onboard a rocket traveling near the speed of light or near a massive black hole. Such standard thought experiments still express the desire of scientists to be able to place one of the simplest instruments in situations where time behaves in a counter-intuitive way, and measure directly the distortions of spacetime caused by massive objects.

And what if the clocks were already there for us to find? And not only one type of clock but a dazzling variety: plain clocks, amazingly accurate clocks useful for their precision, and even really bad clocks useful exactly for their unreliability?

The Universe’s clocks are pulsars.

### 1.1 What Are Pulsars?

Pulsars are small and extremely dense neutron stars emitting a beam of radio waves and, in some cases, X-rays or gamma-rays. Neutron stars are formed when stars with masses in the range $8 - 20 M_\odot$ explode as supernovae and leave behind a compact, highly magnetized core. As there is no nuclear fusion balanc-
ing the inward pull of gravity within the core remnant, it collapses until neutron degeneracy pressure equilibrates with gravity. Neutron stars have radii $\sim 10$ km, and masses in the range $1.3 - 1.7 \, M_\odot$ have been measured. Their average density, $\sim 7 \times 10^{14}$ g cm$^{-3}$, is larger than that of an atomic nucleus, making them the densest known objects after black holes. During collapse, angular momentum is conserved, and as a result, the newborn neutron star rotates tens of times per second.

A neutron star is a natural particle accelerator due to its intense magnetic field $\gtrsim 10^{12}$ G. Charged particles move at relativistic speeds along open magnetic field lines in the magnetic pole regions and emit radio waves coherently. If the magnetic axis is inclined with respect to the rotational axis, every time a magnetic pole sweeps through an observer’s line of sight, a radio pulse is detected. Because pulsars are extremely dense, their rotation rates are stable, making them very good natural clocks. The precise intervals between successive pulses emitted by some pulsars rival atomic clocks in accuracy.

1.2 Notable Discoveries and Astrophysics Applications

The first pulsar discovery was serendipitous: in 1968 Jocelyn Bell Burnell was studying the effects of interplanetary scintillation on compact radio sources when she noticed a pulsed signal with a period of 1.337 s. Further observations revealed that the signal was consistently detected from the same sky coordinates, the pulses were dispersed as expected for a signal traveling through ionized interstellar gas, and the intervals between successive pulses were extremely precise, with the only noticeable variation accounted for by the Earth’s
orbital motion (Hewish et al., 1968). The mysterious source was originally named LGM-1 (“Little Green Men 1”) because its celestial origin and regular pulses were reminiscent of a beacon put in place by an extraterrestrial civilization. However, three more pulsed signals (LGM-2, LGM-3, and LGM-4) with different periods and coming from different sky positions were discovered soon afterwards, making a natural phenomenon a more likely explanation (Pilkington et al., 1969). LGM-1 became CP 1919 (Cambridge Pulsed source at RA of 19\(^{h}\) 19\(^{m}\)), and is now catalogued as PSR B1919+21, one of more than 1700 known pulsars. LGM-2, 3, and 4 are now known as PSR B0834+06, PSR B0950+08, and PSR B1133+16.

Soon after Bell Burnell’s original pulsar discovery, Thomas Gold and Franco Pacini independently proposed that pulsars were rapidly rotating neutron stars (Gold 1968, Pacini 1968). Also in 1968, radio pulses with a period of 0.033 s were detected from a source in the Crab Nebula (Staelin & Reifenstein, 1968). This discovery proved the neutron star nature of pulsars: an object composed of anything less dense than neutron star matter would break apart spinning at such a rate. The detection was also the first to show the association between a pulsar and a supernova remnant. The supernova progenitor of the Crab pulsar and nebula was observed in 1054 AD and described in chronicles or depicted in pottery by several cultures around the world.

Using the Arecibo telescope, Donald Backer and collaborators discovered the first millisecond pulsar, PSR B1937+21, which has a period of 1.56 ms (Backer et al., 1982). It is isolated and a very stable rotator. Such objects are targets of long-term monitoring observations as part of the Pulsar Timing Ar-
ray, a project aiming to detect nanohertz gravitational waves\textsuperscript{1 2 3}. B1937+21 remained the fastest known pulsar for almost 25 years despite hundreds of pulsar discoveries in the meantime. In 2006, Jason Hessels and collaborators found PSR J1748-2446ad, a binary pulsar with a rotation period of 1.39 ms in the globular cluster Terzan 5 (Hessels et al., 2006). This object is the fastest known rotator to date.

Russell Hulse and Joseph Taylor discovered the first pulsar in a binary system in 1974 with the Arecibo telescope (Hulse & Taylor, 1975). PSR B1913+16 orbits a common center of mass with a neutron star companion once every 7.75 h. Hulse and Taylor demonstrated that the orbit is shrinking and the rate of shrinkage matches what is expected by General Relativity if the system is losing energy due to gravitational wave emission. Hulse and Taylor were awarded the Nobel Prize in 1993 for presenting the first observational evidence for the existence of gravitational waves.

The first double pulsar binary system, J0737-3039, was found by Marta Burgay and collaborators with the Parkes telescope (Burgay et al., 2003). The two pulsar companions have periods of 0.023 and 2.8 s and orbit each other every 2.4 h. The proximity of two massive neutron star companions that are moreover accurate radio pulsar clocks allows for multiple tests of General Relativity to be carried out by long-term timing of this system. In addition, the binary is seen almost edge-on, allowing studies of the pulsars’ magnetospheres by observing one companion’s emission passing through the other companion’s magnetosphere at each eclipse.

\textsuperscript{1}http://www.nanograv.org
\textsuperscript{2}http://www.atnf.csiro.au/research/pulsar/ppta/
\textsuperscript{3}http://www.astron.nl/stappers/epta/doku.php
1.3 Pulsar Intermittency

The details of the radio pulsar emission mechanism have been a persistent mystery since the first pulsar discovery. Theoretical models of the emission mechanism rely on electron-positron pair plasma accelerated to relativistic speeds in the pulsar magnetosphere. On the observational side, clues about the nature of the emission mechanism may be elicited from the properties of objects whose regular pulsed emission appears to be disrupted.

Several types of intermittent neutron stars have been identified based on their pulse amplitude distributions and the fraction of time that periodic emission is observed. One such class consists of nulling pulsars, first discovered by Backer (1970). In these sources, the pulsed flux sharply decreases, typically in less than one spin period. Pulses are not detectable for several or many consecutive periods before the flux just as sharply increases back to its normal value. A subset of nulling pulsars exhibit more extreme behavior, with the pulsed emission remaining off 30 – 95% of the time (Deich et al. 1986, Lewandowski et al. 2004, Wang et al. 2006).

Two other new transient pulsar classes have recently been reported: the intermittent pulsar PSR B1931+24 (Kramer et al. 2006) and Rotating Radio Transients (RRATs, McLaughlin et al. 2006). PSR B1931+24 is on for ~ 5 days, abruptly shuts off in less than 10 s and remains quiescent for 25 – 35 days at a time. The spin-down rate is 50% larger while the pulsed emission is on than when it is off, which can be explained by magnetospheric currents being much stronger during the “on” phase and affecting the spin-down torque.

RRATs have on average longer periods than the normal pulsar population
and emit only a few pulses per hour. An outstanding question regarding intermittent RRAT-like objects is whether they are simply extreme nullers which remain in the “off” state most of the time, or is the underlying reason for their intermittency fundamentally different from the mechanism causing nulling. Another question is whether such objects are a distinct physical class of neutron star with magnetospheric processes which give rise to their intermittency, or just an empirical class that has emerged because of detection criteria.

1.4 Galactic Center Pulsars

Sagittarius A* (Sgr A*) is an intense compact radio source at the center of the Galaxy that has long been hypothesized to harbor a supermassive black hole. Ghez et al. (2000) imaged the region around Sgr A* at 2.2 $\mu$m over several years and found that stars near Sgr A* exhibit significant accelerations in their orbital motion about the Galactic center. Based on these measurements, the mass of the black hole is estimated to be $\sim 2.6 \times 10^6 M_\odot$. More recently, Gillessen et al. (2009) derived an estimate of $(4.31 \pm 0.42) \times 10^6 M_\odot$ and $R = 8.33 \pm 0.35$ kpc for the black hole mass and distance. Long-term tracking of stellar orbits near Sgr A* allows for mapping the gravitational potential in the region as well as studying the properties of the black hole and ultimately differentiating between hypotheses that suggest a single supermassive black hole at the center of the Galaxy versus a black hole plus a cluster of dark objects.

In an idealized experiment, a gravitational potential can be best mapped out by populating it with accurate clocks. As the clocks move through the gravitational well, a distant observer would detect a time-variable deviation in the in-
tervals between successive ticks due to the relativistic bending of space-time by massive objects. The astrophysical objects that best approximate accurate clock behavior are pulsars. If we discover pulsars in tight orbits around Sgr A* we can perform this idealized experiment in reality on the supermassive black hole in the center of the Galaxy, leading to measurements of its mass and spin, and a map of the gravitational potential in the region. The estimates of Gillessen et al. (2009) have an astrometric accuracy of 300 µas, which at the distance of Sgr A* corresponds to a spatial accuracy of $\sim 4 \times 10^{11}$ m. Pulsar timing residuals on the order of 10 ms (a conservative estimate) allow spatial accuracy that is five orders of magnitude better.

### 1.5 Chapter Outline

Chapter 2 describes the stages of a pulsar search pipeline with a particular emphasis on the Cornell search code used in the surveys described in this thesis. Chapter 3 presents results on intermittent pulsars discovered by the PALFA survey and discusses selection effects that affect the detectability of transient and intermittent radio sources. This chapter was published in the Astrophysical Journal as Deneva et al. (2009). Chapter 4 focuses on Galactic center surveys at 5 and 9 GHz and limits on the periodic and single pulse flux density at these frequencies derived based on survey parameters. Chapter 5 presents the results of a 2 GHz survey of the Galactic center and follow-up timing of two out of three new pulsars. This chapter was published in the Astrophysical Journal Letters as Deneva, Cordes & Lazio (2009). Chapter 6 develops a simulation of the Galactic center pulsar population and will also be submitted to the Astrophysical Journal. Chapter 7 discusses directions for future work.
CHAPTER 2
SEARCH METHODOLOGY FOR PULSAR SURVEYS

Processing pulsar data is computationally intensive and processing data from a large survey, managing data products, and making them available to the community is often a multi-institution effort. We outline the stages of the Cornell pulsar search pipeline, which was used to process data from the PALFA survey and Galactic center (GC) surveys discussed in this work. We describe the mechanisms of data archival and database management used to provide public access to both raw data and data products, and present web service tools which cross-reference the PALFA data archive with archives from other surveys through the National Virtual Observatory.

2.1 Data Acquisition

Rotation periods of known radio pulsars range from 1.4 ms (PSR J1748−2446ad) to 11.7 s (PSR J1841−0456) and pulse structure on time scales as short as a few nanoseconds has been identified (Hankins et al., 2003). In order to study phenomena occurring at these time scales, we must sample pulsar emission at a comparably fast rate. One of the ultimate goals of pulsar searches is to detect objects with sub-millisecond rotation periods. Such a discovery would indicate exotic, extremely dense states of matter most likely composed of deconfined strange quarks. Sub-millisecond pulsars would be at least in part “strange stars”: predicted and extensively modelled but yet unseen (Glendenning, 2000).

Fast-sampling hardware allows pulsar astronomers to detect and study pulsars with ever shorter rotation periods and resolve finer and finer pulse struc-
ture, allowing a window into the pulsar emission mechanism and the properties of the pulsar magnetosphere, where radio emission originates. By the very nature of their targets, pulsar astronomers are at the forefront in terms of data taking rate and data volume. This section gives an overview of the specialized instruments make this possible.

2.1.1 Receivers

The Arecibo L-band Feed Array (ALFA) is a seven-beam receiver used by the Pulsar-ALFA (PALFA) survey and other large surveys targeting Galactic and extragalactic sources. It is sensitive to emission in the 1.23 - 1.53 GHz band. For the purpose of pulsar surveys, the chosen receiver center frequency strikes a middle ground between low frequencies that suffer from scattering broadening by Galactic ionized gas, and high frequencies, where pulsars are typically (but not always) weaker because of their steep, power-law spectra. The ALFA beams have elliptical sky footprints and beam widths of ~ 3.5’. They are arranged in a hexagon and the seven-beam power pattern including the near-in sidelobes covers an area of 24’ × 26’ (Cortés 2002, Cordes et al. 2006).

Since the declination range accessible to the Arecibo telescope does not allow it to see the Galactic center (GC), GC surveys were performed with the Green Bank Telescope using single-beam receivers at 2, 5, and 9 GHz. Follow-up timing and spectrum estimation observations were performed at 1.5, 2, 5 and 9 GHz. Table 2.1 lists the parameters for ALFA and the four GBT receivers used for work described in this thesis. The receiver parameters affecting survey sensitivity are the gain $G$ and the system-equivalent flux density $S_{sys}$, which de-
Table 2.1: Receivers used for the PALFA survey and GC surveys and follow-up observations.

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Beams</th>
<th>Frequency range (GHz)</th>
<th>Beam width (FWHM) (')</th>
<th>G (K/Jy)</th>
<th>S_{sys} (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALFA</td>
<td>7</td>
<td>1.23 - 1.53</td>
<td>3.5</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>L-band</td>
<td>1</td>
<td>1.15 - 1.73</td>
<td>9</td>
<td>2.0</td>
<td>10</td>
</tr>
<tr>
<td>S-band</td>
<td>1</td>
<td>1.73 - 2.60</td>
<td>5.8</td>
<td>1.9</td>
<td>11</td>
</tr>
<tr>
<td>C-band</td>
<td>1</td>
<td>3.95 - 6.10</td>
<td>2.5</td>
<td>1.9</td>
<td>8</td>
</tr>
<tr>
<td>X-band</td>
<td>1</td>
<td>8.00 - 10.00</td>
<td>1.4</td>
<td>1.8</td>
<td>15</td>
</tr>
</tbody>
</table>

notes the receiver contribution to the rms noise. \( S_{sys} = T_{sys} / G \), where \( T_{sys} \) is the system temperature.

### 2.1.2 Correlation Spectrometers

Correlators shift sequences of voltage samples with respect to one another and record the value of the correlation functions for a predefined number of lags. Pulsar search pipelines operate on data in the time-radio frequency domain. After data-taking is completed, autocorrelation functions recorded to disk by correlators are converted to spectra offline by software making use of the Wiener-Khinchin theorem. If the discrete autocorrelation function of a signal \( x \) at a lag value \( k \) is \( R(k) = \sum_n x_n x_{n-k}^* \), the power spectrum value at a radio frequency \( f \) is given by the discrete Fourier Transform of \( R(k) \), \( S(f) = \sum_k R(k) e^{-i2\pi kf} \).

The Wideband Arecibo Pulsar Processors (WAPPs, Dowd et al. 2000) are four dual-board backends used at the Arecibo Telescope to record correlation functions in a variety of modes, and were the backend of choice for the PALFA survey from 2004 to 2009. For the purposes of pulsar searching, autocorrelation functions are computed for two polarizations and summed before being written.
to disk as 16-bit unsigned integers.

During pulsar surveys we want to minimize the radiometer noise

\[ \sigma_n = \frac{T_{\text{sys}}}{G \sqrt{N_{\text{pol}} \Delta \nu T_{\text{obs}}}}, \]

(2.1)

where \( T_{\text{sys}} \) is the system temperature, \( G \) is the telescope gain, \( N_{\text{pol}} = 2 \) is the number of polarization channels summed, \( \Delta \nu \) is the bandwidth, and \( T_{\text{obs}} \) is the observation time. To optimize survey sensitivity, we must use as large a bandwidth and as long an observation time as possible. For the PALFA survey, the maximum bandwidth per WAPP board of 100 MHz is used, and each board handles data from one beam of the ALFA receiver. Since there are seven receiver beams and eight WAPP boards, the second board of WAPP 4 records dummy output which is discarded during data processing.

The WAPPs can compute autocorrelation functions for up to 512 lags and are capable of sampling times down to 16 \( \mu \text{s} \). However, the combination of these extreme parameters yields a data rate of 64 MB/s, which cannot be written to disk fast enough with current computer hardware. The PALFA survey uses the WAPPs in a three-level quantized mode with 256 lags and a sampling time of 64 \( \mu \text{s} \). This setup provides a sustainable data rate of 8 MB/s, high time resolution less than the rotation periods of even the fastest anticipated pulsar discoveries, and a large enough number of channels to mitigate dispersion broadening (addressed in detail in 2.2.2).

The Galactic center pulsar surveys described in this thesis were performed with the SPIGOT correlation spectrometer at the GBT. The SPIGOT provides autocorrelation functions and records them to disk in Flexible Image Transport System (FITS, Wells et al. 1981) data format. The maximum Spigot bandwidth of 800 MHz was used for the GC surveys with 1024 lags and a sampling time.
of 81.92 µs. Autocorrelation functions were recorded as 16-bit integers, for an adequate dynamic range and a sustainable data rate of 25 MB/s.

2.1.3 Digital Filterbank Spectrometers

In contrast to correlators, filterbank backends record data as radio frequency spectra and no Fourier transformation of correlation functions is necessary. Older analog machines consist of banks of hardware filters for individual radio frequency channels. Digital polyphase filterbanks are a generalization of the Discrete Fourier Transform performed in hardware to construct the spectral response of each channel (for a technical overview see Crochiere & Rabiner 1983). This method achieves better control over spectral leakage and the individual channel band shape.

When data are taken with a correlation spectrometer and autocorrelation functions then converted to dynamic spectra via a DFT, bright narrow-band radio frequency interference (RFI) will exhibit sidelobe “ringing” and contaminate a wider range of frequency channels, making it harder to excise during data processing. Data taken with digital filterbank spectrometers are less susceptible to this effect and narrow-band RFI can be more easily excised.

Starting in 2009, the backend used by the PALFA survey is the PDEV\(^1\) spectrometer designed by the late Jeff Mock. It consists of 14 boards, two per beam of the ALFA receiver in order to enable simultaneous data-taking for two commensal projects. Each board handles two 172 MHz frequency bands. For the pur-

\(^{1}\text{http://www.naic.edu/~phil/hardware/pdev/usersGuide.pdf; } \text{"PDEV" may mean "Prototype in Development", although by the manual’s admission it is not an abbreviation of anything.}\)
poses of the PALFA survey, the two bands are centered on 1300 and 1450 MHz, allowing use of the entire receiver bandwidth of 300 MHz. The PDEV spectrometer can write out between 4 and 8192 frequency channels, in steps of powers of 2. The PALFA survey uses a mode with 512 channels, and spectra are written out every 65 $\mu$s to a separate set of files for each frequency band.

2.2 Pulsar Search Pipeline

While this section focuses on the Cornell pulsar search code\(^2\), the outlined steps are common to all pulsar search pipelines, such as the Sigproc\(^3\) and Presto\(^4\) packages. A good search pipeline is sensitive not only to already known and observed classes of radio pulsars and transients but also to types of signals that are expected to exist based on astrophysical theory but have not yet been detected, such as sub-millisecond pulsars or radio bursts emitted by annihilating black holes. Figure 2.1 shows the stages necessary to extract plausible periodic and transient signal candidates from raw data.

There are three main branches to a pulsar search. A conventional periodicity search assumes a constant interval between successive pulses and is most sensitive to isolated pulsars. A binary periodicity search targets pulsars orbiting a common center of mass with a companion. A binary pulsar’s observed rotation period is Doppler-shifted and varies in time due to the non-uniform relative velocity between pulsar and observer. A single pulse search targets isolated radio bursts from celestial sources.

\(^2\)http://arecibo.tc.cornell.edu/PALFA/
\(^3\)http://sigproc.sourceforge.com
\(^4\)http://www.cv.nrao.edu/~sransom/presto
2.2.1 Dynamic Spectrum RFI Excision

The starting point of data processing is to form a dynamic spectrum $S(t, f)$ obtained directly from a filterbank backend or through Fast Fourier Transforms of autocorrelation functions from a correlator. Data are often contaminated with a smorgasboard of narrow or wide-band radio frequency interference (RFI)
caused by terrestrial radio sources. Some sources of RFI detected by the Arecibo telescope are airport radars, weather balloons, GPS and communications satellites, cell phone towers, as well as instrumental resonances of telescope components or leakage due to insufficient shielding of electronics. RFI may vary on time scales similar to those of pulsar emission and therefore we want to excise it before searching the data for pulsar signals. We accomplish this by constructing a “mask”: a two-dimensional representation of contaminated regions in the time-frequency plane $S(t, f)$.

First data are smoothed in time to obtain a decimated dynamic spectrum. To decimate by $\Delta t_{\text{dec}}$, we average $n = \Delta t_{\text{dec}} / \Delta t_{\text{samp}}$ samples and the resulting dynamic spectrum is

$$S'(t', f) = \left[ \frac{1}{n} \sum_{k=\lfloor jn \rfloor}^{(j+1)n} S\left( k \Delta t_{\text{samp}}, \kappa \Delta f \right) \right].$$  \hspace{1cm} (2.2)

The mean $\mu(f)$ and rms $\sigma(f)$ of each frequency channel are computed and recomputed over several iterations after discarding outlier values. Points for which $S'(t', f) - \mu(f) > m \sigma(f)$ are recorded as contaminated with RFI (typically $m = 3$).

The average bandpass for the duration of the observation is computed, and a procedure similar to that described in the previous paragraph is used to identify persistent spectral lines, which are then replaced by interpolation to produce a clean/corrected bandpass $B(f)$. As the bandpass shape and the total power in the band varies with time, a scale factor $a(t')$ is calculated which gives a best fit to the bandpass shape at time $t'$ when multiplied by the average clean bandpass.

If a point in the decimated dynamic spectrum $S'(t', f)$ is flagged as contaminated with RFI, all points in the raw, undecimated time spectrum $S(t, f)$ for
which $|t - t'| < \Delta t_{dec}$ are corrected. Their replacement values are calculated as the product of the average clean bandpass shape and the scale factor, $B(f) a(t')$.

Fig. 2.2 and Fig. 2.3 show plots of dynamic spectra of the bright pulsar B0301+19 before and after RFI excision. Most of the RFI is successfully excised and individual pulsar pulses become visible in the cleaned dynamic spectrum. Fig. 2.4 shows the mask calculated from the decimated dynamic spectrum and used to flag points contaminated with RFI in this observation.

### 2.2.2 Dedispersion

Once RFI has been excised from the full-resolution dynamic spectrum, we combine all channels in order to take advantage of power in the entire bandpass when searching for pulsar signals. The group velocity of electromagnetic radiation passing through a medium is frequency-dependent, such that higher frequencies travel faster through ionized interstellar gas and arrive earlier than low frequencies. The varying delays of frequencies within a bandwidth $\Delta \nu$ result in pulse dispersion across the bandwidth that must be corrected for before summing frequency channels. The dispersion measure $DM$ is defined as the integral of the column density of free electrons along the line of sight to a pulsar,

$$DM = \int_0^D n_e(l) dl.$$  \hspace{1cm} (2.3)

Then the relative delay in arrival times between two frequencies $f_1$ and $f_2$ is

$$\Delta t_{DM} = 4.15 \text{ ms} \left( \frac{DM}{\text{pc cm}^{-3}} \right) \left( \frac{f_1}{\text{GHz}} \right)^{-2} - \left( \frac{f_2}{\text{GHz}} \right)^{-2}.$$  \hspace{1cm} (2.4)

If the total bandwidth is $\Delta \nu$ and the observing frequency $f_c >> \Delta \nu$, this relation can be simplified to

$$\Delta t_{DM} \approx 8.3 \mu s \left( \frac{DM}{\text{pc cm}^{-3}} \right) \left( \frac{\Delta \nu}{\text{MHz}} \right) \left( \frac{f_c}{\text{GHz}} \right)^{-3}.$$  \hspace{1cm} (2.5)
Figure 2.2: Before RFI excision: Greyscale of the decimated dynamic spectrum of an Arecibo observation of the bright pulsar B0301+19 with the ALFA receiver and PDEV spectrometer. Dark vertical lines in the greyscale correspond to harmonics of the San Juan airport radar. The top panel shows the average clean bandpass $B(f)$ in black and identified persistent narrow-band RFI in red. The side panel shows a time-varying scale factor $a(t')$ which gives a best fit to the current bandpass shape when multiplied by the average clean bandpass. Some of the structure in $a(t')$ is due to pulses from the pulsar.
Figure 2.3: After RFI excision: Decimated dynamic spectrum of the same observation of B0301+19, with points contaminated by RFI $S'(t', f)$ replaced by the average clean band multiplied by the scale factor, $B(f)a(t')$. The faint horizontal lines are pulsar pulses.

Eqn. 2.4 is normally used to calculate relative delays between frequency channels in the dynamic spectrum and shift them appropriately with respect to a reference frequency (typically the lowest or highest channel in the band) before summing all channels.

When searching for pulsars, we do not know a priori whether the data contain any pulsar signals or what their $DM$ may be. We dedisperse dynamic
Figure 2.4: Dynamic spectrum mask used to flag and clean RFI in the observation of PSR B0301+09 from Fig. 2.2. Black circles represent points in the decimated dynamic spectrum flagged as contaminated with RFI, with the circle size proportional to the deviation from the local mean. The “occupancy” value above the plot is the fraction of the decimated dynamic spectrum that was flagged for cleaning.
spectra with a list of trial $DM$ values chosen depending on the observation parameters involved in Eqn. 2.4, as well as the properties of the targeted pulsar population. The $DM$ for various distances along a particular line of sight can be estimated from the NE2001 model of the distribution of ionized gas in the Galaxy (Cordes & Lazio, 2003), which takes into account a thin and thick disk gas component, the Galactic spiral arms, known HII regions, and a dense region of ionized gas around the Galactic center. Estimated $DM$ values for pulsars in the portions of the Galactic plane visible to the Arecibo telescope ($30^\circ \leq l \leq 78^\circ$ and $162^\circ \leq l \leq 214^\circ$ for $b = 0^\circ$) are $\lesssim 1000$ pc cm$^{-3}$ and therefore the PALFA trial $DM$ list includes dispersion measures in the range $0 - 1000$ pc cm$^{-3}$. By contrast, the NE2001 model predicts $DM \approx 1700$ pc cm$^{-3}$ for pulsars within the dense scattering region surrounding Sgr A*, so that the Galactic center surveys described in Chapter 5 and Chapter 4 use trial $DM$s in the range $0 - 2500$ pc cm$^{-3}$.

After the full-resolution dynamic spectra are dedispersed for searching, there are two causes of residual dispersion smearing: the finite width of a frequency channel, and the difference between the actual pulsar $DM$ and the closest value in the trial $DM$ list. Dispersion smearing across a frequency channel is given by Eqn. 2.5 with the channel width $\Delta\nu_{ch}$ substituted for the total bandwidth $\Delta\nu$. Similarly, if $\delta DM$ is the error in $DM$,

$$\Delta t_{DM, err} \approx 8.3 \, \mu s \left( \frac{\delta DM}{\text{pc cm}^{-3}} \right) \left( \frac{\Delta\nu}{\text{MHz}} \right) \left( \frac{f_c}{\text{GHz}} \right)^{-3} \cdot$$  

(2.6)

The total amount of dispersion smearing due to these two effects is $\Delta t_{DM} = \left( \Delta t_{DM, ch}^2 + \Delta t_{DM, err}^2 \right)^{1/2}$.

The spacing between trial $DM$ values is determined based on how much residual dispersion smearing can be tolerated, taking into account that in the worst case, $\delta DM$ is equal to half the spacing between consecutive trial values. In
Figure 2.5: Mapping of DM channel vs. DM value for the Galactic center surveys at 5 and 9 GHz described in Chapter 4 (left) and the PALFA survey of the Galactic plane (right).

generally, the acceptable amount of dispersion smearing is a fraction of the period of the fastest-rotating pulsar we want to be able to detect, or of the scattering broadening expected based on the amount of ionized gas along the search line of sight, whichever is larger. Thus, when looking for pulsars near the Galactic center, where observed and estimated scattering times are tens to hundreds of milliseconds, we can use a larger spacing between trial $DM$ values than when searching in the Galactic plane, where scattering is much less pronounced and we can hope to discover pulsars with periods less than 1 ms.

Figure 2.5 shows the mapping of DM channel (the sequence number of a trial DM in the DM list) vs. DM value for the Galactic center surveys at 5 and 9 GHz described in Chapter 4 and the PALFA survey, which looks for pulsars in the Galactic plane. In the GC trial DM list, the spacing between consecutive DMs is 50 pc cm$^{-3}$ for $DM = 10 – 1050$ pc cm$^{-3}$ and 500 pc cm$^{-3}$ for $DM = 1050 – 2050$ pc cm$^{-3}$. The large spacing is chosen because of the large, un-
correctable scattering broadening when looking towards the Galactic center and because at 5 and 9 GHz, $\Delta t_{DM, ch}$ and $\Delta t_{DM, err}$ are negligible in comparison to scattering broadening. In contrast, the observing frequency of 1.4 GHz of the PALFA survey and the fact that dispersion broadening is likely to dominate over scattering for sources in the Galactic plane dictates a DM spacing from $0.3 \text{ pc cm}^{-3}$ for trial $DM = 0 - 187 \text{ pc cm}^{-3}$ to $3 \text{ pc cm}^{-3}$ for $DM = 570 - 1000 \text{ pc cm}^{-3}$.

### 2.2.3 Periodicity Search

After dedispersion, we have as many dedispersed time series as trial DMs and we want to search each of them for periodic pulsed signals. The standard approach is to use a Discrete Fourier Transform (DFT) and look for harmonics in the Fourier frequency domain (corresponding to the pulsar rotation frequency). If a time series sampled at intervals $\Delta t$ and containing $N$ samples is denoted as $x(j \Delta t)$, the value of its DFT at a frequency bin $k \Delta f$ is

$$X(k \Delta f) = \frac{1}{N} \sum_{j = 0}^{N-1} x(j \Delta t) \exp \left( - \frac{2\pi i j k}{N} \right).$$  \hspace{1cm} (2.7)

The frequency bin width $\Delta f = 1/T_{obs}$, and the highest frequency bin is the Nyquist frequency, $f_N = 1/2\Delta t$. In practice, the highest frequency is given by $1/\Delta t$, but since the time series consists of real numbers, the resulting Fourier components are symmetric with respect to $f_N$ because the DFT is Hermitian, $X((N - k) \Delta f) = X(k \Delta f)^*$.

The time series is typically Gaussian white noise-like and therefore its Fourier power spectrum is flat. However, low-frequency RFI and instrumental variations introduce a red noise component into the spectrum with a $1/f^{-x}$ ($x \approx 2$) dependence of power on frequency. In order to avoid red noise biasing a
periodicity search towards low frequencies, the spectrum is flattened by dividing it into successive segments and removing a running mean or median from each segment.

The appearance of the power spectrum of a time series containing a pulsar signal in addition to Gaussian noise depends on the width, shape, and amplitude of the pulses. In general, pulses have an intrinsic Gaussian-like shape with single or multiple components, and the duty cycle \( f_{\text{dc}} = W/P \) is \( \sim 5\% \) for canonical pulsars and up to \( \sim 25\% \) for millisecond pulsars. In the limit of a pulse so broad that its shape is close to a sinusoid, there is only one harmonic present in the spectrum, at the sinusoid’s frequency, \( 1/P \). For a narrower pulse, more than one Fourier component is needed to adequately describe the pulse shape and harmonics at frequencies which are integer multiples of \( 1/P \) become more prominent. In searching for pulsar signals, we want to identify harmonics and add the power from the respective frequency bins in the spectrum before applying any thresholds or significance tests to candidate signals. In general, the number of harmonics present is \( \sim P/W \) for \( W \ll P \). Figures 2.6 and 2.7 show power spectra of PALFA observations of the bright pulsars B1933+16 and B1937+21, respectively. B1933+16 has a period of 0.359 s and \( f_{\text{dc}} \approx 2\% \) and its spectrum shows \( > 200 \) harmonics. In contrast, there are only 6 obvious harmonics in the spectrum of B1937+21, which has \( P = 0.00155 \) s and \( f_{\text{dc}} \approx 10\% \).

For an observation time \( T_{\text{obs}} \), pulse period \( P \), amplitude \( A \) and width \( W \) a noiseless Gaussian pulse train is

\[
x(t) = \sum_{k=1}^{\text{int}(T_{\text{obs}}/P)} A_k \exp \left[ -\frac{2(t - kP)^2}{W^2} \right].
\]

The period-averaged pulse amplitude \( \langle x \rangle_\phi \) is a measure of the pulsar’s flux density and therefore detectability. For \( T_{\text{obs}} \gg P \), \( N_p = \text{int}(T_{\text{obs}}/P) \), and \( \sigma \equiv W/2 \), we
Figure 2.6: Time series and power spectrum of a 1.44 GHz PALFA observation of the bright pulsar B1933+16 ($P = 0.359$ s) after dedispersing with $DM = 158$ pc cm$^{-3}$. The top panel shows the dedispersed time series in arbitrary units vs. time. The second panel from the top shows the complete power spectrum, and the lowest three panels show three zoom levels on lower-frequency parts of the spectrum.
Figure 2.7: Time series and power spectrum of a 1.44 GHz PALFA observation of the bright millisecond pulsar B1937+21 ($P = 0.00155$ s) after dedispersing with $DM = 71$ pc cm$^{-3}$. The top panel shows the dedispersed time series in arbitrary units vs. time. The second panel from the top shows the complete power spectrum, and the lowest three panels show three zoom levels on lower-frequency parts of the spectrum. The fundamental harmonic of the pulsar is at 645 Hz, and a spike at 60 Hz is due to RFI from the electric mains.
can express it as

\[ \langle x \rangle_\phi \equiv \frac{1}{T_{\text{obs}}} \int_0^{T_{\text{obs}}} x(t) \, dt \quad (2.9) \]

\[ = \frac{1}{T_{\text{obs}}} \sum_{k=1}^{N_p} A_k \int_{-\infty}^{\infty} \exp \left[ -\frac{2}{W^2} (t - kP)^2 \right] dt \quad (2.10) \]

\[ = \frac{1}{T_{\text{obs}}} \sum_{k=1}^{N_p} A_k \int_{-\infty}^{\infty} \exp \left[ -\frac{t^2}{2\sigma^2} \right] dt \quad (2.11) \]

\[ = \frac{\sqrt{2\pi}}{2} \frac{W}{T_{\text{obs}}} \sum_{k=1}^{N_p} A_k \quad (2.12) \]

\[ = \frac{\sqrt{2\pi}}{2} f_{dc} \langle A \rangle. \quad (2.13) \]

The Fourier transform of the Gaussian pulse train is

\[ \tilde{X}(f) = \int_{-\infty}^{\infty} x(t) \exp[-i2\pi ft] \, dt \quad (2.14) \]

\[ = \frac{\sqrt{2\pi}}{2} W \exp \left[ -\frac{\pi^2 W^2 f^2}{2} \right] \sum_{k=1}^{N_p} A_k \exp[-ikP2\pi f], \quad (2.15) \]

where we have exploited the properties of the Fourier transform giving the Fourier pairs \( e^{-\pi t^2} \Leftrightarrow e^{-\pi f^2} \) and \( f(at) \Leftrightarrow (1/a) \hat{F}(f/a) \).

Frequency bins at \( f = n/P \) (\( n = 1, 2, \ldots \)) are of primary interest and therefore the harmonic power spectrum values become

\[ |\tilde{X}(n/P)| = \frac{\sqrt{2\pi}}{2} W \exp \left[ -\frac{\pi^2 W^2 n^2}{2P^2} \right] \sum_{k=1}^{N_p} A_k. \quad (2.16) \]

The Cornell pulsar search pipeline performs a harmonic sum for \( N_h = 1 \) to 16 harmonics by stepping through frequency bins in the power spectrum, assuming the current bin is the highest harmonic of a total of \( N_h \) present, and recording the resulting harmonic sum value. The harmonic frequency \( f_h \) of a pulsar signal will likely not lie at the center of a frequency bin, \( f_k \), leading to a “scalloping” effect: bleeding of power into adjacent bins. This is taken into consideration by
each harmonic being expressed as a weighted sum of the power in bins $k - 1$ through $k + 1$. After adding $N_h$ harmonics, the harmonic sum is

$$H(N_h) = \frac{\sqrt{2\pi} W}{2} \sum_{n=1}^{N_h} \exp \left[ -\frac{\pi^2 W^2 n^2}{2p^2} \right] \sum_{k=1}^{N_p} A_k.$$  

(2.17)

For actual data, the time series are noise-like since pulsar signals are typically weak. We can calculate the rms noise in the power spectrum as

$$\sigma_{|\tilde{X}|}^2 = \left\langle |\tilde{X}(f)|^2 \right\rangle = \int_0^{T_{\text{obs}}} \int_0^{T_{\text{obs}}} \langle x(t) x(t') \rangle \exp \left[ -i2\pi f (t - t') \right] dt dt',$$

(2.18)

where we make use of the property of the Fourier transform relating a convolution in the time domain to a product in the Fourier domain. Since the noise decorrelates on a time scale $W_n \sim \Delta t$, $\langle x(t) x(t') \rangle = \sigma_n^2 W_n \delta(t - t')$, where $\sigma_n$ is the rms noise in the time domain. Finally, for the rms noise in the Fourier domain we have

$$\sigma_{|\tilde{X}|} \approx \sigma_n \sqrt{W_n T_{\text{obs}}}. \quad (2.19)$$

We need to compare the signal-to-noise ratios of harmonic sums obtained by adding a varying number of harmonics and therefore $H(N_h)$ must be weighted appropriately by taking into account Gaussian noise. If summing $N_h$ harmonics of approximately equal magnitude, the sum grows linearly as $N_h$, while the noise grows as $\sqrt{N_h}$. We select periodic candidates by imposing a detection threshold $m \sigma_{|\tilde{X}|}$ on the harmonic sum signal-to-noise ratio

$$(S/N)_H = \frac{H(N_h)}{\sqrt{N_h} \sigma_{|\tilde{X}|}}.$$  

(2.20)

Theoretically the value $m$ is chosen so that for the number of trials the expected number of false positives is $< 1$. Signal-to-noise ratios in the Fourier domain are obtained by subtracting a mean Fourier amplitude $\langle |\tilde{X}| \rangle$ and dividing by the rms noise in the Fourier domain $\sigma_{|\tilde{X}|}$. The probability that the S/N of a Fourier
component will exceed the threshold \( m \) by random chance is given by

\[
P(S/N > m) = \exp \left[ - \left( \sigma_{|\tilde{X}|} m + \langle |\tilde{X}| \rangle \right)^2 \right]
\]  

(2.21)

For a time series of \( N \) samples, there are \( N/2 \) Fourier frequency bins in the spectrum and so \( N_{\text{trials}} = N/2 \). We want \( N_{\text{trials}} P(S/N > m) < 1 \). Lorimer & Kramer (2005) show that

\[
m = \frac{\sqrt{\ln(N/2)} - \sqrt{\pi/4}}{1 - \pi/4}.
\]  

(2.22)

For the PALFA survey \( (T_{\text{obs}} = 134 - 268 \text{ s}, \Delta t = 64 \text{ } \mu\text{s}) \) and the GC surveys \( (T_{\text{obs}} = 1 - 6.5 \text{ h}, \Delta t = 82 \text{ } \mu\text{s}) \), \( m = 14 - 16 \). In reality, RFI contributes significantly to the amount of noise and changes its statistics since RFI is non-Gaussian. We use \( m = 7 \) in order to be able to detect pulsars whose \( (S/N)_H \) is rendered lower by the presence of RFI. Two or more candidates which are harmonically related may exceed this threshold, and harmonically related candidates above the detection threshold may appear for multiple trial DMs. The last stage of candidate selection checks for these relations and only keeps the candidate with the largest \( (S/N)_H \) out of a set of harmonically related signals.

If we have detected a pulsar, we estimate its flux density by relating \( (S/N)_H \) to physical quantities. If \( (S/N)_{\text{FFT},1} = |\tilde{X}(n/P)|/\sigma_{|\tilde{X}|} \) is the signal-to-noise of one harmonic in the power spectrum, \( (S/N)_H \sim \sqrt{N_h} (S/N)_{\text{FFT},1} \). Considering that typically \( W \ll P \) and the exponential term in Equation 2.16 is of order unity, from Equations 2.16 and 2.19 we obtain

\[
(S/N)_{\text{FFT},1} \sim \frac{\sqrt{2\pi}}{2} \frac{W}{\sigma_n \sqrt{W_n} T_{\text{obs}}} \sum_{k=1}^{N_p} A_k
\]  

(2.23)

\[
\sim \frac{\sqrt{2\pi}}{2} \frac{\langle A \rangle W}{\sigma_n P} \sqrt{\frac{T_{\text{obs}}}{W_n}}.
\]  

(2.24)

The signal-to-noise of the period-averaged flux density in the time domain

\[
(S/N)_t \approx \frac{\langle A \rangle W}{\sigma_n P},
\]  

(2.25)
so that \((S/N)_{\text{FFT,1}} \sim (S/N)_t \sqrt{N}\) and \((S/N)_H \sim (S/N)_t \sqrt{N N_h}\).

### 2.2.4 Binary Pulsar Search

The DFT-based periodicity search outlined above relies on the intervals between successive pulses being close to equal as seen by the observer. All pulsars spin down gradually as rotational energy is transferred to the emission mechanism and lost via electromagnetic radiation and particle emission. The spin-down rate is typically small enough compared to the rotational period that even for observations lasting several hours it would not significantly affect the value of the harmonic sum \(H(N_h)\) and the chance of discovery. Binary pulsars need special treatment by periodicity searches because of their orbital motion and acceleration. As the pulsar is moving with respect to the observer, the observed interval between pulses changes: it is Doppler-stretched or compressed. A conventional periodicity search will have decreased sensitivity to such pulses because power will be spread over a number of neighboring frequency bins. This problem can be dealt with either in the time domain or in the Fourier domain.

The Cornell pipeline uses a time series resampling method to correct for acceleration due to the orbital motion of binary pulsars. The acceleration \(\ddot{z}(t)\) is the second time derivative of the line-of-sight (l.o.s.) distance to the pulsar, \(z(t)\). The l.o.s. distance is

\[
z(t) = a_1 \sin i \sin \left( \frac{2\pi t}{P_{\text{orb}}} + \phi_0 \right)
\]  

(2.26)

where \(a_1\) is the orbit semi-major axis, \(i\) is the inclination of the orbital plane with respect to the l.o.s., and \(\phi_0\) is a reference orbital phase. The change in the
observed rotation frequency of the pulsar is

$$\dot{\nu} = \frac{d\nu}{dt} = \frac{\Delta \nu}{\Delta t_{\text{samp}}} = \frac{n \Delta f}{T},$$  \hspace{1cm} (2.27)

where $\Delta f$ is the size of a Fourier frequency bin, $n$ is the number of bins the pulse frequency shifts between the start and end of the observation, and $T_{\text{obs}}$ is the length of the observation. Because $\Delta f = 1/T_{\text{obs}}$, $\dot{\nu} = n/T_{\text{obs}}^2$.

Applying the Doppler formula to the observed pulse frequency,

$$\nu(t) = \nu_0 \left(1 - \frac{\ddot{z}(t)}{c}\right) \rightarrow \dot{\nu} = -\frac{\nu_0 \ddot{z}(t)}{c},$$  \hspace{1cm} (2.28)

where $\nu_0 = 1/P$ is the actual rotational frequency of the pulsar. For $T_{\text{obs}} \ll P_{\text{orb}}$ we can approximate the acceleration by a constant for the duration of the observation using $\dot{\nu} = n/T_{\text{obs}}^2$:

$$\ddot{z} = \frac{n \nu_0 c}{T_{\text{obs}}^2}.$$  \hspace{1cm} (2.29)

Let $t$ be the time index of a sample in the original time series, and $t'$ the time index of the same sample in the stretched time series. Then

$$t' = t + \frac{\ddot{z} t^2}{2c} = t + \frac{n \nu_0 t^2}{2 T_{\text{obs}}^2},$$  \hspace{1cm} (2.30)

and the unknown parameter is $nP$. The search includes a loop over trial values of this parameter chosen depending on the desired sensitivity towards different rotational and orbital periods, and companion masses.

The transformed time series is unevenly sampled and not immediately suitable for a DFT-based periodicity search. The next step is to resample the transformed time series at the original $\Delta t_{\text{samp}}$ by interpolation over a range of adjacent samples.

Resampling each dedispersed time series for a number of trial accelerations gets very time-consuming for long observations. Not only do we have to resample each long time series multiple times, but we have to perform a DFT on each
resampled time series, for a total of $N_{DM} \times N_{\text{accel}}$ DFTs. An alternative method models the frequency response in the Fourier domain to a non-uniform pulse period (Ransom et al., 2002). The Presto pulsar search code constructs a series of templates corresponding to the desired trial accelerations and applies them to the Fourier spectrum of each dedispersed time series, attempting to restore to a single frequency bin power spread over multiple bins due to orbital motion. Since acceleration searches assume constant acceleration during the observation, they are most sensitive when the orbital period $P_{\text{orb}} \gtrsim 10 \times T_{\text{obs}}$ and this assumption closely approximates the observed Doppler shift in the pulsar rotation period. On the other hand, if $P_{\text{orb}} \lesssim 0.5 \times T_{\text{obs}}$, the pulsar’s observed rotation frequency will be modulated by the orbital period so that sidebands are present around harmonics in the power spectrum. A modified version of the harmonic sum is then used to recover the pulsar signal (Ransom et al., 2003).

In the case of the PALFA survey, the Einstein@Home\(^5\) distributed computing project bridges the gap for $0.5 \times T_{\text{obs}} < P_{\text{orb}} < 10 \times T_{\text{obs}}$ (2.5min $< P_{\text{orb}} < 50$min). Dedispersed time series are sent to user machines around the world and data analysis is typically performed when a machine is otherwise idle. A series of templates are applied to the time series, correcting for orbital motion based on two parameters: the orbital period and the projected semimajor axis of the orbit. Since this search targets orbital periods of less than an hour and tight binaries are most likely already circularized under the influence of tidal friction, Einstein@Home assumes a circular orbit. This approach has the advantage of completely correcting for orbital motion and ideally a parameter space consisting of all six orbital parameters would be sampled. However, it is computationally intensive. At present, it is only feasible to search a subset of the parameter space

\(^5\)http://einstein.phys.uwm.edu/
by restricting it to circular orbits and the range of orbital periods where other search algorithms significantly lose sensitivity, and by using as a parameter the projected orbital radius, which is degenerate in terms of allowed values for the actual orbit size and inclination.

### 2.2.5 Single Pulse Search

After the steps of RFI excision in the dynamic spectrum and dedispersion, a single pulse search operates on dedispersed time series in order to detect radio transients, intermittent sources, or periodic sources affected by observational biases that make them appear to be intermittent. Since periodicity searches do not distinguish the properties of individual pulses, a single pulse search may also reveal pulsars that occasionally emit giant pulses, which are tens to thousands of times brighter than the average pulse. The Cornell search pipeline employs two single pulse search algorithms: matched filtering and cluster accumulation (friends-of-friends).

The matched filtering approach relies on the convolution of a pulse template with the dedispersed time series. Ideally, a pulse template would consist of one or several superimposed Gaussian templates, reflecting the diversity of pulsar pulse profiles, some of which exhibit multiple peaks. In addition, if searching regions subject to heavy scattering, the pulse template would include an exponential tail, reflecting the effect of multipath propagation due to scattering on the pulse shape. However, convolving multiple templates with multiple (and long) dedispersed time series is very computationally intensive. We approximate true matched filtering by smoothing the time series by adding up to $2^n$
neighboring samples, where \( n = 0 - 7 \), and selecting events above a threshold after each smoothing iteration. The smoothing is done in pairs of samples at each \( n \)-stage, so that the resulting template is a boxcar of length \( 2^n \) samples (Cordes & McLaughlin 2003).

The sampling time used in PALFA observations is 64 \( \mu s \) and therefore the matched filtering search is most sensitive to pulse widths of 64 \( \mu s \) to 8.2 ms. For GC surveys with the SPIGOT, using a sampling time of 82 \( \mu s \), the search is most sensitive to pulse widths of 82 \( \mu s \) to 10.5 ms. This search strategy is not optimal for single pulses from heavily scattered pulsars because the boxcar templates are symmetric, while the scattered pulse shape with an exponential tail is not, and significantly scattered pulses can be wider than \( \sim 10 \) ms. The pulse templates described above have discrete widths of \( 2^n \) samples by algorithm design and there is decreased sensitivity to pulses with widths that are significantly different. In addition, the matched filter search output may be dominated by bright, wide RFI pulses. In that case, a single RFI burst is detected as multiple individual events instead of a single event.

The cluster accumulation algorithm complements matched filtering by not restricting the width of expected pulse detections. The dedispersed time series is processed sequentially. Each event above a threshold which is found is designated as the first of a cluster. A cluster of events is augmented by broadening it to include any adjacent samples above a threshold. Gaps of \( n_{\text{gap}} \) samples are allowed within a cluster, and we typically process data with \( n_{\text{gap}} = 2 \). The brightest sample of a cluster is recorded as the event amplitude, and the total number of samples in the cluster as its width. This approach is less sensitive to weak, narrow pulses but results in significantly fewer spurious events.
Figure 2.8: Single pulse search output after using the matched filtering approach on a beam with blind detections of PSR J1908+0500 and PSR J1908+0457. The four panels on top show (left to right) statistics for the entire observation: number of events vs. S/N and trial DM channel, and DM channel vs. S/N and the actual trial DM value. The bottom panel shows events with $S/N > 5$ vs. DM channel and time, with larger circles denoting brighter events. The strong spike in N vs. DM channel and CM channel vs. S/N corresponds to pulses from PSR J1908+0500 (DM = 201 pc cm$^{-3}$). A weaker spike corresponds to events from PSR J1908+0457 (DM = 360 pc cm$^{-3}$).
Figure 2.9: Single pulse search output after using the cluster accumulation approach on a beam with blind detections of PSR J1908+0500 and PSR J1908+0457. The four panels on top show (left to right) statistics for the entire observation: number of events vs. S/N and trial DM channel, and DM channel vs. S/N and the actual trial DM value. The bottom panel shows events with $S/N > 5$ vs. DM channel and time, with larger circles denoting brighter events. The weak spike in N vs. DM channel and CM channel vs. S/N corresponds to pulses from PSR J1908+0500 ($DM = 201$ pc cm$^{-3}$). Pulses from the weaker PSR J1908+0457 are not detected.
Figure 2.8 shows single pulse search output after using the matched filtering method on a beam containing blind detections of PSR J1908+0500 and PSR J1908+0457, and Figure 2.9 shows equivalent output for the cluster accumulation method. Both pulsars are \( \sim 6\,\prime \) from the beam center. The matched filtering approach picks out some pulses from both pulsars, while the cluster accumulation approach picks out pulses from the brighter PSR J1908+0500 only, and with lower S/N than the matched filtering approach. The cluster accumulated approach results in a lower number of spurious events and legitimate pulse events since a pulse is recorded as a single event regardless of its width. In contrast, the matched filtering approach will record a pulse as multiple events if its width significantly deviates from \( 2^n \) samples.

### 2.3 Data Handling

How data from astronomical surveys is handled is determined by the intent of the survey beyond a one-time processing of data to obtain and publish immediate results. The ingenuity of algorithm design sometimes precedes advances in computer technology so that a novel data processing algorithm may be developed in theory before it is feasible to implement it or routinely use it in practice. For example, Aulbert (2007) explored the application of the Hough transform to searches for binary millisecond pulsars. While promising, this method is not yet widely used because of the considerably longer processing time required compared to the methods outlined in the previous section. On the other hand, technological progress spurred by other fields may inspire the development of new approaches to astronomical data processing. A case in point is the use of Graphical Processing Units (GPUs) for parallel processing of radio astronomy data.
data (e.g. Harris et al. 2008). GPUs are commodity hardware components originally designed for graphical output rendering and targeting video editing applications, immersive virtual environments, and graphics-intensive computer games.

Reprocessing survey data with improved techniques may yield new discoveries. Since new techniques take time to develop, and computing capability also takes time to catch up to algorithms already developed in theory, it is essential that survey data be archived in the long term. It is also essential that both raw data and data processing products be made easily available to the community. The basic categories of uses for archival data and data products are:

1. Trying out new processing methods, which relies on long-term archival of raw data.

2. Comparison and cross-reference of results between different surveys at multiple wavelengths, mandating easy access to both raw data and data products.

3. Manipulation of existing data products for new scientific results, which can be achieved by web applications operating locally on data products and delivering results to remote users.

2.3.1 Archival

After PALFA survey data are taken at the Arecibo Observatory, they are copied to portable hard disks and shipped via FedEx to the Cornell Center for Advanced Computing (CAC). At the CAC, data are permanently archived in a Tivoli Storage Manager (TSM) robotic tape library. In parallel with shipping
raw data, observation logs are uploaded to CAC and parsed to populate a “File Tracking Database” (FTDb) that lists raw data file names, pointing coordinates, dates of observation, and dates of archiving. While all raw data are processed on a Linux cluster at CAC using the Cornell pulsar search code, PALFA members at other institutions also download raw data to process locally.

The tape archive is controlled by a TSM server, which runs on a dedicated machine and maintains an internal database relating data file names to the tapes containing the data files. For the purposes of processing PALFA data at CAC, local users invoke a TSM client from the Linux data processing cluster and raw data is restored directly to a staging area attached to the cluster. After the data is processed, data products are loaded directly from the cluster to a “Data Products Database” (DPDb) also hosted at CAC.

To begin using the tape archive remotely, PALFA members at other institutions register for a web service account with their name, email address, and chosen password. The information is verified by a systems administrator who grants permission for future access. Users query the FTDb remotely from a browser via the web service. Data files can be selected individually from the query results (if one is interested in a particular pointing) or in bulk for a large range of observing days (for general pipeline processing). After users submit a download request through their browser, a TSM client is invoked by the web service and restores the selected data files from the tape archive to an FTP server at CAC. Depending on the amount of data selected, this can take from minutes to hours. The web service then sends an email to the user with instructions how to download the data from the FTP server to a local machine.

Once PALFA members external to Cornell have processed a batch of raw
data files, they upload data products via FTP to the same server which provided FTP access to raw data files. An automated SQL script periodically loads these data products into the DPDb and deletes them from the FTP-accessible area to free up space for more incoming results. Figure 2.10 shows the interactions and flow of information between users, the FTDb, the FTP server, and the DPDb.

As of 2009, there are 150 TB of raw data archived at CAC. All data has been
processed at CAC and data products uploaded to the DPDb. Other processing
sites include McGill University, West Virginia University, Franklin and Marshall
College, University of Texas at Brownsville, and Swinburne University. The
total data volume processed by PALFA members outside Cornell is \( \sim 50 \) TB.
External processing sites use the Presto pulsar search pipeline, while the Cor-
nell pipeline is used at CAC. Processing the entire survey data volume once
with each pipeline allows for independent verification of data products between
pipelines.

2.3.2 Database Access

Data products stored in the DPDb include: bookkeeping pointing information
such as coordinates, observation time, and source name; DMs, periods, signal-
to-noise, pulse shape profiles and other properties of periodic candidates; lists
of single pulse candidates; single-beam and seven-beam plots of single pulse
candidates; plots of dynamic spectra for each beam. An abbreviated table of the
Australia Telescope National Facility database of known pulsars is also main-
tained within the DPDb for quick reference. Users access the DPDb in order
to look up pointing information, download plots or lists of candidates they are
interested in, and display information about candidates sifted according to user-
defined criteria. Database access is accomplished in several ways. Users from
within CAC can query the database directly through SQL Studio; this method is
typically used only for maintenance purposes by database and systems admin-
istrators. PALFA members who make frequent and high-volume transfers to or
from the DPDb can access it directly through a scripting language of their choice
that provides a MSSQL interface (e.g. Python). This type of access is restricted
to PALFA members based at Cornell or Arecibo by default. Users at external sites can obtain access to the DPDb in this manner from specific local machines, after permission is granted manually by a systems administrator at CAC.

The majority of queries to the DPDb are handled by a web service hosted at CAC and accessible from anywhere to registered users. The web service uses the Simple Object Access Protocol (SOAP) and users interact with it via XML messages. As XML is not easily human-readable and writing an application or script to remotely invoke web service functions and parse the returned results can be time-consuming, we provide several PHP scripts that access the DPDb though the web service. The scripts are hosted on a web server at the Cornell Department of Astronomy and can be used from anywhere through a browser. The source code is available on request to users who wish to host them locally or make modifications.

*Tablesearch* is a PHP script that provides basic database browsing functionality: one can select from a list of tables from the DPDb and a list of fields to be displayed, and enter selection criteria (e.g. to display information on all observations taken on a certain day, or all candidates from a certain observation). Fig. 2.11 shows a browser session in which *Tablesearch* was used to bring up single pulse plots of all observations in the database of PSR J0628+09, an intermittent pulsar discovered by PALFA. Users familiar with the SQL language can submit a more complex query through a special field.

There are currently more than two million periodic pulsar candidates in the DPDb. Reliably inspecting and ranking candidates is an important task and major effort for a large survey. Although some algorithms have been developed to accomplish that in an automated manner (Keith et al., 2009), human inspect-
The Tablesearch PHP script lets users query the DPDb from a browser. The CandFlagger script lets users view comprehensive information on individual candidates and the entire pointing on a single page, and add their ranks which are recorded in the DPDb. Fig. 2.12 shows already ranked periodic candidates displayed in a browser. Pressing the “Page” button to the right of any row opens an individual candidate page with plots characterizing the candidate and the observation. Fig. 2.13 shows the individual candidate page page for PALFA discovery J0540+3207. It includes the candidate parameters (period, DM, S/N, number of harmonics), nearby known pulsars, past ranks of the candidate, and plots of the candidate S/N vs. DM and pulse profile. Plots characterizing the entire observation are also displayed: single-beam and seven-beam single pulse plots to immediately check if a candidate pulsar has bright single pulses, and dynamic spectrum plots for assessing data quality and RFI incidence during the
observation. For each inspected candidate, users can add their own ranks and comments which are permanently recorded in the DPDb and can be used in future queries, for example to select for reobservation the candidates with the highest average rank.

2.3.3 Web Service Applications

For a confirmed pulsar or good pulsar candidate, we want to know if there are any nearby structures that may affect its observable properties or give a clue to its origin. For example, an HII region along the line of sight to a pulsar may account for its high DM. The properties of a supernova remnant surrounding a new pulsar discovery may constrain the pulsar age. A bow-shock, jet, or wind
nebula makes a new pulsar a prime target for X-ray follow-up observations in order to investigate interactions between the pulsar magnetosphere and interstellar gas. In many cases, previous surveys at other wavelengths already have archival data for the PALFA survey area. We use these archival data to quickly check for extended structures near pulsars discovered by PALFA. The National Virtual Observatory (NVO) provides public web services that let users access archival data from many surveys at various wavelengths. We provide two PHP scripts hosted at the Cornell Department of Astronomy that perform a cross-match between PALFA pointings and archival images available through the NVO. Fig. 2.14 shows the interaction between remote users, the PALFA DPDb, and NVO web services.

The PHP script *Singlesearch* looks up known pulsars, PALFA pointings, and NVO images within a virtual field of view around coordinates specified by the
Figure 2.14: Remote query of the PALFA results database. If requested, a simultaneous query of National Virtual Observatory databases provides a cross-match between PALFA pointings and coverage of the same sky area by other surveys at multiple wavelengths.

user and displays all the information on a single page (Fig. 2.15). Currently two separate external web services compliant with the NVO subset of the SOAP protocol are used: Skyview (a portal-type web service providing access to images from more than 20 surveys at frequencies from radio to X-rays) and Chandra (service for data from the Chandra X-ray Observatory only). The “Page” button in each row corresponding to an NVO-enabled survey opens a page
with plots of known pulsar positions, PALFA pointings, and image data from the respective survey displayed side by side. Fig. 2.16 shows such a page for PSR J1841−04, which is associated with the Kes73 supernova remnant. On the right is an image of Kes73 from the NRAO VLA Sky Survey (NVSS).

The PHP script Batchsearch\(^6\) has an interface and functionality similar to Singlesearch but is meant to check for archival survey data around multiple coordinate pairs. The main difference between the two scripts is that in Singlesearch, images are not actually downloaded until the user clicks on a “Page” button, and even then only low-resolution JPG images are downloaded for displaying in the user’s browser. Communication with the Skyview hosts for some surveys

\(^6\)Singlesearch and Batchsearch were developed during the 2005 NVO Summer School and won second prize in the summer school software development competition.
Figure 2.16: Individual page showing known pulsar positions (left) and an NVSS image (right) near PSR J1841–04. A supernova remnant, Kes73, is visible in the NVSS image. The link menus at the top and bottom allow for easy paging through images from all surveys that have data near the specified coordinates.

can be slow and in most cases of quick follow-up on one source, the user will want to check data from only a handful of surveys. On the other hand, *Batch-search* is meant to run for a longer time for a list of coordinates and download images found for all specified positions. Additional options within *Batchsearch* include downloading high-resolution FITS images for data processing offline and compressing all downloaded images into a single tarball for easy subsequent download from the web server hosting the script to the user’s local machine.
CHAPTER 3
INTERMITTENT PULSARS

We present radio transient search algorithms, results, and statistics from the ongoing Arecibo Pulsar ALFA (PALFA) survey of the Galactic plane. We have discovered seven objects through a search for isolated dispersed pulses. All of these objects are Galactic and have measured periods between 0.4 and 4.7 s. One of the new discoveries has a duty cycle of 0.01%, smaller than that of any other radio pulsar. We discuss the impact of selection effects on the detectability and classification of intermittent sources, and compare the efficiencies of periodicity and single-pulse searches for various pulsar classes. For some cases we find that the apparent intermittency is likely to be caused by off-axis detection or a short time window that selects only a few bright pulses and favors detection with our single-pulse algorithm. In other cases, the intermittency appears to be intrinsic to the source. No transients were found with dispersion measures large enough to require that they originate from sources outside our Galaxy. Accounting for the on-axis gain of the ALFA system, as well as the low gain but large solid-angle coverage of far-out sidelobes, we use the results of the survey so far to place limits on the amplitudes and event rates of transients of arbitrary origin.¹

3.1 Introduction

Radio pulsars show a wide variety of modulations of their pulse amplitudes, including bursts and nulls, that affect their detectability in surveys. Phenomena seen in some pulsars include short-period nulling, in which a pulsar is not detected for several pulse periods, only to reappear with full strength (Backer

¹This chapter was published in the Astrophysical Journal as Deneva et al. (2009)
1970); eclipses, in which a companion star or its wind or magnetosphere absorbs or disperses the pulsar signal (Fruchter et al. 1988, Stappers et al. 1996, Lyne et al. 1993, Kaspi et al. 2004); long-term nulling or intermittent behavior, in which a pulsar is quiescent for days or weeks (Kramer et al. 2006); and rotating radio transients (RRATs, McLaughlin et al. 2006), pulsar-like objects from which only occasional radio bursts are detected. This paper describes analysis of a large-scale survey using the Arecibo telescope that is sensitive to both periodic and aperiodic signals.

RRATs were first discovered in archive Parkes Multibeam survey data (McLaughlin et al. 2006). Eleven objects, with periods ranging from 0.7 to 7 s and pulse widths of 2 – 30 ms, were found using a single pulse search algorithm (McLaughlin, M. A. 2007). The longer periods of RRATs compared with the general pulsar population suggest similarities with the X-ray populations of X-ray dim isolated neutron stars (XDINSs) and magnetars. RRAT J1819–1458 has been detected at X-ray energies (McLaughlin et al. 2007) with properties that are similar to those of XDINSs and high magnetic field radio pulsars.

A different type of pulse modulation is observed in the case of pulsars emitting giant pulses. Such pulses are tens to thousands of times brighter and an order of magnitude or more narrower than the average pulse (see Knight 2006 for an overview). Giant pulses from the Crab pulsar have substructure on timescales of 2 ns (Hankins et al. 2003), and PSR B1937+21 emits giant pulses as narrow as 16 ns (Popov et al. 2004). Giant micro-pulses from the Vela pulsar have widths ~ 50µs (Johnston et al. 2001), and the slowly rotating pulsars PSR B1112+50, PSR B0031–07, and PSR J1752+2359 occasionally emit bright pulses which are 1 – 10 ms wide, 5 – 30 times narrower than the average pulse.
(Knight 2006). The detection of giant pulses is a potentially powerful method for finding extragalactic pulsars too distant for their normal emission to be detectable by periodicity searches (McLaughlin & Cordes 2003).

A variety of energetic phenomena other than pulsar emission can give rise to fast transients potentially detectable in radio pulsar surveys. Within the Solar System, transient radio events may be generated by energetic particles impacting the Earth’s atmosphere, solar flares, and decameter radio flares originating in Jupiter’s atmosphere. Analogously to the latter, extrasolar planets with strong magnetic fields are expected to be detectable in the 10-1000 MHz range (Farrell et al. 1999, Lazio et al. 2004, Zarka et al. 2001). Magnetic activity on the surfaces of brown dwarfs and particle acceleration in the magnetic fields of flare stars are also known radio flare progenitors (Berger et al. 2001, Berger 2002, García-Sánchez et al. 2003, Jackson et al. 1989). Gamma-ray bursts are predicted to have detectable radio emission at $\sim 100$ MHz (Usov & Katz 2000, Sagiv & Waxman 2002), and radio flares have been observed from some X-ray binaries (Waltman et al. 1995, Fender et al. 1997). Among the most energetic and exotic events in the Universe, supernovae, merging neutron stars and coalescing black holes may produce wide-band radio bursts detectable at extragalactic distances (Hansen & Lyutikov 2001).

In this paper we describe an ongoing survey for pulsars and transient radio sources with the Arecibo telescope. The survey addresses outstanding questions about the nature and emission mechanisms of intermittent radio sources. In § 3.2 we present the PALFA survey parameters, and in § 3.3 we describe the single pulse search and radio frequency interference excision algorithms which are part of the survey data processing pipeline. Section 3.4 contrasts PALFA
detection statistics on known pulsars and new discoveries, and § 3.5 examines selection effects influencing the detection and classification of transient sources. In § 3.6, we apply an intermittency measure method for comparing the efficiency of periodicity and single pulse pulsar searches. In § 3.7, we discuss the properties of individual intermittent objects discovered by PALFA. In § 3.8 and § 3.9, we apply constraints derived from the survey sensitivity and results to the detectability of various energetic phenomena expected to emit radio bursts. Finally, in § 3.10, we present our main conclusions.

3.2 PALFA Survey Observations

3.2.1 Survey Parameters

The PALFA survey started in 2004, shortly after the installation of the seven-beam ALFA receiver on the Arecibo telescope. The survey searches for pulsars and transients in the inner and outer Galactic plane regions accessible to Arecibo (see below).

The ALFA receiver is well-suited for survey observations, allowing simultaneous data collection from seven fields, each $\sim 3.5'$ (FWHM) across. Taking into account the hexagonal arrangement of the beams on the sky and the near sidelobes, the combined power-pattern is approximately $24' \times 26'$ (Cordes et al. 2006). We observe a 100 MHz passband centered on 1440 MHz in each of the seven telescope beams. Wideband Arecibo Pulsar Processors (WAPPs; Dowd et al. 2000) are used to synthesize 256-channel filterbanks spanning these bands at intervals of 64 $\mu$s. During observations, full-resolution data are recorded to disk
and, in parallel, decimated down to a time resolution of 1 ms and searched for periodic signals and single pulses by a quick-look processing pipeline running in real time at the Arecibo Observatory (Cordes et al. 2006). This approach allows for immediate discovery of relatively bright pulsars with periods longer than a few milliseconds. Searching full-resolution data allows detection of millisecond pulsars and narrower single pulses and is done offline at participating PALFA institutions as the processing is much more computationally intensive.

Table 3.1 lists various ALFA system and survey parameters, including the sky area corresponding to processed and inspected data reported on in the present paper and the total sky area observed to date (see Cordes et al. 2006 for a detailed explanation of other parameters). Standard observation times are 268 s for inner Galaxy pointings ($30^\circ \lesssim l \lesssim 78^\circ, |b| \leq 5^\circ$) and 134 s for outer Galaxy pointings ($162^\circ \lesssim l \lesssim 214^\circ, |b| \leq 5^\circ$). Some early observations had a duration of 134 s and 67 s for inner and outer Galaxy pointings, respectively. The quoted system temperature of 30 K is measured looking out of the Galactic plane. The initial threshold of $5\sigma$ for the single pulse search is used when selecting events from dedispersed time series based on their signal-to-noise ratios only, before any filtering is applied. While there are a significant number of events due to random noise above this threshold, identification of an event as a genuine pulse takes into account not only its signal-to-noise ratio but also the fact that it is detected at a contiguous range of trial dispersion measures, which is in general not true of spurious events. Thus weak pulses can be correctly identified, while they would be excluded if the threshold was set according to Gaussian noise statistics.
Table 3.1: PALFA survey parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center frequency (GHz)</td>
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<tr>
<td>Total bandwidth (MHz)</td>
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<td>Channel Bandwidth (MHz)</td>
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<td>Sampling time (µs)</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>Ring pixels</td>
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<tr>
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</tr>
<tr>
<td>Main beam plus near sidelobes (1 pixel)</td>
<td>18</td>
</tr>
<tr>
<td>Main beam plus near sidelobes (7 pixels)</td>
<td>24 ¥ 26</td>
</tr>
<tr>
<td>Inner Galaxy</td>
<td></td>
</tr>
<tr>
<td>Observation time per pointing (s)</td>
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</tr>
<tr>
<td>Observed (deg²)</td>
<td>156</td>
</tr>
<tr>
<td>Processed a (deg²)</td>
<td>99</td>
</tr>
<tr>
<td>Anticenter</td>
<td></td>
</tr>
<tr>
<td>Observation time per pointing (s)</td>
<td>134, 67</td>
</tr>
<tr>
<td>Observed (deg²)</td>
<td>119</td>
</tr>
<tr>
<td>Processed a (deg²)</td>
<td>87</td>
</tr>
<tr>
<td>Detection threshold (σ)</td>
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</tr>
<tr>
<td>Single pulse search (initial threshold)</td>
<td>5</td>
</tr>
<tr>
<td>Fourier Transform periodicity search</td>
<td>7.5</td>
</tr>
</tbody>
</table>

a Full-resolution data processed with the Cornell pulsar search code.

3.2.2 Survey Sensitivity

Here we compute the maximum distance at which sources of a given luminosity are be detectable by the PALFA survey, $D_{\text{max}}$. We then compare the sensitivity of the PALFA survey to previous work done with the Parkes Multibeam system (Manchester et al. 2001, McLaughlin et al. 2006).

The rms noise in a radio transient search, where the effective observation
time is equal to the pulse width, is

\[ \sigma_n = \frac{S_{sys}}{\sqrt{N_{pol} \Delta f W}}, \]  

(3.1)

where \( S_{sys} \) is the system-equivalent flux density, \( N_{pol} = 2 \) is the number of polarization channels summed and \( \Delta f \) is the bandwidth. A pulse’s observed width \( W \) may be broadened compared to its intrinsic width \( W_i \) by several effects. After dedispersing the raw data and obtaining a dedispersed time series, there is residual dispersive broadening due to the finite width of a frequency channel and the error of the trial dispersion measure (DM) used compared to the actual pulsar DM. Scatter broadening is not correctable and will have a contribution that depends on observing frequency and varies with direction on the sky. In general,

\[ W \approx \left( W_i^2 + \Delta t_{DM,ch}^2 + \Delta t_{DM,\text{err}}^2 + \Delta t_{sc}^2 \right)^{1/2}, \]  

(3.2)

where \( \Delta t_{DM,ch} = 8.3 \mu s DM \Delta f_{ch}/f^3 \) is the dispersive broadening across a frequency channel of width \( \Delta f_{ch} \) (MHz) for an observing frequency \( f \) (GHz), \( \Delta t_{DM,\text{err}} \) is the dispersive broadening due to the difference between the trial and actual DM of the source, and \( \Delta t_{sc} \propto f^{-4} \) is the scattering broadening. Broadening conserves pulse area, so that the intrinsic and observed peak flux densities are related through \( S_{p,i} W_i = S_p W \). If \( S_{p,\text{min}} = m\sigma_n \) is the detection threshold, the minimum detectable intrinsic peak flux density is

\[ S_{p,i,\text{min}} = \left( \frac{W}{W_i} \right) \frac{mS_{sys}}{\sqrt{N_{pol} \Delta f W}}. \]  

(3.3)

For a one steradian pulsar radio beam, a source of intrinsic peak luminosity \( L_{p,i} \) can be detected out to a maximum distance of

\[ D_{\text{max}} = \left( \frac{L_{p,i}}{S_{p,i,\text{min}}} \right)^{1/2} = L_{p,i}^{1/2} \left( \frac{W_i}{W} \right)^{1/2} \left( \frac{N_{pol} \Delta f W}{mS_{sys}} \right)^{1/4}. \]  

(3.4)
For a steadily emitting pulsar with period-averaged luminosity $L$ and duty cycle $f_{dc}$, we have $L_p \approx L/f_{dc}$.

The amount of pulse broadening depends on system parameters as well as dispersion and scattering, which vary with direction on the sky so that $W = W(W_i, l, b, f, \Delta f, N_{ch}, S_{sys}, \Delta t)$. We use the NE2001 model of Galactic ionized electron density (Cordes & Lazio 2003) to calculate representative results for $D_{\text{max}}$ in the direction $l = 35^\circ, b = 0^\circ$, a region of overlap between PALFA and the Parkes Multibeam survey. Fig. 3.1 shows $D_{\text{max}}$ vs. $L_{p,i}$ detection curves using a threshold $m = 6$ for both surveys. For lower luminosities, sources are not visible to large enough distances for scattering to affect detectability and the inverse square law dominates the detection curve so that $D_{\text{max}} \propto L_{p,i}^{-1/2}$. For larger distances and smaller intrinsic pulse widths, scattering and (residual) dispersion smearing make pulses increasingly harder to detect and $D_{\text{max}}$ increases more slowly with $L_{p,i}$.

### 3.3 Single Pulse Search Methods

This section describes processing methods employed by the Cornell pulsar search pipeline\(^2\) at the Cornell Center for Advanced Computing and the Swinburne University of Technology. The PRESTO search code \(^3\) is run independently at West Virginia University, University of British Columbia, McGill University and the University of Texas at Brownsville. PRESTO uses a similar matched filtering algorithm to the one described below, but a different RFI excision scheme and trial DM list.

---

\(^2\)http://arecibo.tc.cornell.edu/PALFA/

\(^3\)http://www.cv.nrao.edu/~sransom/presto
Figure 3.1: Maximum distance at which transients with various peak luminosities and intrinsic pulse widths of (top to bottom for each set of curves) 50, 5, and 0.5 ms can be detected by the PALFA and Parkes Multibeam surveys. The linear portion of the curves corresponds to a luminosity-limited regime. In that regime, $D_{\text{max}}$ is about twice as large for PALFA than for the Parkes Multibeam survey because of the larger sensitivity of the Arecibo telescope. Breaks in the curves correspond to a transition from luminosity-limited to scattering-limited detection for PALFA and to a dispersion-limited regime for Parkes. The difference is due to the smaller channel width of PALFA (0.4 MHz) compared to Parkes (3 MHz).

We dedisperse raw data with 1272 trial DMs in the range $0 - 1000$ pc cm$^{-3}$. In order to find individual pulses from intermittent sources we operate on dedis-
persed time series with two time domain algorithms: matched filtering, which has been the standard in single pulse searching so far, and a friends-of-friends algorithm. After single pulse candidates have been identified we use a stacking method in the time-frequency plane to verify that the pulses are dispersed and the sweep observed across frequencies follows the dispersion relation, as expected for non-terrestrial sources. Certain types of terrestrial signals, e.g. swept-frequency radars, have pulses whose appearance in the time-frequency plane may approximate dispersion by ionized gas, but on closer inspection such pulses generally deviate significantly from the cold plasma dispersion relation.

### 3.3.1 Matched Filtering

Matched filtering detection of broadened pulses relies on the convolution of a pulse template with the dedispersed time series. Ideally, a pulse template would consist of one or several superimposed Gaussian templates, reflecting the diversity of pulsar pulse profiles, some of which exhibit multiple peaks. In addition, multipath propagation due to scattering adds an exponential tail to the pulse profile. We approximate true matched filtering by smoothing the time series by adding up to $2^n$ neighboring samples, where $n = 0 - 7$, and selecting events above a threshold after each smoothing iteration. The smoothing is done in pairs of samples at each $n$-stage, so that the resulting template is a boxcar of length $2^n$ samples (Cordes & McLaughlin 2003). The sampling time used in PALFA observations is 64 $\mu$s and therefore our matched filtering search is most sensitive to pulse widths of 64 $\mu$s to 8.2 ms. This search strategy is not optimal for single pulses from heavily scattered pulsars because the templates are symmetric, while the scattered pulse shape with an exponential tail is not,
and significantly scattered pulses can be wider than $\sim 10$ ms.

### 3.3.2 Finding Time-Domain Clusters

Two issues make a complement to matched filtering necessary. The pulse templates described above have discrete widths of $2^n$ samples by algorithm design and there is decreased sensitivity to pulses with widths that are significantly different. In addition, the matched filter search output may be dominated by bright, wide pulses from radio frequency interference (RFI). In that case, a single RFI burst is detected as an overwhelming number of individual events instead of a single event. The cluster algorithm is similar to the friends-of-friends search algorithm used to find galaxies in optical images (Huchra & Geller 1982), and complements matched filtering by not restricting the width of expected pulse detections. The dedispersed time series is processed sequentially. Each event above a threshold which is found is designated as the first of a cluster. A cluster of events is augmented by broadening it to include any adjacent samples above a threshold. Gaps of $n_{\text{gap}}$ samples are allowed within a cluster, and PALFA data is processed with $n_{\text{gap}} = 2$. The brightest sample of a cluster is recorded as the event amplitude, and the total number of samples in the cluster as its width. This approach is less sensitive to weak, narrow pulses but results in significantly fewer spurious events due to RFI.

A limiting factor for the largest pulse width detectable by both the matched filtering and friends-of-friends search algorithms is the fact that data are analysed in blocks much shorter than the complete time series length. The mean and standard deviation of a block are used for thresholding events found within the
block. This approach minimizes the effect of baseline variations with time scales much longer than typical pulsar pulse widths of a few to a few tens of ms. The disadvantage is that only pulses with $W \ll T_{\text{block}}$ can be detected. In processing PALFA data, we use blocks of length $T_{\text{block}} = 4096 \times 64 \mu s = 0.26$ s. According to the NE2001 model of ionized gas in the Galaxy (Cordes & Lazio 2003), a scattering broadening time of that magnitude in the inner-Galaxy part of the PALFA survey corresponds to $DM > 1000$ pc cm$^{-3}$ and a maximum search distance well outside of the Milky Way for most directions we survey. However, lines of sight intersecting HII regions can result in large dispersion measures and scattering times and are therefore selected against. Any intergalactic scattering that broadens pulses beyond about 0.1 s will also cause events to be selected against.

### 3.3.3 Example Results

Fig. 3.2 shows standard single pulse search output for the discovery observation of PSR J0627+16 (§ 8.1). The main panel shows signal-to-noise ratio (S/N) vs. DM and time for events with S/N > 5. The panels on top illustrate event statistics for the observation: from left to right, number of events vs. S/N and DM, and DM vs. S/N. The pulsar detection is manifested as a peak in the histogram of number of events vs. DM. There is a corresponding peak in the DM vs. S/N plot, since the several detected pulses are significantly brighter than background noise in the dedispersed time series.

Fig. 3.3 and Fig. 3.4 show events in DM-time space for another PALFA single pulse discovery, PSR J1928+15 (§ 8.5). In this case, three closely spaced bursts were found at $t \sim 100$ s, $DM \sim 250$ pc cm$^{-3}$. The pulsar is detected at a range
Figure 3.2: Single pulse search output for PSR J0627+16. The bottom panel shows events with S/N > 5 vs. time and DM with larger circles denoting brighter bursts. Panels on top from left to right show histograms of the number of events vs. S/N and DM, and a scatter plot of event DM vs. S/N. A fit to the narrow peak of event DM vs. S/N indicates a pulse width ~ 2 ms (Cordes & McLaughlin 2003).
of DMs, with the signal to noise ratio increasing as trial DM values approach the actual pulsar DM and decreasing as trial DMs further on recede from the pulsar DM. In contrast, events due to interference from terrestrial signals at $t \sim 46, 71, 82, 90, 118$ s span the entire range of trial DMs and their signal to noise ratios do not show a significant variation with DM.

Figure 3.3: Events with $S/N > 4$ from the discovery PALFA observation of PSR J1928+15 are displayed in the DM-time plane. Events aligned vertically and spanning all trial DM values at $t \sim 46, 71, 82, 90, 118$ s are due to terrestrial interference. Three closely spaced bursts were found at $t \sim 100$ s, DM $\sim 250$ pc cm$^{-3}$. 
Figure 3.4: A magnification of the area around the PSR J1928+15 bursts in the dedispersed time series (top) and the DM-time plane (bottom). The intervals between successive bursts are 0.403 s, establishing the pulsar period. Larger circles denote brighter bursts, and the brightest burst has $S/N \sim 60$ in the dedispersed time series.

If an excess of candidate pulses is identified in the dedispersed time series for a particular trial DM, we use the expected dispersion sweep across the frequency band in order to test if the pulses are from non-terrestrial origin. For a pulse with $S/N \gtrsim 10$ in the time series, we extract a chunk of raw data centered on its time of arrival and look for a sweep across frequency that follows
Figure 3.5: Dispersion sweep in the time-frequency plane of the brightest single pulse detected from (a) PSR J1928+15 and (b) PSR J1946+24; (c) Stacked dynamic spectrum of the five brightest pulses detected from PSR J0627+16; (d) Stacked dynamic spectrum of the two brightest pulses detected from PSR J1909+06. The pulses are dispersed, such that the higher frequencies arrive earlier.

the dispersion relation (Fig. 3.5 a, b).
3.3.4 Time-Frequency Plane Stacking

In the case of multiple weaker pulses detected in the same beam, we extract a raw data chunk centered on the arrival time of each pulse, stack the chunks and look for a dispersion sweep in the resulting cumulative dynamic spectrum (Fig. 3.5 c, d).

Stacking can induce spurious dispersion sweeps in the time-frequency plane even when the data consist of only Gaussian-distributed noise. Single pulse events identified in dedispersed time series by definition correspond to sums over a given dispersion path that are above average. When these are used to select chunks for summing, the statistical fluctuations will build up to show a dispersed pulse in the time-frequency plane that follows the cold-plasma dispersion law perfectly. We simulated this effect by generating a time-frequency plane of Gaussian noise, dedispersing it, and selecting events above threshold from the resulting time series. We extracted chunks from the fake time-frequency plane centered on each event and stacked them, thus reproducing the procedure used on real data.

Selecting events with signal-to-noise above a threshold $m_d$ in the dedispersed time series yields a biased set of noise-only samples in the time-frequency plane. On the other hand, when stacking dynamic spectra, points in the stacked dynamic spectrum must have a minimum signal-to-noise $m_c \sim 2$ for a dispersion sweep to be discernible by eye. The rms noise in the dedispersed time series after summing $N_{ch}$ channels is a factor of $\sqrt{N_{ch}}$ larger than the rms noise in the time-frequency plane. The rms noise in the stacked dynamic spectrum after stacking $N_c$ chunks is a factor of $\sqrt{N_c}$ larger than the rms noise in the time-frequency plane. We calculate the average deviation from the mean in the time-
frequency plane implied by the two thresholds $m_d$ and $m_c$, equate them, and obtain

$$N_c \geq (m_c/m_d)^2 N_{ch}. \quad (3.5)$$

For the PALFA survey and our processing pipeline, $N_{ch} = 256$ and $m_d = 5$. Therefore if $N_c \gtrsim 40$ data chunks are added there will be a spurious, dispersed pulse in the resulting stacked dynamic spectrum even if the chunks contain only noise. Since the noise decorrelates over $1−2$ samples, the pulse will have a width on the order of $64−128 \mu s$. To avoid the induced spurious-event effect, the width and S/N of stacked dynamic spectra should be compared with those that would result from noise only. All of our detections that use stacking satisfy the criteria $W >> 64 \mu s$ and $N_c << 40$. Typically we sum chunks centered on the brightest $2−5$ pulses for a single pulse candidate, which is safely below the $N_c$ limit. In the case of PSR J1909+06 (Fig. 3.5d) only 2 chunks were added and the dispersed swath in the time-frequency plane is 1 ms wide.

### 3.3.5 RFI Excision

The RFI environment at the Arecibo telescope and the 7-beam configuration of the ALFA receiver present both challenges and opportunities for RFI mitigation to facilitate searching for single pulses. PALFA survey data are dedispersed with trial dispersion measures of $0 − 1000 \text{ pc cm}^{-3}$. RFI pulse intensity typically peaks at $DM = 0 \text{ pc cm}^{-3}$, and incidental low-intensity pulses whose S/N peaks at $DM = 0 \text{ pc cm}^{-3}$ tend to be smeared below the detection threshold for dedispersed time series with trial $DM > 50 − 100 \text{ pc cm}^{-3}$. A more complex signature is observed for Federal Aviation Administration (San Juan airport) radar pulses,
which are unfortunately common in Arecibo observations. The radar rotation period is $P_r = 12$ s, and each pulse has an envelope that is $\sim 1$ s wide and consists of sub-pulses with variable period on the order of $2 - 3$ ms. Depending on telescope orientation, radar pulses may be detected in all, some, or none of the ALFA beams due to reflections off the telescope structure. Radar pulses are up to two orders of magnitude brighter than pulsar pulses and, without mitigation, can completely dominate single pulse search results. In addition, the modulation of the radar signal is manifested as detections with $DM \neq 0$ pc cm$^{-3}$ so that unlike other non-radar RFI, their S/N vs. DM signature cannot be used for excision.

We exploit the known radar characteristics as well as the pattern of pulse detection in the 7 ALFA beams to excise both radar and non-radar RFI. The first part of our excision algorithm targets radar pulses. After a list of single pulse events is generated for all trial DMs, we bin the events for trial $DM = 0 - 3$ pc cm$^{-3}$ in time (by 0.1 s) and record the number of events in each time bin. Then we treat the histogram as a time series and perform a discrete Fourier transform. A peak near the radar rotation frequency indicates a significant number of radar pulses in the data. From the Fourier components we extract the phase and find the arrival time of the earliest radar pulse, $t_0$. Since the envelope width is $\sim 1$ s, events within 0.5 s of that location are excised, and the procedure is repeated for events near $t = t_0 + NP_r$, where $N$ is an integer. The more radar pulses are present, the better the performance of this technique because the radar peak in the DFT is more prominent and the pulses’ arrival times are determined more precisely. However, if only a couple of strong radar pulses are present within the typical 268 s PALFA integration time, they may be bright enough to dominate event statistics, yet the DFT method does not excise non-
periodic incidental RFI. Consequently, after applying the DFT-based method we use an additional RFI filter that handles aperiodic cases.

The second filter uses the number and proximity of beams in which an event is detected in order to determine if it is due to RFI. Again events for trial DM $= 0 \pm 3$ pc cm$^{-3}$ from each beam are binned in time. After detecting peaks indicating an excess of events for the respective time bins, the algorithm cross-checks between results for all seven beams, and each event falling within a histogram peak receives a penalty grade based on how many beams’ histograms exhibit a peak and how close to each other they are on the sky. Most pulsars detected blindly via a single pulse search appear in one beam or two adjacent beams, and very bright pulsars may be detected in three or four adjacent beams. We set the excision penalty threshold just below the value corresponding to the latter configurations and excise events accordingly. This method complements the DFT cleaning scheme and effectively excises sparse radar blasts as well as non-periodic RFI detected in multiple beams. The application of the two excision algorithms makes a marked difference in the final single pulse search output for pointings contaminated with RFI (Fig. 3.6, Fig. 3.7). The figure shows some false positives, for example a clump of pulsar pulses in beam 4 around $t = 80$ s are excised due to low-level RFI at low DMs occurring in non-adjacent beams in the same 0.1 s time bins as the pulses. Lowering the threshold according to which an excess of events is defined and time bins are marked for excision reduces false positives but also diminishes the effectiveness of RFI excision. While tens of pulses are detected within 134 s from the bright pulsar B2020+28 (Fig. 3.6, Fig. 3.7), for sources discovered via a single pulse search the number is an order of magnitude smaller (see § 7). Therefore the chance of RFI occurring simultaneously with pulses of intermittent sources and causing them
to be excised is much lower.

Figure 3.6: Single pulse search output for a blind detection of pulsar B2020+28 before excising radar and incidental RFI. Each row shows results from one ALFA beam. From left to right, panels show: events with $S/N > 5$ vs. DM channel and time, number of events vs. DM channel, and event $S/N$ vs DM channel.
Figure 3.7: Single pulse search output for a blind detection of pulsar B2020+28 after excising radar and incidental RFI. Each row shows results from one ALFA beam. From left to right, panels show: events with $S/N > 5$ vs. DM channel and time, number of events vs. DM channel, and event $S/N$ vs DM channel. The pulsar detection in beams 3 and 4 is evident after RFI events are excised.

3.4 PALFA Pulsar Detection Statistics

The PALFA survey has made a total of 354 blind detections of 172 pulsars up to late 2008. Following quick-look processing of the data with degraded time and frequency resolutions at the time that data are acquired (Cordes et al. 2006), data
Table 3.2: Pulsar detection statistics by algorithm.

<table>
<thead>
<tr>
<th>Pulsars</th>
<th>FFT only</th>
<th>SP only</th>
<th>FFT and SP</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Known</td>
<td>48 (38%)</td>
<td>5 (4%)</td>
<td>73 (58%)</td>
<td>126</td>
</tr>
<tr>
<td>New</td>
<td>28 (61%)</td>
<td>6 (13%)</td>
<td>12 (26%)</td>
<td>46</td>
</tr>
</tbody>
</table>

More than half of the detected known pulsars and only a quarter of the newly discovered objects were seen by both the periodicity and single pulse search algorithms. There is also a significant difference in the fraction of pulsars detected only via a single pulse search. In total, 74% of the new pulsars as opposed to 42% of the known pulsars were detected either only by FFT search or only by single pulse search. The much higher percentage of new pulsars to be detected only by one algorithm means that most of the PALFA discoveries are either periodic emitters too weak to show up in single pulse searches or intermittent objects whose emission is too heavily modulated be detected by a periodicity search. Considering that bright pulsars are more likely to be seen by
Table 3.3: Parameters of PALFA single pulse discoveries.

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>$RA^a$</th>
<th>$DEC^a$</th>
<th>$P$</th>
<th>$W$</th>
<th>DM</th>
<th>$D^b$</th>
<th>$S^c_p$</th>
<th>$T_{tot}$</th>
<th>$N_{tot}$</th>
<th>Rate</th>
<th>Comment</th>
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<tbody>
<tr>
<td></td>
<td>(hh:mm:ss)</td>
<td>(deg:mm)</td>
<td>(s)</td>
<td>(ms)</td>
<td>(pc cm$^{-3}$)</td>
<td>(kpc)</td>
<td>(mJy)</td>
<td>(s)</td>
<td>(h$^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J0627+16</td>
<td>06:27:13(7)</td>
<td>16:12(2)</td>
<td>2.180</td>
<td>0.3</td>
<td>113</td>
<td>3.2</td>
<td>150</td>
<td>7454</td>
<td>48</td>
<td>23</td>
<td>§ 3.7.1</td>
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<tr>
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<td>09:09(2)</td>
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<td>10</td>
<td>88</td>
<td>2.5</td>
<td>85</td>
<td>1072</td>
<td>42</td>
<td>141</td>
<td>§ 3.7.2</td>
</tr>
<tr>
<td>J1854+03</td>
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<td>03:04(2)</td>
<td>4.559</td>
<td>50</td>
<td>216</td>
<td>5.5</td>
<td>9</td>
<td>388</td>
<td>9</td>
<td>84</td>
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<td>06:40(2)</td>
<td>0.741</td>
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<td>35</td>
<td>2.2</td>
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<td>393</td>
<td>35</td>
<td>320</td>
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<td>101</td>
<td>268</td>
<td>4</td>
<td>54</td>
<td>§ 3.7.7</td>
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</tbody>
</table>

$^a$ Position uncertainties correspond to the angular radius (out to 50% of boresight power) of an individual ALFA beam in the discovery observation.

$^b$ Estimate from the NE2001 model of Galactic electron density (Cordes & Lazio 2003).

$^c$ Peak flux density at 1.4 GHz defined as $S = (S/N)S_{sys}/\sqrt{N_{pol}DFW}$, where $S/N$ is the signal to noise ratio of the brightest detected pulse.
both the FFT and SP search, and they are also more likely to have already been found by previous, less sensitive surveys, this indicates that PALFA is probing deeper and finding pulsars that are farther away or less bright than the known objects in the same region of the Galactic plane.

Single pulse searches have not been routinely carried out on survey data in the past, with the exception of Phinney & Taylor (1979), Nice (1999), who discovered PSR J1918+08 via a single pulse search, and McLaughlin et al. (2006), who found 11 RRATs. Therefore, the proportion of single-pulse-only detections is higher for the PALFA discoveries than the known pulsars. The five known pulsars detected only by single pulse search are known steady emitters which were seen away from the beam center and therefore with reduced sensitivity.

### 3.5 Selection Effects and Intermittency

The sample of PALFA single pulse discoveries (§ 3.7) includes one object which has not been detected again despite reobservations (J1928+15), two sources detectable in re-observations through their time-averaged emission (PSR J0628+09 and PSR J1909+06), and four long-period objects, one of which has the smallest known duty cycle for any radio pulsar (PSR J0627+16).

Among the 11 Parkes RRATs, 10 were successfully redetected in subsequent Parkes observations, and one (J1839–01) has not been redetected despite multiple attempts (McLaughlin et al. 2006). PSR J0848–43 and PSR J1754–30 can sometimes be detected through their time-averaged emission with sensitive, low-frequency observations (McLaughlin, M. A. 2007). Six of the sources have periods greater than 2 s.
In this section we discuss selection effects which may account for some of the observational characteristics of intermittent sources. Characteristics of this population which remain unexplained by observational biases may indicate underlying intrinsic differences between these objects and conventional radio pulsars. They may belong to a genuinely intermittent and physically different class of neutron stars.

### 3.5.1 Multiplicative Effects

We can define a general model for observed signal intensity in terms of the time and frequency-dependent flux density $S_i(t, \nu)$ as

$$I(t, \nu) = G_t(t, \nu) G_{ISS}(t, \nu) S_i(t, \nu) + n(t, \nu) + RFI(t, \nu),$$

(3.6)

where $G_t$ is the telescope gain, $G_{ISS}$ is the variation factor due to interstellar scintillation, $n(t, \nu)$ is radiometer noise, and $RFI(t, \nu)$ is the contribution from terrestrial radio frequency interference.

Variations in telescope gain across the beams of the multi-beam receiver or within the power pattern of a single beam impact the detectability of a pulsar as either a single pulse or periodic source. As shown by the reobservations of PSR J0627+16, PSR J1909+06, PSR J0848–43 and PSR J1754–30, classifying a source as intermittent may be due to insufficient sensitivity to detect its periodic emission during the discovery observation. The effectiveness of single pulse vs. FFT-based periodic search depends on the pulse amplitude distribution, and the observed pulse amplitude distribution in turn depends on the pulsar location with respect to the telescope beam power pattern. Fig. 3.8 shows the probability density function (PDF) of event amplitude for PSR B1933+16, a strong pulsar.
detected in two beams of the same PALFA pointing. One beam of the ALFA receiver is pointing directly at the pulsar and the low-intensity tail of the distribution is clearly visible since all pulses are above the detection threshold. The pulsar is also detected in the first sidelobe of an adjacent beam, in which case only the brightest pulses are above the detection threshold and only the high-intensity tail of the distribution is visible. Thus an off-axis detection of a steadily emitting pulsar may misrepresent it as an intermittent source.

A different set of effects which affect detectability in single pulse vs. periodic search is due to intervening ionized gas. Turbulence in the ionized interstellar gas and the motion of the pulsar with respect to the gas introduce phase modulations in the pulsar emission which cause the observed intensity to change over time and frequency. In general, the scintillation gain factor has contributions from both diffractive (DISS) and refractive (RISS) interstellar scintillation, such that \( G_{\text{ISS}}(t, \nu) = G_{\text{DISS}}(t, \nu) G_{\text{RISS}}(t, \nu) \) (Rickett, 1990). The detectability of nearby pulsars with low DMs can be significantly affected by DISS, which can have time scales comparable to typical survey pointing times (minutes) and frequency scales \( \Delta f_{\text{DISS}} \ll f \). In terms of the observing frequency \( f \) and the pulsar distance \( D \), the DISS time scale \( \Delta t_{\text{DISS}} \propto f^{1.2} D^{-0.6} \). The scintillation bandwidth \( \Delta f_{\text{DISS}} \) and scattering timescale \( \tau_s \) are related through \( 2\pi \Delta f_{\text{DISS}} \tau_s \approx 1 \). An empirical fit from Bhat et al. (2004) for \( f \) in GHz and \( \tau_s \) in ms gives an estimate for \( \tau_s \) based on DM:

\[
\log \tau_s = -6.46 + 0.154 \log \text{DM} + 1.07 (\log \text{DM})^2 - 3.86 \log f, \quad (3.7)
\]

but there is significant scatter about this relationship. When the scintillation bandwidth and time scale are small, averaging over the observation time and bandwidth can quench DISS.
Figure 3.8: Observed single pulse PDFs for PSR B1933+16 in two beams of a PALFA pointing: on source (right) and 6 arc minutes away (left, shaded). All pulses are detected individually in the on-source beam, while only the high intensity tail of the distribution is detected via a single pulse search in the off-source beam. A sidelobe detection of a canonical pulsar will pick out the brightest pulses and may misrepresent the pulsar as an intermittent source.
For refractive scintillation, $\Delta f_{\text{RISS}} \propto f$ and $\Delta t_{\text{DISS}} \propto f^{0.57} D^{1.6}$. Unlike for DISS, the time scale of RISS increases with distance and therefore it can become very long for distant pulsars with relatively high DMs. Both RISS and DISS can either help or hinder pulsar detection due to the time-variable constructive or destructive interference of wave fronts they cause. For a single-pass survey, this means that some weak pulsars may be detected because they are modulated above the detection threshold, and some pulsars that are otherwise bright enough may be missed because of scintillation modulation. Cordes & Lazio (1991) discuss in detail the detection probability for scintillating pulsars by single-pass and multi-pass surveys. Since PALFA is a single-pass survey, it may have missed pulsars that scintillate on time scales comparable to or longer than the observation time. None of our discoveries in Table 3.3 appear to be affected by DISS, though RISS over long time scales may affect the objects with higher DMs.

3.5.2 Observation Time vs Pulsar Period

The detectability of a pulsar as a periodic source depends on the integrated pulse flux within the observation, which is determined by the number of periods within the observation time, $N_p = T_{\text{obs}}/P$, along with the pulse amplitude distribution. For the same integrated flux per pulse, fewer periods within a fixed $T_{\text{obs}}$ mean that long-period pulsars are less likely to be detected than short-period pulsars by any method relying on detecting integrated flux such as an FFT-based search or a continuum imaging survey. For FFT searches in particular, this effect is compounded by the fact that when $N_p$ is small, the harmonics of interest are in the low-frequency part of the power spectrum, which is often dominated by non-Gaussian red noise and RFI. Hereafter we use the term
“small-$N_p$ bias” to refer to the combined influence of these effects on pulsar detectability.

### 3.6 Intermittency Measure

Both the periodicity and single pulse searches perform with varying efficiency depending on an object’s degree of intermittency. In this section we present an intermittency measure method to quantify the relative performance of the two search algorithms, apply it to results from the Parkes Multibeam and PALFA surveys, and discuss general implications for surveys.

#### 3.6.1 Definition

We can compare the detectability of objects by periodicity and single pulse search and attempt to narrow down different classes of intermittent emitters by calculating the intermittency ratio

$$ r = \frac{(S/N)_{SP}}{(S/N)_{FFT}} $$

for each object in our sample of PALFA and Parkes detections. McLaughlin & Cordes (2003) derive

$$ r = \left( \frac{2\eta}{\zeta N_p^{1/2}} \right) \frac{S_{\text{max}}}{S'_{av}}, $$

where $\zeta \approx 1.06$ and $\eta \sim 1$ for a Gaussian pulse shape, $S_{\text{max}}$ is the maximum expected pulse intensity within $N_p = T_{\text{obs}}/P$ periods and $S'_{av}$ is a modified average pulse peak intensity.
The intermittency ratio is a system-independent measure of the efficiency of the two types of search for objects with different degrees of intermittency. In Fig. 3.9, expected values of $r$ vs. $N_p$ are shown for an exponential pulse amplitude PDF and power-law distributions with various indices. Lower limits on $r$ are given for intermittent sources which were not detected via periodicity search. In addition, we show $r$ values for pulsars that were detected using both the periodicity and single-pulse search algorithms in the PALFA and Parkes Multibeam surveys. A total of 283 PALFA pulsar detections and 255 Parkes Multibeam detections are shown in the plot, including multiple detections of some objects.

3.6.2 Implications for Surveys

In Fig. 3.9, long-period pulsars are predominantly found in the upper left (small $N_p$, large $r$) and millisecond pulsars in the lower right (large $N_p$, small $r$). PSR B0525+21, with $r \sim 7$, has $P = 3.7$ s and $DM = 51$ pc cm$^{-3}$, which make it susceptible to both the small-$N_p$ bias and diffractive scintillation and therefore it is detected more readily as a single pulse source. At the other extreme is PSR B1937+21, a millisecond pulsar which emits giant pulses but is nevertheless detected with a much higher S/N in the periodicity search than in the single pulse search ($r < 0.07$) because its period is small compared to the PALFA observation time and the normal pulse amplitude is exceptionally steady (Jenet & Gil 2004). This indicates that the effect of $N_p$ on detectability can overshadow individual properties, and in survey mode millisecond pulsars will show up overwhelmingly as periodic sources. In that case, processing the data with a single pulse search algorithm can reveal the presence of giant pulses in an oth-
Figure 3.9: The intermittency ratio $r$ vs $N_p = T_{\text{obs}}/P$ for 283 PALFA (filled hexagons) and 255 Parkes Multibeam (squares, open hexagons) pulsar detections. Squares denote the 10 Parkes RRATs with period measurements, including two which can sometimes be detected through their time-averaged emission. The criterion for inclusion of canonical pulsars was a simultaneous periodic and single pulse detection. PALFA points include both blind survey detections and targeted test observations of known pulsars. Arrows denote lower limits for PALFA and Parkes intermittent sources. Points with bars show the average $r$ for a set of observations of the same object, with the bars denoting the maximum and minimum $r$ values. Millisecond pulsar detections appear at lower right. Dotted lines show $r$ for power-law pulse amplitude PDFs with indices from 0.5 to 2.0. A ratio of $10^5$ was assumed for the cutoff intensities $S_1$ and $S_2$ (McLaughlin & Cordes 2003). The dashed line shows $r$ for an exponential PDF. A single pulse search performs better than an FFT periodicity search for $r > 1$. 
In-between PSR B0525+21 and PSR B1937+21, from upper left to lower right is a relatively smooth distribution of pulsars whose intermittency ratios are predominantly determined by the influence of $N_p$ on the detectability of all types of periodic emitters. We look for unusual objects among the outliers from that trend. There are a number of pulsars detected both in periodicity and single pulse search in the region where $r = 1 - 5$, including PSR B0656+14, which occasionally emits bursts much brighter than the average pulse and would arguably be classified as a RRAT if located farther away (Weltevrede et al. 2006). Inter-spersed among them in the region are most of the PALFA and Parkes intermittent sources. PSR J1909+06, which was not detected in a periodicity search but is visible as a periodic source when folded with its known period, has $r = 1.3$, and the long-period PALFA intermittent sources PSR J1854+03 and PSR J1946+24 have $r = 1.0$ and 1.8, respectively. Of the Parkes intermittent sources, seven have $r < 3$. PSR J1754−30 ($r = 0.2$) and PSR J0848−43 ($r = 0.7$) were detected through their time-averaged emission in low frequency follow-up observations. In the $r > 5$ region we find only five objects: PSR B0525+21, the Crab pulsar, Parkes intermittent sources PSR J1317−5759 and PSR J1819−1458, and PALFA intermittent source PSR J1928+15. The Crab pulsar has a high intermittency ratio due to its giant pulses but is otherwise a relatively steady emitter as periodic emission is consistently detected even if the giant pulses are ignored. Of the remaining three intermittent sources none are young pulsars like the Crab. The pulse amplitude distributions of PSR J1317−5759 and PSR J1819−1458 are described by power laws with indices $\sim 1$ (McLaughlin et al. 2006), smaller than measured giant pulse indices of $\sim 2 - 3$ (e.g. Kinkhabwala & Thorsett 2000, Cordes et al. 2004).
We conclude from Fig. 3.9 is that periodicity and single pulse searches should be used in combination by pulsar surveys since there are types of sources which are best detected by either method. As more intermittent objects are found, placing them in $r - N_p$ space may help us identify physically distinct populations. In addition, repeated sky coverage can probe intermittency at time scales of days to months.

### 3.7 Single Pulse Discoveries

Table 3.3 lists parameters of the seven pulsars discovered by PALFA via a single pulse search. In this section we discuss each object’s properties in detail and describe the steps taken in addition to the PALFA processing pipeline in order to verify the signals’ celestial origin and calculate the pulsar period from times of arrival of single pulses.

#### 3.7.1 PSR J0627+16

PSR J0627+16 was discovered when nine single pulses were detected at a trial $\text{DM} = 125 \text{ pc cm}^{-3}$ (Fig. 3.2). The period estimated from the pulse arrival times in the discovery observation is $P = 2.180$ s. What is unusual about this object is its very narrow peak in $S/N$ vs. $\text{DM}$ space, indicating a narrow pulse (Cordes & McLaughlin 2003). Fig. 3.5c shows the cumulative dynamic spectrum after stacking raw data chunks aligned around the five brightest pulses. A fit to the dispersion sweep in the time-frequency plane gives a best $\text{DM}$ of 113 pc cm$^{-3}$ and when the raw data chunk around the brightest pulse is dedispersed with
this DM, the FWHM pulse width is only 0.3 ms.

Two follow-up observations at 0.33 and 1.4 GHz yielded 17 pulses in 50 minutes and 22 pulses in 72 minutes, respectively. After removing bright single pulses from the dedispersed time series and replacing the respective time samples with a running average, periodic emission with $P = 2.180$ s was detected throughout the 0.33 GHz observation, confirming the period estimate from the discovery observation at 1.4 GHz and the presence of underlying normal emission.

Many of the RRATs detected by McLaughlin et al. (2006) have short duty cycles, calculated as the ratio between the average width of single pulses and the period. PSR J0627+16 has the smallest known duty cycle, $f_{dc} = 0.01\%$ by this definition. However, for steady emitters the duty cycle is typically defined as the ratio of the folded pulse profile FWHM and the period. Individual pulses may occur in a phase window wider than any individual pulse and corresponding to the folded profile width. At 1.4 GHz, the individual 0.3 ms pulses of J0627+16 occur in a 8 ms window, while at 0.33 GHz individual pulses have widths of 0.3 – 2 ms and occur in a 15 ms window. The folded pulse profile at 0.33 GHz has FWHM of 60 ms, suggesting that bright pulses may be confined to a narrower window than pulses comprising the underlying normal emission.

The detection of bright single pulses and a weak periodic signal from PSR J0627+16 when data are folded with an accurate period estimate, along with the absence of a periodic detection in search mode weighs in favor of the proposition of Weltevrede et al. (2006) that some RRATs may have periodic emission with highly variable pulse amplitudes.
3.7.2 PSR J0628+09

PSR J0628+09 was discovered by detecting three pulses at $\text{DM} = 88 \, \text{pc cm}^{-3}$. The period estimated from the pulse times of arrival was 2.48 s. In follow-up observations the pulsar was also detected in periodicity searches as it emits on average several bursts per minute. The periodicity detections and the larger number of single pulses in subsequent observations allowed the actual pulsar period of 1.241 s to be determined (Cordes et al. 2006).

3.7.3 PSR J1854+03

PSR J1854+03 was discovered in 2008 via a single pulse search performed on full-resolution survey data. Four pulses were detected at $\text{DM} = 216 \, \text{pc cm}^{-3}$ during the 268 s observation. The period $P = 4.559 \, \text{s}$ was estimated by taking the smallest difference between times of arrival (TOAs) of two consecutive pulses and verifying that intervals between all four TOAs are integer multiples of it. A confirmation observation with the more sensitive central ALFA beam yielded within 120 s five pulses whose arrival times match the estimated period.

3.7.4 PSR J1909+06

PSR J1909+06 was observed in 2006 but not identified as a candidate until 2007 when the full-resolution data were searched for single pulses. Two pulses with a width of $\sim 1 \, \text{ms}$ and signal to noise ratio of 6 and 9 were detected at $\text{DM} = 35 \, \text{pc cm}^{-3}$. The stacked dynamic spectrum clearly shows a dispersion sweep (Fig. 3.5d). PSR J1909+06 was discovered in data from the off-axis beam
2 of the multi-beam ALFA receiver. Since the on-axis gain of the center beam is 10.4 K/Jy compared to 8.2 K/Jy for the other six beams (Cordes et al. 2006), we aimed the center beam at the discovery coordinates for a confirmation observation. For the same integration time of 268 s, 8 pulses with $S/N > 5$ were detected in the confirmation observation. We used the pulse arrival times to determine a period and arrived at a best estimate of $P = 0.741$ s.

### 3.7.5 PSR J1919+17

During the 2007 discovery observation of PSR J1919+17, multiple pulses at DM = 148 pc cm$^{-3}$ were detected in beam 4 of the ALFA receiver, with no corresponding periodic detection. A Fast Folding Analysis (Staelin 1968, Kondratiev et al. 2009) was used to narrow down the period to $P = 2.081$ s, which was confirmed in 2008, when the pulsar was detected as a normal periodic emitter with the more sensitive central ALFA beam. The pulsar has a double-peak profile with the two peaks ~ 100 ms apart, which most likely made it difficult to find its period from pulse arrival times alone.

### 3.7.6 PSR J1928+15

PSR J1928+15 was discovered in 2005 by detection of what looked like a single bright pulse at DM = 245 pc cm$^{-3}$ in a 120 s observation (Fig. 3.3). More detailed analysis revealed that the event was in fact composed of 3 separate pulses occurring at intervals of 0.403 s, with the middle pulse being brighter by an order of magnitude than the other two (Fig. 3.4). In Fig. 3.5a the dispersion of the
brightest pulse by ionized interstellar gas is shown in the time-frequency plane, evidence of the non-terrestrial origin of the pulses. A fit to the pulse signal in the time-frequency plane resulted in a refined estimate of $\text{DM} = 242 \, \text{pc cm}^{-3}$. Despite multiple follow-up observations, the source has not been detected again.

Given the DM of this source, 242 pc cm$^{-3}$, it is unlikely that the non-detection can be attributed to diffractive scintillation. Since the three pulses are equally spaced, they can be interpreted as a single event seen in successive rotations of a neutron star. This signature might be accounted for by an object that is dormant or not generally beamed toward the Earth and whose magnetosphere is perturbed sporadically by accretion of material from an asteroid belt (Cordes & Shannon, 2008).

### 3.7.7 PSR J1946+24

PSR J1946+24 has $\text{DM} = 96 \, \text{pc cm}^{-3}$ and $P = 4.729 \, \text{s}$ and was discovered by detecting 4 individual pulses. The intervals between detected pulses in this case were all $> 20 \, \text{s}$. The brightest detected pulse of PSR J1946+24 has $S/N = 29$ and its dispersion sweep is visible in the time-frequency plane without any stacking (Fig. 3.5b).

### 3.7.8 Summary of Timing Solutions

Single pulse arrival times collected over multiple follow-up observations were used to obtain partial timing solutions for PSR J0628+09, PSR J1909+06, PSR J1919+17, PSR J1854+03 and PSR J1946+24 and verify their estimated peri-
ods. The periods of PSR J0627+16 and PSR J1909+06 were verified by manually folding raw data and detecting a periodic signal. Finally, despite the fact that PSR J1928+15 was not detected after the discovery observation, the ∼ 0.403 s intervals between the three pulses detected from that source differ by only ∼ 2 ms, which is approximately half the FWHM pulse width and therefore provides a period estimate to that precision. We are currently timing the six sources which were successfully redetected. Obtaining phase-connected timing solutions will enable us to compare them to other neutron star populations and will yield positions which will facilitate observations at higher wavelengths.

3.8 Constraints on Fast Transients

The PALFA survey was designed to detect pulsars and pulsar-like objects by identifying either (or both of) their periodic or single-pulse emission, as discussed earlier in this paper. The same data may also be used to detect transient events from other Galactic and extragalactic sources. At minimum, the PALFA survey can place limits on the rate and amplitude distribution of radio transients that are shorter than about 1 second in duration. Possible source classes for short-duration transient events, to name a few, include flare stars, magnetar bursts, gamma-ray bursts (GRBs), and evaporating black holes. GRBs have diverse time scales spanning ∼ 10 ms to 1000 s. Mergers of double neutron-star (DNS) binaries and neutron star-black hole (NS-BH) binaries are proposed sources for short bursts, and they may also emit contemporaneous radio pulses (Paczynski 1986, Hansen & Lyutikov 2001). Merger rates in the Galaxy are estimated to be ∼ 1 to 150 Myr⁻¹ for DNS binaries from pulsar surveys and a factor of 20-30 less for NS-BH binaries from population synthesis studies (E.g.,
Rantsiou et al. 2008). Event rates of detectable events depend critically on the luminosity of radio bursts but are likely to be comparable to the rate of short-duration GRBs, and thus smaller than \( \sim 1 \) event day\(^{-1}\) hemisphere\(^{-1}\). Another phenomenon that may produce rare, bright pulses is the annihilation of primordial black holes (Rees 1977). Phinney & Taylor (1979) estimate the Galactic rate for such events to be \(< 2 \) kpc\(^{-3}\) yr\(^{-1}\). Other possibilities are discussed in Cordes (2007).

Motivated by these considerations, we discuss the constraints that can be made on transient events from PALFA survey data obtained to date. First, we note that most — but not all — of the aperiodic events detected to date in PALFA data (as reported in § 3.7) and in the Parkes Multibeam Survey by McLaughlin et al. (2006), appear to be periodic when they are reobserved sufficiently to establish a periodicity. Additionally, all events detected so far in both surveys have dispersion measures that can be accounted for by ionized gas in the Galaxy (using the NE2001 model), suggesting that the emitting sources are closely related to the standard Galactic pulsar population. By contrast, Lorimer et al. (2007) recently detected a strong (30 Jy), isolated burst with duration \( \sim 5 \) ms that shows DM \( \sim 375 \) pc cm\(^{-3}\), too large to be accounted for by modeled foreground material in the Galaxy or by plasma in the Small Magellanic Cloud, which is somewhat near the direction the event was found.

### 3.8.1 Discriminating Celestial Events from RFI

In addition to detecting radio sources on axis in data streams from each of the seven beams of the ALFA system, it is possible to detect strong events off axis
with low but non-zero sensitivity over almost the entire hemisphere centered on the zenith. Consequently, it is possible to detect relatively low-rate but very bright transients off axis as well as the much weaker but higher rate single pulses that we have detected in the on-axis parts of the beam pattern.

To establish that a given event is celestial in nature, we need to distinguish it from terrestrial interference. For on-axis events, this classification process is aided by the directionality of the seven beams and the expectation that most real events are likely to be seen in three or fewer contiguous beams rather than in all seven beams. Bright events may violate this expectation, however, because near-in sidelobes are fairly large (c.f. Figure 1 of Cordes et al. 2006). Celestial and terrestrial radio signals can also enter the seven beams of the ALFA receiver indirectly — far off the nominal pointing axis — through reflection and scattering off telescope support structures, as with any antenna. Extremely bright signals (celestial or terrestrial) may be detected after scattering into one or more beams, and the effective gain is approximately that of an isotropic radiator with small gain for events incident far off axis from the pointing direction. For the Arecibo telescope, which has an intricate support structure with many possible scattering surfaces, such wide-angle incidence is likely to provide multiple paths for radiation to enter the feed optics. Radiation arriving along multiple paths will constructively and destructively interfere across ALFA’s focal plane, so that the event’s strength will be nonuniform in the different data streams.

When radiation enters the telescope optics from wide angles, it is difficult to distinguish celestial from terrestrial signals based on the nominal pointing direction of the telescope and on whether they are detected in a single beam, a subset of beams, or all beams. Conceivably, extremely bright events from a
single radio source could be emitted at very rare intervals that would be detected when the telescope is pointed nominally at directions separated by tens of degrees (but within the same hemisphere). Such sources and events will be exceedingly difficult to disentangle from terrestrial RFI.

Of course the most powerful confirmation of a particular event is the detection of similar events in reobservations of the same sky position. For most of the events reported in § 3.7 and by McLaughlin et al. (2006), redetections have been made in this manner. They have also relied on establishing that their signatures in the frequency-time plane conform to what is expected. The simplest celestial signals are narrow pulses that show differential arrival times in accord with the cold-plasma dispersion law (e.g. Cordes & McLaughlin 2003). Celestial objects may also show the effects of multipath propagation through the interstellar medium (ISM) either in the frequency structure that is produced in the spectra of nearby pulsars or in the asymmetric broadening of the pulses from more distant objects. For cases where spatial information associated with the nominal telescope pointing direction is insufficient to constrain the celestial nature of a particular event, we must rely especially on a detailed study of the event’s structure in the time-frequency plane. Indeed the time-frequency structure of the event discussed by Lorimer et al. (2007) was a key part of the argument for its classification as a celestial event.

3.8.2 Simple Model for ALFA Beam Patterns

A given reflector and feed antenna have a net antenna power pattern with a main lobe and near-in sidelobes that is similar to an Airy function with a main-
lobe angular width $\sim \lambda/D_a$, where $D_a$ is the effective reflector diameter. The wide-angle part of the antenna pattern has far-out side lobes that are independent of $D_a$ and have average gains $G \sim 1$, similar to that of an isotropic antenna. However peaks in the far-out side lobe pattern can have gains significantly larger than $G = 1$, corresponding to special directions where scattering from the telescope support structure is especially efficient. For the Arecibo telescope, we expect side lobes to have the same general properties, with the caveat that support structures will introduce further complexity in the far-out side lobe pattern that varies as the telescope is used to track a source. Tracking a sky position is done by rotating the azimuth arm and moving the Gregorian dome along the azimuth arm, thus changing the scattering geometry. We therefore expect the side lobe structure to change significantly with azimuth and elevation of the targeted position on the sky. For the seven-beam ALFA system, the main beams by design sample different parts of the sky, as do the near-in side lobes. At wider angles, the power pattern of each feed overlaps the others but with considerable variation in gain from feed to feed.

To derive simple constraints on burst amplitudes and rates, we expand the gain for each feed into inner beam and wide-angle terms:

$$G(\theta, \phi) = G_{\text{max}} P_n(\theta, \phi) + (1 - \eta_B),$$  \hspace{1cm} (3.10)

where $\theta$ and $\phi$ are polar and azimuthal angles, respectively; $P_n(\theta, \phi)$ is the power pattern for the main beam and near-in side lobes; $\eta_B$ is the main-beam efficiency, and $(1 - \eta_B)$ is the average level of the far-out side lobes. The boresight gain is

$$G_{\text{max}} = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi}{\Omega_A} = \frac{4\pi \eta_B}{\Omega_{\text{MB}}},$$  \hspace{1cm} (3.11)

where $A_e$ is the effective telescope area, and $\Omega_A$ and $\Omega_{\text{MB}} = \eta_B \Omega_A$ are the solid angles of the antenna power pattern and of the main beam, respectively. The
system equivalent flux density is

\[ S_{\text{sys}} = \frac{T_{\text{sys}} 2k}{A_e} = \frac{8\pi k T_{\text{sys}}}{\lambda^2 G_{\text{max}}}, \]  

(3.12)

where \( k \) is the Boltzmann constant and \( T_{\text{sys}} \) is the system temperature. The minimum detectable flux density is

\[ S_{\text{min}} = \frac{m S_{\text{sys}}}{\sqrt{N_{\text{pol}} \Delta f W}}, \]  

(3.13)

which is a function of the event duration, \( W \), as well as system parameters. It is useful to define \( S_{\text{min},1} \) as the minimum detectable flux density for unit gain using Eq. 3.12 with \( G_{\text{max}} = 1 \). Substituting into Eq. 3.13 yields, for two polarizations and \( \Delta f = 100 \text{ MHz} \),

\[ S_{\text{min},1} = 10^{4.9} \text{ Jy} \left( \frac{m}{5} \right) \left( \frac{10 \text{ ms}}{W} \right)^{1/2} \left( \frac{T_{\text{sys}}}{30 \text{ K}} \right); \]  

(3.14)

we note that for some directions, the system temperature can differ from the fiducial 30 K used.

### 3.9 Constraints on Event Rates and Amplitudes

We now derive limits that can be placed on the rate and amplitudes of transient events using our simple model for the antenna power pattern. Let \( \zeta \) be the event rate per unit solid angle from a population of sources, which implies a total number \( \zeta T_{\text{obs}} \Delta \Omega \) in a total observation time \( T_{\text{obs}} \). If no events are detected, we can place an upper limit on the rate \( \zeta_{\text{max}} \) for minimum flux density, \( S_{\text{min}} \).

We treat the response of the antenna power pattern as azimuthally symmetric about the bore axis, so \( G(\theta, \phi) \rightarrow G(\theta) \), and calculate the gain as a function of polar angle from the bore axis. For each annulus of solid angle \( \Delta \Omega \), the upper
bound on the rate is
\[ \zeta_{s,\text{max}} \leq \frac{1}{M \Delta \Omega \Delta T_{\text{obs}}}, \] (3.15)
for flux densities greater than
\[ S_{\text{min}} = \frac{S_{\text{min,1}}}{G(\theta)}. \] (3.16)

The multiplier \( M \) accounts for whether a given ALFA feed and receiver combination samples the same patch of sky or not. For the main lobes, \( M = 7 \) while for the far-out sidelobes, \( M = 1 \).

We evaluate fiducial values by integrating respectively over the main beams and over the remainder of the power patterns. For a main-lobe beam width of 3.5 arc min, \( \Omega_{\text{MB}} \approx 10^{-2.6} \text{ deg}^2 \) and \( G_{\text{max}} \approx 10^{7.0} \). Using the average gain over the main beam out to the half-power point, \( \langle G \rangle \approx G_{\text{max}} / (2 \ln 2) \), we have
\[ S_{\text{min}} = \frac{2 \ln 2 S_{\text{min,1}}}{G_{\text{max}}} \approx 11 \text{ mJy} \left( \frac{m}{5} \right) \left( \frac{10 \text{ ms}}{W} \right)^{1/2} \left( \frac{T_{\text{sys}}}{30 \text{ K}} \right) \] (3.17)
and
\[ \zeta_{s,\text{max}} = \frac{1}{7 \Omega_{\text{MB}} T_{\text{obs}}} \approx 0.12 \text{ hr}^{-1} \text{ deg}^{-2} \left( \frac{461 \text{ hr}}{T_{\text{obs}}} \right). \] (3.18)

Integrating over wide angles, and using \( \eta_B \approx 0.7 \), we estimate
\[ S_{\text{min}} \approx \frac{S_{\text{min,1}}}{1 - \eta_B} \approx 10^{5.4} \text{ Jy} \left( \frac{m}{5} \right) \left( \frac{10 \text{ ms}}{W} \right)^{1/2} \left( \frac{T_{\text{sys}}}{30 \text{ K}} \right), \] (3.19)
where the far-out sidelobes have an average gain of \( 1 - \eta_B \), and
\[ \zeta_{s,\text{max}} = \frac{1}{2 \pi \epsilon T_{\text{obs}}} \approx \frac{10^{-7.0}}{\epsilon} \text{ hr}^{-1} \text{ deg}^{-2} \left( \frac{461 \text{ hr}}{T_{\text{obs}}} \right). \] (3.20)
where \( \epsilon \approx 1 \) is the fraction of the hemisphere actually covered by the far-out sidelobes.

Results for PALFA data are shown in Fig. 3.10. Within the half-power beam width the constraints are strong on the flux density but weak on the event rate.
while the opposite is true for the far-out sidelobes, represented by the part of the curve below $\zeta \approx 0.03 \, \text{h}^{-1} \, \text{deg}^{-2}$. The asymptotic value of the curve corresponding to the maximum, boresight gain differs from the fiducial value calculated above because the latter is an average over the main beam. In our simple model the near-in sidelobes are not included explicitly so our curves overestimate $S_{\text{min}}$ at the corresponding polar angles. However, the limits change rapidly, so this does not change the salient features of the figure, which are the seven order-of-magnitude difference in constrained amplitudes and the eight order of magnitudes on the event rates between the main lobs and the far-out sidelobes.

### 3.9.1 Comparison with Other Results

A brief summary of our results is that (a) a small number of events has been detected from sources that are consistent with their membership in the radio pulsar population, but with a much greater deal of modulation in some cases; (b) no very strong pulses have been identified in the far-out sidelobes of the Arecibo telescope and (c) no bursts have been detected that are extragalactic in origin.

Here we compare our results with those of Lorimer et al. (2007), who surveyed high-Galactic-latitude regions that included the Magellanic Clouds and who discovered a single reported pulse, with amplitude 30 Jy. They surveyed $\sim 9 \, \text{deg}^2$ with a detection threshold $\sim 300 \, \text{mJy}$, about 100 times fainter than the detected pulse amplitude. To compare any two surveys, we initially assume a population of radio sources that is homogeneously distributed in Euclidean space and we ignore propagation effects that might limit the detectability of
Figure 3.10: Constraints on the single pulse event and minimum detectable flux density. The curve uses a total observation time $T = 461$ h and an assumed pulse width of $W = 10$ ms. The three points, from left to right, correspond to the far-out sidelobes, the break between the main beam and far-out sidelobes (at $\zeta_s \approx 0.03 \text{ h}^{-1} \text{ deg}^{-2}$), and the boresight gain. The shaded region is excluded by the PALFA data.
bursts from distant sources. The number of events detected $N \propto \Omega_i T D_{\text{max}}^3$ for a survey of duration $T$ that samples instantaneously a solid angle $\Omega_i$. For multi-beam systems with $N_{\text{pix}}$ pixels, $\Omega_i = N_{\text{pix}} \Omega_1$, where $\Omega_1$ is the solid angle of a single beam. We assume events have the same peak luminosity and pulse width $W$ and are detectable to a distance $D_{\text{max}}$. The ratio of number of detected events in two surveys with total observation times $T_{\text{obs},a}$ and $T_{\text{obs},b}$, and bandwidths $\Delta f_a$ and $\Delta f_b$ is

$$\frac{N_b}{N_a} = \left( \frac{T_{\text{obs},b}}{T_{\text{obs},a}} \right) \left( \frac{N_{\text{pix},b} \Omega_1 b}{N_{\text{pix},a} \Omega_1 a} \right) \left( \frac{D_{\text{max} b}}{D_{\text{max} a}} \right)^3 \left( \frac{\Delta f_b}{\Delta f_a} \right)^{3/4}. \quad (3.21)$$

As pointed out by Lorimer et al. (2007), the same survey that detected the 30-Jy pulse should have yielded many more detections if the assumptions of a volume limited sample apply. Using Eq. 3.21, the lone 30 Jy pulse implies there should have been $N_b/N_a \approx (m_a/m_b)^{3/2} = 10^3$ additional detections above a 100-times fainter threshold. In the 90 h of follow up observations, there should have been $N_b/N_a \approx (T_{\text{obs},b}/T_{\text{obs},a})(m_a/m_b)^{3/2} \approx 80$ additional detections. Comparing the Parkes and PALFA surveys\footnote{For PALFA, we use 7 pixels each of size 3.5 arcmin, 461 h of observations, a threshold of $m = 5$, a system-equivalent flux density of 4 Jy, and 100 MHz bandwidth. For the Parkes survey we use 13 beams of 14 arcmin diameter, 480 h, a threshold of 600, $S_{\text{sys}} = 40$ Jy, and 288 MHz bandwidth.}, we estimate that the PALFA survey should have identified $\sim 600$ pulses above threshold.

The PALFA survey’s null result on extragalactic events is therefore in accord with Lorimer et al.’s non-detection of events weaker than the single strong event they reported. With the assumptions made, these results suggest that the non-detections of pulses weaker than the 30-Jy pulse are inconsistent with the source population having a distribution that is homogeneous and isotropic.
3.9.2 Caveats

There are caveats on these results related to the assumptions about the source population and to the possible role of propagation effects in limiting detectability. The minimum detectable flux density for the PALFA survey is 30 mJy for a 5-ms pulse, implying that a pulse of 30 Jy strength emitted at a distance $D_{\text{event}}$ is detectable to a distance $D_{\text{max}}$ given by $D_{\text{max}}/D_{\text{event}} \approx (30 \text{ Jy}/0.03 \text{ Jy})^{1/2} \approx 32$. If the lone event detected by Lorimer et al. is from a source at the attributed distance $D_{\text{event}} \sim 0.5 \text{ Gpc}$ (based on assigning about half of the DM to the intergalactic medium), the PALFA survey would detect fewer pulses than estimated above (for constant luminosity) because the universe is not old enough and from red-shifting of the spectrum if it is steep in frequency. Nonetheless, a cosmological population of constant-luminosity sources would extend to $\sim 8$ times the attributed distance, implying from the first form of Eq. 3.21 that $\sim 7$ pulses should have been detected in the PALFA survey, on average, while $\sim 500$ weaker pulses should have been seen in the discovery survey with Parkes. The difference in yield under this alternative scaling results from the fact that the PALFA survey can detect sources well beyond the cosmological population while the Parkes survey is comparatively shallower (by a factor of ten in flux density, i.e. 300 compared to 30 mJy), but covers a factor of 30 greater solid angle. Consideration of a broad luminosity function does not alter these conclusions qualitatively. However, we would generally expect the pulse amplitude distribution to extend to lower flux densities (from lower luminosities) given that the sole reported event was much larger than the threshold and that, therefore, many more pulses are expected compared to the constant-luminosity assumption.

Pulse broadening from multipath propagation in either the ISM or the in-
tergalactic medium (IGM) can also limit the numbers of events detected in a
survey because the broadening increases with source distance. The maximum
detectable distance is therefore diminished, as demonstrated for the ISM in Fig-
ure 3.1. Lorimer et al. argued that the strong frequency dependence of the
width of the 30-Jy pulse was consistent with multipath propagation through a
turbulent, ionized IGM. If so, sources from a greater distance would be less-
easily detectable. In the simplest scattering geometries, scattering conserves the
area of the pulse, so matched filtering yields a test statistic with $S/N \propto (W/\tau_d)^{1/2}$
when the pulse broadening time $\tau_d$ is much larger than the intrinsic pulse width
(Cordes & McLaughlin 2003). The 30-Jy pulse therefore could have been broad-
ened by an additional factor of $10^4$ and the $S/N$ still would have been above
threshold. The much longer pulses ($\sim 10^4 \times 5 \text{ ms} = 50 \text{ s}$) would have been dif-
ficult if not impossible to identify in the time series owing to high-pass filtering
used to mitigate baseline fluctuations. The high-pass filtering was explicit in
the Parkes Multibeam data acquisition but is part of the post-processing in the
PALFA analysis. Such very broadened pulses could be detected by imaging
surveys with relatively short integration times like the NRAO VLA Sky Sur-
vey (NVSS) and future surveys with the Australian Square Kilometer Array
Pathfinder\textsuperscript{5} or the Allen Telescope Array\textsuperscript{6}.

In between this extreme case of 50-s broadening and the reported pulse
width of $\sim 5 \text{ ms}$ is a substantial search volume in which more distant sources
could have produced detectable events. Broadening from sources at redshifts
greater than one is increased by the larger electron density but is lessened by
the frequency redshift, so the net scaling of the pulse broadening with redshift
depends on how the scattering material is distributed along the line of sight.

\textsuperscript{5}http://www.atnf.csiro.au/projects/askap
\textsuperscript{6}http://ral.berkeley.edu/ata
3.10 Conclusions

We have examined the current state of knowledge about various classes of intermittent radio-loud neutron stars, summarized selection effects that may affect the classification of intermittent sources, and presented our data processing methods and results from single pulse searches performed on PALFA survey data. One of our single-pulse discoveries is a relatively persistent emitter that, like many other pulsars, shows a broad amplitude distribution, from which a few bright pulses were detected. Two sources were detected as normal periodic emitters when observed at a lower frequency (PSR J0627+16) and with the more sensitive central beam of the ALFA receiver (PSR J1919+17). Four objects were most likely not detected via periodicity search because of their long periods ($P > 2$ s) compared to the PALFA observation time of $134 - 268$ s, and one intermittent object (PSR J1928+15) was discovered by detecting three pulses emitted on successive rotations but it was not detected again despite multiple reobservations.

Most of the PALFA sources that were discovered solely through the single-pulse analysis have subsequently been found to be sporadic but with measurable and consistent rates of detectable pulses. The Parkes survey had similar results. However, two sources (the Parkes source PSR J1839−01 and the PALFA source PSR J1928+15) are much more irregular even though an underlying periodicity has been found in each case. We therefore distinguish between cases where the apparent sporadic behavior is due to a detection threshold that selects only the strongest pulses from a broad distribution (e.g. Weltevrede et al. 2006) and those where emission is truly intermittent.
A major issue is related to the question, if we see transients from a given sky direction only once, how can we figure out what phenomena produce them. We must archive radio survey data and characterize the wide variety of detected radio transients outside the framework of rotating neutron stars if necessary. Archived data may yield new discoveries if reprocessed with improved search algorithms and a database of transient signals would be an invaluable reference as theoretical understanding of energetic radio events and prediction of their signatures improves. The PALFA survey is taking steps in both directions: raw data are stored in a tape archive and data processing products are indexed in a database at the Cornell Center for Advanced Computing and currently work is under way to make them publicly available via a web portal.\footnote{http://arecibo.tc.cornell.edu}
CHAPTER 4
HIGH-FREQUENCY GALACTIC CENTER PULSAR SEARCHES

We present the results of two pulsar surveys performed at 9 GHz with the Green Bank telescope. In 2004 we searched a grid of pointings centered on Sgr A*, and in 2006 we targeted individual sources from the VLA survey of Lazio & Cordes (2008) that exhibit extended structure similar to pulsar wind nebulae or steep spectra characteristic of pulsars. Also in 2006, we performed a deep search on Sgr A* itself, integrating for 6.5 h at 5 and 9 GHz. No periodic signals or single pulses were found in either survey. We calculate flux density limits on any such signals in our search fields, summarize hardware and software improvements made since the completion of the surveys, and outline directions for future pulsar search projects in the vicinity of Sgr A*.

4.1 Introduction

Of the ~ 1800 pulsars presently known, only 18 are within 2° of the Galactic center, and only five are within 1°, including the three pulsars we discovered at 2 GHz (Deneva, Cordes & Lazio, 2009). Ghez et al. (2003) present evidence that the cluster around Sgr A* consists mainly of early-type stars. Considering their short lifetimes (~ $10^7$ yr), their presence means that either star formation in the region is ongoing, or there has been a recent starburst in the Galactic center. Since stars with masses of 10 – 20 $M_\odot$ are neutron star (NS) progenitors, the presence of young massive stars near Sgr A* suggests that there must exist a numerous NS population as well. This leads to the conclusion that a sizable fraction of the NSs would be active radio pulsars, and Pfahl & Loeb (2004) estimate that there are ~ 100 – 1000 active pulsars orbiting around Sgr A* with
periods of less than 100 years. The discovery of any pulsars near Sgr A* would be a gold mine for diverse future studies of this elusive region.

Pfahl & Loeb (2004) argue that a population of stellar-mass black holes (BHs) exists in the Galactic center due to tidally induced migration, e.g. \( \sim 100 \) black holes 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 in the Galactic center may be as high as \( \sim 10^7 \) pc\(^{-3} \), which by analogy with globular clusters would make the region rich in pulsar binaries and millisecond pulsars. Combined with the proposed stellar-mass BH population, this makes the Galactic center a prime target for discovering NS-BH binaries.

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 BH, and even estimating its spin. Combined with the effects of the inferred population of stellar-mass BHs, these measurements would allow mapping of the gravitational potential in the Galactic center.

The spatial as well as period and age distributions of pulsars near Sgr A*, along with 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.

For pulsars in tight orbits around Sgr A*, observations over a few months or
years will reveal a time variation of the dispersion measure (DM) that would be indicative of the properties of the ionized gas along the line of sight to the pulsar. There have been estimates of the shape of the scattering screen between us and the Galactic center (Cordes & Lazio, 1997) as a thin screen, or a cylindrically or spherically symmetric shell around Sgr A*. In reality, its shape is unknown and any pulsars discovered in the region would help constrain it. Observations of pulsars from within or behind the screen would also provide a valuable addition to the NE2001 code (Cordes & Lazio, 2003) that models the distribution of ionized gas in the Galaxy by allowing us to fine-tune its performance for the region around Sgr A*.

Gas velocities in the Galactic center are high ($\geq 100$ km/s), so even if a pulsar’s orbital motion is not very fast, there may be observable changes in its DM over the course of a few months due to the turbulent motion of gas along the line of sight. This can be used to study the structure of ionized plasma near Sgr A* on scales as small as a few AU.

The difficulties in detecting pulsars in the Sgr A* region stem from the severe pulse broadening due to scattering by ionized interstellar gas. At frequencies traditionally used for pulsar searches ($\leq 1.4$ GHz), the pulse smearing due to scattering is prohibitively large for searching. Cordes & Lazio (2003) predict a broadening of $\sim 1200$ s at 1.4 GHz for pulsars located at the position of Sgr A*, which renders detecting even long-period pulsars impossible at this frequency. Because of the steep dependence of scattering broadening on frequency, $\tau_s \propto \nu^{-4.4}$, searching at frequencies $\geq 5$ GHz can mitigate this effect. Pulsars have power-law spectra so their flux declines with increasing frequency ($S_\nu \propto \nu^{-\alpha}$), but a sizable fraction of known pulsars exhibit relatively flat spectra. For ex-
ample, of 276 pulsars with derived spectral indices in the ATNF catalogue, 75 have a spectral index \( \alpha > -1.4 \) and 38 have \( \alpha > -1 \). Therefore, the corresponding subset of GC pulsars would be more readily detectable. With this in mind, we embarked on a comprehensive pulsar search of the region around Sgr A* at 9 GHz with the Green Bank telescope.

### 4.2 Observations and Data Reduction

Our observations in 2004 and 2006 were carried out using a center frequency of 9 GHz, except for a single 5 GHz observation of Sgr A* in 2006. All observations used the SPIGOT backend with a bandwidth of 800 MHz divided into 1024 channels. Two polarization channels were sampled every 82 \( \mu s \) and summed before being recorded to disk. The first portion of our high-frequency search for pulsars in the Galactic center was carried out in 2004, when we focused on the Sgr A* stellar cluster. Figure 4.1 shows our 20 grid pointings superimposed on a 0.33 GHz image of the Galactic center, and Table 4.1 lists the pointing positions. The observation time for each grid pointing was 1.5 h.

Also in 2004 we observed six sources from the 1.4 GHz 2LC VLA catalog of Lazio & Cordes (2008). Some of the sources in the 2LC catalog were also detected at 0.37 GHz by Douglas et al. (1996) and/or 5 GHz by Zoonematkermani et al. (1990), allowing their spectral indices to be estimated. We selected our 2LC targets based on their proximity to Sgr A* (\( \lesssim 1^\circ \)), and at least one of (1) a steep spectrum, which is characteristic of radio pulsars, and (2) extended structure reminiscent of a pulsar wind nebula. We also observed two steep-spectrum sources from the TXS catalog of Douglas et al. (1996) not detected by the 2LC
survey. Our last non-grid target from 2004 was the supernova remnant SNR0.9-0.1. Table 4.2 lists individual sources near the Galactic center targeted in our 2004 and 2006 surveys, and Figure 4.2 shows their locations superimposed on the 0.33 GHz image of LaRosa et al. (2000).

In 2006 we performed a deep search on Sgr A*, integrating for 6.5 h at both 5 and 9 GHz in order to maximize the chance of finding weak pulsars and pulsars with steep spectra. The observations at two different frequencies also allow immediate confirmation and spectral index estimation. In addition, we observed 11 2LC sources and two extended structure sources identified as pulsar wind nebulae. Wang et al. (2005) report the discovery of the X-ray pulsar wind nebula G359.95-0.04, similar in properties to the Mouse pulsar wind nebula, which is powered by PSR J1747-2958. Park et al. (2005) propose the presence of a high-velocity neutron star (the Cannonball) associated with the supernova remnant Sgr A* East. Both objects have a “cometary” shape, with a bright head and an extended tail, a morphology exhibited by high-velocity pulsars whose wind impacts the interstellar medium and creates a bow shock. The spectral properties of G359.95-0.04 and the Cannonball are also well matched by pulsar wind nebula models. Since G359.95-0.04 is within the 9 GHz beam radius of Sgr A*, we performed two separate pointings on the Cannonball only.

Full-resolution data at 5 and 9 GHz were dedispersed with 21 evenly spaced trial DM values in the range $50 - 1050$ pc cm$^{-3}$, and three higher trial DMs: 1550, 2050, and 2550 pc cm$^{-3}$. In the worst case, a pulsar’s actual DM falls midway between successive trial DM values and the dispersion smearing after dedispersing is

$$\Delta t_{\text{DM}} = \frac{8.3 \mu s \, \delta DM \, \Delta v_{\text{MHz}}}{f_{\text{GHz}}^3},$$

(4.1)
Figure 4.1: Search pointings (circles) at 9 GHz overlaid on a 0.33 GHz image of the Galactic center by LaRosa et al. (2000). Diamonds show the positions of PSRs J1746–2850I, J1746–2850II, and J1745–2910 discovered at 2 GHz by Deneva, Cordes & Lazio (2009) with the GBT. Triangles show PSRs J1746–2856 and J1745–2912 found by Johnston et al. (2006) at 3.1 GHz with the Parkes telescope. Squares denote the Arches and Quintuplet clusters.
Figure 4.2: Individual search targets at 9 GHz overlaid on a 0.33 GHz image of the Galactic center by LaRosa et al. (2000). Open circles denote 2LC sources (Lazio & Cordes, 2008), crosses denote TXS sources (Douglas et al., 1996), and a star shows a compact object in SNR0.9-0.1 that has since been associated with a pulsar wind nebula (Camilo et al., 2009). White crosses show the Cannonball and G359.95–0.04, two objects whose properties suggest they may be pulsar wind nebulae (Wang et al. 2005, Park et al. 2005). Filled symbols as in Fig. 4.1.
Table 4.1: Search grid pointings observed at 9 GHz in 2004.

<table>
<thead>
<tr>
<th>Pointing</th>
<th>RA</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGR-0-00 (Sgr A*)</td>
<td>17:45:39.95</td>
<td>-29:00:28.20</td>
</tr>
<tr>
<td>SGR-1-01</td>
<td>17:45:43.14</td>
<td>-29:00:28.20</td>
</tr>
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<td>SGR-1-02</td>
<td>17:45:41.54</td>
<td>-28:59:46.76</td>
</tr>
<tr>
<td>SGR-1-03</td>
<td>17:45:38.35</td>
<td>-28:59:46.76</td>
</tr>
<tr>
<td>SGR-1-04</td>
<td>17:45:36.76</td>
<td>-29:00:28.20</td>
</tr>
<tr>
<td>SGR-1-05</td>
<td>17:45:38.35</td>
<td>-29:01:09.64</td>
</tr>
<tr>
<td>SGR-1-06</td>
<td>17:45:41.54</td>
<td>-29:01:09.64</td>
</tr>
<tr>
<td>SGR-2-01</td>
<td>17:45:46.33</td>
<td>-29:00:28.20</td>
</tr>
<tr>
<td>SGR-2-02</td>
<td>17:45:44.73</td>
<td>-28:59:46.76</td>
</tr>
<tr>
<td>SGR-2-03</td>
<td>17:45:43.14</td>
<td>-28:59:05.32</td>
</tr>
<tr>
<td>SGR-2-04</td>
<td>17:45:39.95</td>
<td>-28:59:05.32</td>
</tr>
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<td>SGR-2-05</td>
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<td>-28:59:05.32</td>
</tr>
<tr>
<td>SGR-2-06</td>
<td>17:45:35.16</td>
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</tr>
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<td>SGR-2-07</td>
<td>17:45:33.57</td>
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<td>17:45:35.16</td>
<td>-29:01:09.64</td>
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<td>SGR-2-09</td>
<td>17:45:36.76</td>
<td>-29:01:51.08</td>
</tr>
<tr>
<td>SGR-2-10</td>
<td>17:45:39.95</td>
<td>-29:01:51.08</td>
</tr>
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<td>SGR-2-11</td>
<td>17:45:43.14</td>
<td>-29:01:51.08</td>
</tr>
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<td>SGR-2-12</td>
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<tr>
<td>SGR-3-02</td>
<td>17:45:47.92</td>
<td>-28:59:46.76</td>
</tr>
</tbody>
</table>

where $\delta DM$ is the difference between the pulsar DM and the closest trial DM, $\Delta \nu_{\text{MHz}}$ is the total bandwidth, and $f_{\text{GHz}}$ is the center observing frequency. For the dense part of the trial DM list, $\delta DM_{\text{max}} = 25 \text{ pc cm}^{-3}$, and $\Delta t_{\text{DM, max}} = 1.3 \text{ ms}$ and 0.2 ms at 5 and 9 GHz, respectively. For the sparsely spaced trial DMs, $\delta DM_{\text{max}} = 250 \text{ pc cm}^{-3}$, and $\Delta t_{\text{DM, max}} = 13 \text{ ms}$ and 2 ms at 5 and 9 GHz, respectively. In order to take advantage of the fact that pulsars tend to have steep spectra and therefore any millisecond pulsars in the search region are likely to be brighter at 5 than at 9 GHz, the sole 6.5 h observation at 5 GHz was smoothed by 0.65 ms and dedispersed with 60 evenly spaced trial DMs in the range 50–3000 pc cm$^{-3}$. For the smoothed 5 GHz data, $\delta DM_{\text{max}} = 25 \text{ pc cm}^{-3}$ and $\Delta t_{\text{DM, max}} = 1.3 \text{ ms}$.
Table 4.2: Sources observed in 2004 and 2006. Unless otherwise stated, the observing frequency is 9 GHz.

<table>
<thead>
<tr>
<th>Source</th>
<th>RA (hh:mm:ss)</th>
<th>DEC (dd:mm:ss)</th>
<th>$T_{\text{obs}}$ (h)</th>
<th>$S_{\text{FFT, max}}$ ($\mu$Jy)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sgr A*</td>
<td>17:45:39.9</td>
<td>-29:00:28</td>
<td>6.5</td>
<td>5</td>
<td>2006</td>
</tr>
<tr>
<td>J174545.5-285829</td>
<td>17:45:45.5</td>
<td>-28:58:29</td>
<td>2</td>
<td>8</td>
<td>2006</td>
</tr>
<tr>
<td>2LC0.005-0.89</td>
<td>17:49:07.16</td>
<td>-29:23:34.90</td>
<td>1.5</td>
<td>10</td>
<td>2004</td>
</tr>
<tr>
<td>2LC0.098-0.051</td>
<td>17:46:02.1</td>
<td>-28:52:44</td>
<td>1</td>
<td>12</td>
<td>2006</td>
</tr>
<tr>
<td>2LC0.305+0.394</td>
<td>17:44:48.8</td>
<td>-28:28:12</td>
<td>1</td>
<td>12</td>
<td>2006</td>
</tr>
<tr>
<td>2LC0.426-0.058</td>
<td>17:46:51.3</td>
<td>-28:36:10</td>
<td>1.5</td>
<td>10</td>
<td>2004</td>
</tr>
<tr>
<td>2LC0.440+0.587</td>
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<td>-28:15:15</td>
<td>1</td>
<td>12</td>
<td>2006</td>
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<td>-28:34:48</td>
<td>1</td>
<td>12</td>
<td>2006</td>
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<tr>
<td>2LC0.520+0.040</td>
<td>17:46:41.8</td>
<td>-28:28:18</td>
<td>1</td>
<td>12</td>
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<tr>
<td>2LC358.600-0.060</td>
<td>17:42:28.0</td>
<td>-30:09:34</td>
<td>1</td>
<td>12</td>
<td>2006</td>
</tr>
<tr>
<td>2LC358.917+0.072</td>
<td>17:42:44.1</td>
<td>-29:49:15</td>
<td>1</td>
<td>12</td>
<td>2006</td>
</tr>
<tr>
<td>2LC359.011-0.001</td>
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<td>-29:46:47</td>
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<tr>
<td>2LC359.073+0.148</td>
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<td>2LC359.3+0.5</td>
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<td>12</td>
<td>2004</td>
</tr>
<tr>
<td>TXS1741-290</td>
<td>17:44:25.96</td>
<td>-29:01:42.60</td>
<td>1.5</td>
<td>10</td>
<td>2004</td>
</tr>
<tr>
<td>SNR0.9+0.1</td>
<td>17:47:22.20</td>
<td>-28:12:06.00</td>
<td>0.5</td>
<td>17</td>
<td>2004</td>
</tr>
</tbody>
</table>

Dedispersed time series were searched for periodic signals from solitary pulsars using a conventional FFT search (Section 2.2.3) and binary pulsars using an acceleration search (Section 2.2.4). The time series were also searched for individual pulses using the friends-of-friends and matched filtering methods described in Section 2.2.5. Figures 4.3 - 4.5 are typical diagnostic output of the FFT search, showing the dedispersed time series, the power spectrum, and three zoom levels of the low-frequency part of the spectrum. In the time series panels
of the three figures, a sharp drop in intensity at $t \approx 5400$ s is due to a strong blast of RFI causing the spectrometer to temporarily saturate. Baseline fluctuations towards the end of the observation are due to strong intermittent RFI (Appendix A). A spike in the spectrum corresponding to the 60 Hz electric mains is prominent in Figure 4.3, which shows output for trial $DM = 100$ pc cm$^{-3}$. In Figure 4.4 ($DM = 500$ pc cm$^{-3}$), the intensity of the spike has diminished, and in Figure 4.5 ($DM = 2000$ pc cm$^{-3}$) it is completely absent. Since terrestrial signals have $DM = 0$ pc cm$^{-3}$, dedispersing with higher DMs eventually causes them to be smeared out below the level of rms noise in the Fourier domain.

Figure 4.6 shows single pulse search output for the 6.5 h observation of Sgr A* at 5 GHz from 2006. Useful even statistics for the entire observation are plotted on top: number of events vs. S/N and trial DM channel, and DM channel vs. S/N and the actual trial DM value. Because of the length of the observation and the large number of events, the bottom panel shows events with $S/N > 5$ vs. DM channel and time only for the first 500 s of the observation, with larger circles denoting brighter events. DM channel vs. time plots for the entire observation are in Appendix A. In the panel on top left, the almost vertical line denotes the expected distribution of events due to Gaussian noise. The distribution of events in this observation does not conform to it because of bright RFI in the second half of the pointing (Appendix A). Figure 4.7 and Appendix B show the same type of output for the 6.5 h observation of Sgr A* at 9 GHz. A bright dispersed pulse or a set of weaker pulses peaking at the same trial DM have a characteristic appearance in the plots of number of pulses vs. DM channel and DM channel vs. S/N (see Figure 3.2).
Figure 4.3: Time series and power spectrum of a 6.5 hour 5 GHz pointing on Sgr A* after dedispersing with $DM = 100 \text{ pc cm}^{-3}$. The top panel shows the dedispersed time series in arbitrary units vs. time. Baseline fluctuations towards the end of the observation are due to strong intermittent RFI (Appendix A). The second panel from top shows the complete power spectrum, and the lowest three panels show three zoom levels on lower-frequency parts of the spectrum. A spike at 60 Hz is due to RFI from the electrical mains.
Figure 4.4: Time series and power spectrum of a 6.5 hour 5 GHz pointing on Sgr A* after dedispersing with $DM = 500$ pc cm$^{-3}$. The top panel shows the dedispersed time series in arbitrary units vs. time. Baseline fluctuations towards the end of the observation are due to strong intermittent RFI (Appendix A). The second panel from top shows the complete power spectrum, and the lowest three panels show three zoom levels on lower-frequency parts of the spectrum. A spike at 60 Hz is due to RFI from the electrical mains.
Figure 4.5: Time series and power spectrum of a 6.5 hour 5 GHz pointing on Sgr A* after dedispersing with $DM = 2000 \text{ pc cm}^{-3}$. The top panel shows the dedispersed time series in arbitrary units vs. time. Baseline fluctuations towards the end of the observation are due to strong intermittent RFI (Appendix A). The second panel from top shows the complete power spectrum, and the lowest three panels show three zoom levels on lower-frequency parts of the spectrum.
Figure 4.6: Single pulse search output for a 6.5 h observation of Sgr A* at 5 GHz. The four panels on top show (left to right) statistics for the entire observation: number of events vs. S/N and trial DM channel, and DM channel vs. S/N and the actual trial DM value. A hump at low DM in the N vs. DM channel histogram is due to strong RFI towards the end of the observation. The bottom panel shows events with S/N > 5 vs. DM channel and time for the first 500 s of the observation, with larger circles denoting brighter events. Vertically aligned events near the start of the observation may be due to a dispersed pulse or weak swept-frequency RFI. DM channel vs. time plots for the entire observation are in Appendix A.
Figure 4.7: Single pulse search output for a 6.5 h observation of Sgr A* at 9 GHz. The four panels on top show (left to right) statistics for the entire observation: number of events vs. \( S/N \) and trial DM channel, and DM channel vs. \( S/N \) and the actual trial DM value. The bottom panel shows events with \( S/N > 5 \) vs. DM channel and time for the first 500 s of the observation, with larger circles denoting brighter events. At \( t \sim 250 \) s frequent RFI pulses detected at all trial DMs begin to overwhelm the search results. DM channel vs. time plots for the entire observation are in Appendix B.

4.3 Results

4.3.1 Flux Density Limits

We did not detect any periodic signals or single pulses in our search pointings near the Galactic center at 5 and 9 GHz. We calculate upper limits on the flux
density of periodic signals using the radiometer equation

\[ S_{\text{FFT, max}} = \frac{m T_{\text{sys}}}{\eta G \sqrt{N_h N_{\text{pol}} \Delta \nu T_{\text{obs}}}}. \]  

(4.2)

where \( T_{\text{sys}} \) is the system temperature, \( G \) is the telescope gain, \( N_h = 16 \) is the maximum number of harmonics summed in a periodicity search as described in Section 2.2.3, \( N_{\text{pol}} = 2 \) is the number of polarization channels summed, \( \Delta \nu \) is the bandwidth, and \( T_{\text{obs}} \) is the observation time. The threshold applied is \( m \sigma \), and \( m = 6 \) for our FFT search. At 5 GHz, \( G = 2 \) K/Jy and \( T_{\text{sys}} = 19 \) K, and at 9 GHz, \( G = 1.8 \) K/Jy and \( T_{\text{sys}} = 27 \) K. We estimate that the sky background temperature \( T_{\text{sky}} \ll 1 \) K at the two frequencies in the direction of the Galactic center by scaling from the numbers of Reich & Reich (1988), who find \( T_{\text{sky}} = 12 \) K at 1.4 GHz and \( T_{\text{sky}} \propto \nu^{-2.5} \). For the 9 GHz grid search pointings listed in Table 4.1, \( T_{\text{obs}} = 1.5 \) h, giving an upper limit estimate on periodic signals of \( S_{\text{FFT}} \lesssim 10 \) \( \mu \)Jy. The periodic flux density upper limits for individual targeted sources near the Galactic center are listed in Table 4.2.

For single pulses, the effective observation time is equal to the pulse width, and we can express the upper limit on the single pulse flux density as

\[ S_{\text{SP, max}} = \frac{m T_{\text{sys}}}{\eta G \sqrt{N_{\text{pol}} \Delta \nu W}}. \]  

(4.3)

We want to estimate whether we would have detected any of the intermittent sources discovered by the Parkes Multibeam survey (McLaughlin et al., 2006) or the PALFA survey (Chapter 3) if these sources were at the distance of Sgr A* and affected by the heavy scattering in the region. In order to do that, we use the sources’ reported pulse widths, peak flux densities, and distance estimates based on the NE2001 model of ionized gas in the Galaxy (Cordes & Lazio, 2003). All intermittent sources were discovered at 1.4 GHz. Assuming the average pulsar spectral index \( \alpha = -1.5 \) and a power-law spectrum \( S \propto \nu^\alpha \), we scale
their flux densities to 5 and 9 GHz. From the NE2001 model we obtain the scattering broadening at \( D = 8.5 \) kpc in the direction of Sgr A* for our observing frequencies, \( \tau_{sc, \nu} = 1.94 \) s and \( \tau_{sc, 9 \, \text{GHz}} = 0.147 \) s.

The intrinsic pulse width for pulsars generally decreases slowly with increasing radio frequency (\( W_{\text{int}} \propto \nu^{-x} \), where \( x \approx 0.3 \)) as high-frequency emission is generated deeper in the emission cone above the pulsar’s magnetic pole where the emission region is narrower. Ruderman & Sutherland (1975) predict that the pulse profile component separation \( \Delta \theta \propto \nu^{-0.33} \) based on a vacuum gap model of the pulsar emission region. Thorsett (1991) finds that the component separation asymptotically approaches a constant at high frequencies (\( \gtrsim 1 \) GHz) and the model \( \Delta \theta = A \nu^\alpha + \theta_{\text{min}} \) fits well the observed variation of \( \Delta \theta \) with frequency but \( \alpha \) varies widely between different pulsars. In any case, the intrinsic pulse width variation with frequency between 1.5 and 9 GHz is negligible compared to the scattering broadening expected for sources near Sgr A* and we ignore it in the following analysis. We can also ignore the effect on the observed pulse width by the sampling time used \( \Delta t_{\text{samp}} \) and dispersion smearing across a channel width \( \Delta f_{\text{DM}} \) because both quantities are \( << \tau_{sc} \). Therefore, for the observed pulse width we have

\[
W_{\text{obs}} = \sqrt{W_{\text{int}}^2 + \tau_{sc}^2 + \Delta t_{\text{DM}}^2 + \Delta t_{\text{samp}}^2} \approx \sqrt{W_{\text{int}}^2 + \tau_{sc}^2}, \tag{4.4}
\]

Ignoring the variation of the intrinsic pulse width \( W_{\text{int}} \) with frequency, we adopt the reported 1.4 GHz pulse widths \( W_{1.4 \, \text{GHz}} = W_{\text{int}} \). Since pulse broadening preserves total pulse area while decreasing the pulse amplitude, taking into account scattering we have for the peak flux density

\[
S_{pk, \nu, \text{sc}} = \frac{S_{pk, \nu} W_{\text{int}}}{W_{\text{obs}}}, \tag{4.5}
\]

where \( S_{pk, \nu} = S_{pk, 1.4 \, \text{GHz}} \left( \nu/1.4 \right)^\alpha \).
Figure 4.8 shows $S_{\text{SP, max}}$ for various widths $W$ for data obtained with the SPIGOT and GUPPI backends. Also shown are $S_{\text{pk, } \nu}$ for the Parkes and PALFA intermittent sources at 5 and 9 GHz if scattering is ignored or taken into account. If scattering is ignored, at 9 GHz, one source would be detectable in a GUPPI, but not SPIGOT, observation, while at 5 GHz several sources would be detectable regardless of which backend is used. However, scattering renders all intermittent sources undetectable at either 5 or 9 GHz.

### 4.3.2 The Supernova Remnant G0.9+0.1

The supernova remnant G0.9+0.1 was one of the sources targeted in our 9 GHz search in 2006. Based on the non-detection of any periodic signals, we calculate that a periodic source in our G0.9+0.1 search field has a flux density $S_{\text{9 GHz}} \leq 17 \mu\text{Jy}$. Camilo et al. (2009) report the discovery of the young pulsar PSR J1747–2809 ($P = 52$ ms, $DM = 1133$ pc cm$^{-3}$) in G0.9+0.1. The pulsar was found at 2 GHz with the GBT and its period-averaged flux density is $S_{\text{2 GHz}} = 40 \mu\text{Jy}$. Assuming a power-law spectrum and the average pulsar spectral index of -1.5, PSR J1747–2809 would have a flux density of only 4 $\mu$Jy at 9 GHz, significantly below the detection threshold for our 0.5 h observation of G0.9+0.1. An observation time of $\sim 9$ h would be necessary in order to detect the pulsar at 9 GHz with the GBT.
Figure 4.8: Peak flux density vs. pulse width at 9 GHz (top) and 5 GHz (bottom) of the eleven Parkes RRATs (McLaughlin et al., 2006) and the seven PALFA intermittent sources (Chapter 3) if they were placed 8.5 kpc away at the Galactic center and scattering is ignored (circles) or taken into account (triangles). A solid line shows the single pulse peak flux density upper limit vs. pulse width for our SPIGOT observations. A dashed line shows what the upper limit would be if the newer GUPPI backend is used.
4.3.3 The Galactic Center Radio Arc

The Galactic center Radio Arc is an extended linear structure of ionized gas perpendicular to the Galactic plane ~ 15′ from Sgr A* that contains non-thermal filaments. Serabyn & Morris (1994) suggest that the filaments are formed when particles from nearby molecular clouds are accelerated to relativistic speeds along lines of constant magnetic field. In this region (at least in projection), within a radius of only 5′ are the Arches and Quintuplet clusters, the young pulsar J1746–2850I, the pulsar with the highest known dispersion measure J1746–2850II (Chapter 5), and the steep-spectrum radio source 2LC0.098-0.051 that we searched for pulsations at 9 GHz (Figure 4.2). At one end of the Radio Arc, ~ 12′ from this concentration of objects is the pulsar J1746–2856 (Johnston et al., 2006).

While we have not systematically searched the Radio Arc for pulsars, part of it was included in our 2 GHz GBT search on 2007, resulting in the discovery of J1746–2850I and J1746–2850II. The Arches and Quintuplet clusters both contain young massive stars, which are neutron star progenitors. In addition, the presence of three known pulsars and one steep-spectrum candidate in the Radio Arc near the clusters compared with the scarcity of either known pulsars or pulsar candidates in the vicinity of Sgr A* indicates that the Radio Arc region warrants a deeper pulsar search in the future.

4.3.4 Data Processing Issues

Several problems affected data quality during the 2004 grid search at 9 GHz. At the time of the observations, the SPIGOT backend was still under testing.
and occasionally unstable. Of our total of 72 allocated hours in 2004, 18\% were lost to telescope and SPIGOT technical problems. On processing the acquired data, in 5 search pointings we found abrupt power fluctuations across the whole band (Fig. 4.9) which rendered parts of our data unusable. The fluctuations may be due to SPIGOT malfunction, or clipping or 16-bit rollover of the lags caused by drifting of the spectrometer levels. An input level “holding” function implemented since prevents the latter and we did not see the same wide-band power fluctuations in our 2006 data. Our single pulse search code also detected long-period intermittent pulsed RFI in the majority of the 2004 pointings. The high S/N ($\geq 10$, compared to typical S/N thresholds of $3.5 - 5$ used in single pulse searches) and wide temporal extent of the RFI made giant pulse searching difficult.

During six search pointings in 2004, bad weather conditions made detecting even bright known pulsars difficult (Fig. 4.10), likely because of pointing and focus corrections errors. A set of software tools accessed through the Astronomer’s Integrated Desktop (ASTRID) has been developed since 2006 to facilitate observations, including calculating and applying pointing and focus corrections robustly and automatically.

In 2009, a polyphase filterbank backend, the Green Bank Ultimate Pulsar Processing Instrument (GUPPI), became available for use with the GBT. For equal telescope and observation parameters, a 3-level correlator like the SPIGOT has rms noise higher by $1/\eta = 25\%$ compared to a filterbank like GUPPI ($\eta \approx 0.8$ is a quantization efficiency factor). In addition, since dynamic spectra are obtained from autocorrelation functions via a DFT, bright narrow-band RFI can exhibit sidelobe “ringing” and contaminate a wider range of frequency chan-
Figure 4.9: Dynamic spectrum of a Galactic Center search observation from 1 May 2004 with wide-band power jumps. The top panel shows the average bandpass shape, excluding the time indices for the power jumps. The right side panel shows variation in the scale factor, which is a measure of the total power. Channels when data is taken with a correlator, making it harder to excise during data processing.
Figure 4.10: Observations of the bright pulsar B1933+16 at 9 GHz taken in bad (left) and good (right) weather. Greyscale panels show intensity in folded sub-integrations, with an average pulse profile plotted on top (the horizontal axis extends over 2 periods). Even though the observation time is twice as long in the first observation, the pulsar is not detected.

4.4 Conclusions and Future Work

At 9 GHz, we have searched for pulsars a grid of 20 pointings within a radius of 3.5′ of Sgr A*, 15 steep-spectrum sources from the VLA catalog of Lazio & Cordes (2008), two steep-spectrum sources from the TXS catalog of Douglas et al. (1996), two candidate pulsar wind nebulae, and the supernova remnant G0.9+0.1. In addition, we performed deep searches on Sgr A* itself at 5 and 9 GHz for the maximum tracking time of the GBT for the Galactic center, 6.5 h,
at each frequency. In the absence of any detections of periodic signals or individual dispersed pulses, we derive flux density upper limits for both types of signals in our search fields. Technical problems and bad weather adversely affected the chance of detecting pulsars in a significant fraction of our 9 GHz pointings. Short observation times (~ 1 h) may cause pulsars with steep spectra or weak pulsars with average spectra to be missed. An example of the latter is our 2006 non-detection of the weak young pulsar in the supernova remnant G0.9+0.1, which Camilo et al. (2009) discovered in a deep search at 2 GHz.

On the single pulse front, we find that the severe scattering at Sgr A* expected based on the NE2001 model of ionized gas in the Galaxy would make any of the known RRATs undetectable at 5 – 9 GHz if they were placed at the Galactic center. However, even for a very steep spectrum and severe scattering broadening, giant pulses from young pulsars like the Crab would be detectable.

The presence of many young massive stars in the central Sgr A* cluster as well as the Arches and Quintuplet clusters indicates that neutron star progenitors abound near the Galactic center. This in turn leads to the conclusion that a sizable neutron star population exists as well, including young, Crab-like pulsars whose bright giant pulses would be detectable through the dense scattering region surrounding Sgr A*. Another population that would be favorably selected is young pulsars with flat spectra resembling those of magnetars. Indeed, one such object (PSR J1746−2850I) was found ~ 11′ from Sgr A*, near the Arches and Quintuplet clusters (Chapter 5). This pulsar, along with two other high-DM pulsars (PSR J1746−2850II and PSR J1746−2856) and the steep-spectrum radio source 2LC0.098-0.051, resides in the Radio Arc. Compared to the relative sparsity of known pulsars and pulsar candidates elsewhere near Sgr A* this points to the Radio Arc as a region that may be a good target for a future pulsar sur-
vey. We are making the first step in that direction via the ongoing deep pulsar searches at 2 and 5 GHz of the Arches and Quintuplet clusters, which are also in the Radio Arc. The fact that all five known pulsars within 1° of Sgr A* were discovered at 2 – 3 GHz may indicate that steep pulsar spectra and/or insufficient sky coverage because of small beam size are a significant factor contributing to the absence of discoveries at higher frequencies. Therefore, where pulsar candidates have been identified from imaging surveys like the 2LC survey of Lazio & Cordes (2008), our next step is to search deeper and at a lower frequency (2 GHz). 2LC and TXS pulsar candidates that are $\gtrsim 15'$ away from the central Sgr A* cluster are unlikely to suffer from the severe scattering that makes observing frequencies of $\gtrsim 5$ GHz necessary when looking directly at the Galactic center.
CHAPTER 5
DISCOVERY OF THREE PULSARS FROM A GALACTIC CENTER
PULSAR POPULATION

We report the discovery of three pulsars whose large dispersion measures and angular proximity to Sgr A* indicate the existence of a Galactic center population of neutron stars. The relatively long periods (0.98 to 1.48 s) most likely reflect strong selection against short-period pulsars from radio-wave scattering at the observation frequency of 2 GHz used in our survey with the Green Bank Telescope. One object (PSR J1746-2850I) has a characteristic spindown age of only 13 kyr along with a high surface magnetic field $\sim 4 \times 10^{13}$ G. It and a second object found in the same telescope pointing, PSR J1746-2850II (which has the highest known dispersion measure among pulsars), may have originated from recent star formation in the Arches or Quintuplet clusters given their angular locations. Along with a third object, PSR J1745-2910, and two similar high-dispersion, long-period pulsars reported by Johnston et al. (2006), the five objects found so far are 10 to 15 arc min from Sgr A*, consistent with there being a large pulsar population in the Galactic center, most of whose members are undetectable in relatively low-frequency surveys because of pulse broadening from the same scattering volume that angularly broadens Sgr A* and OH/IR masers.\(^1\)

\(^1\)This chapter was published in the Astrophysical Journal Letters as Deneva, Cordes & Lazio (2009)
5.1 Introduction

The scientific pay-offs from finding pulsars orbiting near Sgr A* are potentially very high and fall into three main categories. Measurements of relativistic effects through timing of pulsars in tight orbits around Sgr A* would provide methods for better constraining the mass of the central black hole and even estimating its spin (e.g. Laguna & Wolszczan 1997, Wex & Kopeikin 1999, Pfahl & Loeb 2004). Timing measurements will also characterize the distribution of dark matter near Sgr A* either in the form of a cluster of black holes and neutron stars or in a smoothly distributed volume containing dark-matter particles (Bertone & Merritt 2005, Weinberg et al. 2005). The spatial, age and period distributions of pulsars near Sgr A* will help describe the stellar population in the region and discriminate between hypotheses attempting to explain the presence of the central cluster of young massive stars: stellar collisions and mergers, migration, and a past episode of intensive star formation. Finally, using pulsars to probe the scattering region around Sgr A* will lead to refinement of electron density models for the inner Galaxy.

There are at least three stellar clusters in the Galactic center region containing massive stars, the progenitors of radio pulsars. Ghez et al. (2003) present evidence that the central cluster around Sgr A* includes early-type stars. Since stars with masses of about $8 \sim 20 M_\odot$ are neutron star (NS) progenitors, it is plausible that a considerable NS population exists as well. This leads to the conclusion that a sizable fraction of the NSs would be active radio pulsars. Pfahl & Loeb (2004) estimate that there are $\sim 100 \sim 1000$ active pulsars orbiting Sgr A* with periods of less than 100 years. Cordes & Lazio (1997) show that some of these pulsars will be detectable at the distance of the Galactic center, even at the high
frequencies needed to mitigate pulse broadening from scattering.

Apart from the central star cluster around Sgr A*, the Arches and Quintuplet clusters are the densest stellar associations within 0.5 of the Galactic center. Both clusters are composed mainly of young massive stars whose supernova explosions will have produced neutron stars young enough to be active radio pulsars. Stolte et al. (2008) show that the radial distance from the Galactic center to the Arches cluster is $62 \pm 23$ pc if the cluster is in a circular orbit around Sgr A*, but its distance may be as large as 200 pc.

Of the nearly 2000 pulsars known up to now, only two are within 1 of Sgr A*: PSR J1746−2856 and PSR J1745−2912, which were discovered by Johnston et al. (2006) in a 3.1 GHz survey with the Parkes telescope and have dispersion measures (DMs) of 1168 and 1130 pc cm$^{-3}$, respectively. Johnston et al. (2006) also report the absence of detections by a 8.4 GHz Parkes survey, which indicates there are not many pulsars with flat enough spectra to be detected at high frequencies. The non-detections are also consistent with electron-density models that predict that scattering at frequencies up to $\sim 10$ GHz strongly affects the detectability of pulsars near Sgr A* (Cordes & Lazio, 1997).

As part of a larger program to probe the Galactic center pulsar population and ionized gas environment, we have surveyed the inner 0.5 around Sgr A* at 2 GHz with the Green Bank telescope. Pulse broadening due to scattering varies with frequency approximately as $\tau_s \propto \nu^{-4}$, so the broadening expected at 2 GHz is $\sim 5$ times larger than at 3.1 GHz. This effect is partially mitigated by the fact that most pulsars have moderate to steep spectra and are more easily detected at lower frequencies when scattering is not a factor.
Figure 5.1: The grid of 2 GHz survey pointings from 2007 overlaid on a 0.33 GHz image of the Galactic center (LaRosa et al., 2000). Circles correspond to the 5.8′ FWHM beam size of the Green Bank telescope at 2 GHz. Diamonds denote the positions of J1746–2850I, J1746–2850II, and J1745–2910, and triangles denote the positions of J1746–2856 and J1745–2912. Crosses show actual position uncertainties. For J1746–2850I, J1746–2850II, and J1746–2856 the position uncertainties are smaller than the marker size. Squares show the positions of the Arches and Quintuplet clusters.
5.2 Survey Parameters and Data Processing

The survey was carried out in September 2007 with the Green Bank telescope, using a center frequency of 1.95 GHz and the SPIGOT backend with a bandwidth of 800 MHz. The lower 200 MHz of the receiver band was excluded from the analysis due to the presence of severe radio frequency interference. The effective analyzed bandwidth was 600 MHz divided into 768 channels. Data were taken with a sampling time of 82 µs in two polarizations, which were summed before further processing. The grid of survey pointings around Sgr A* is shown in Fig. 5.1 overlaid on a 330 MHz image of the Galactic center region. We observed 37 grid pointings for one hour each, but data from 8 pointings were not usable due to technical issues and these pointings are omitted from the figure.

Data processing was performed at the Cornell Center for Advanced Computing (CAC) using the Cornell pulsar search code\(^2\) and the Presto package\(^3\). The full-resolution data were searched with 1245 evenly spaced trial DM values in the range 10 - 2000 pc cm\(^{-3}\), and 155 evenly spaced values in the range 2000 - 2500 pc cm\(^{-3}\). Data were also searched over 1000 values from 100 to 2100 pc cm\(^{-3}\) with time resolution of 0.65 ms and 300 values from 2100 to 3000 pc cm\(^{-3}\) with 1.3 ms resolution. A Fast Fourier Transform was performed on the resulting time series and the power spectrum was searched for periodic signals by summing up to 16 harmonics and applying a harmonic sum threshold of 6\(\sigma\).

Time series were also searched for individual dispersed pulses using two algorithms, one that applies simple templates (Cordes & McLaughlin 2003) and another that searches for clusters of related points (Cordes et al. 2004) using a

\(^2\)http://arecibo.tc.cornell.edu/PALFA/
\(^3\)http://www.cv.nrao.edu/~sransom/presto
friends-of-friends group-finding algorithm (see Fig. 1 in Huchra & Geller 1982; see Chapter 3 for detailed description of application to single pulse searching). The matched filtering approach smoothes each time series with rectangle functions of widths $2^n$ samples, where $n = 0 - 7$, and searches for events above a $5\sigma$ threshold. It is most sensitive to pulses whose widths are close to one of the boxcar filter widths, for a maximum width of 10 ms. The cluster algorithm identifies individual samples above a $3\sigma$ threshold and then combines contiguous points into events to which the larger $5\sigma$ threshold is applied.

5.3 Survey Results

Table 5.1 summarizes the properties of the three discovered pulsars. PSR J1746–2850I and PSR J1746–2850II were discovered in the same survey pointing and were confirmed with the Green Bank Telescope in June 2008; subsequent monthly timing observations at 2 GHz are ongoing. We observed both pulsars at 1.5 and 4.8 GHz with the dual goals of estimating their spectral indices and improving their position measurements. We also observed PSR J1946–2850I at 9 GHz in order to confirm that its relatively flat spectrum extends to higher frequencies. PSR J1745–2910 was discovered in February 2009 and will be timed starting in June 2009. Profiles of the three pulsars are shown in Figure 5.2.

We estimated the period-averaged flux density for each pulsar by scaling from signal-to-noise ratio of the folded pulse profile $(S/N)_{\text{prof}}$ using the calculated radiometer noise level for the sum of two polarization channels:

$$ S = \frac{(S/N)_{\text{prof}} T_{\text{sys}}}{G \sqrt{N_{\text{pol}} \Delta v T_{\text{obs}}/n_{\text{bin}}}}, $$

and we have used $T_{\text{sys}}$ of 32 K, 27 K, 19 K, and 27 K at 1.4, 2, 4.8, and 9 GHz,
Table 5.1: Three new pulsars toward the Galactic center.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>J1746-2850I</th>
<th>J1746-2850II</th>
<th>J1745-2910</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>17h 46m 06.6''(2)</td>
<td>17h 46m 03.7''(1)</td>
<td>17h 45m 16''(34)</td>
</tr>
<tr>
<td>DEC (J2000)</td>
<td>-28 50' 42''(5)</td>
<td>-28 49' 19''(21)</td>
<td>-29 10'(3)</td>
</tr>
<tr>
<td>P (s)</td>
<td>1.0771014910(4)</td>
<td>1.478480373(2)</td>
<td>0.982</td>
</tr>
<tr>
<td>( \dot{P} ) (s/s)</td>
<td>1.34311(2) \times 10^{-12}</td>
<td>1.27(6) \times 10^{-14}</td>
<td></td>
</tr>
<tr>
<td>DM (pc cm(^{-3}))</td>
<td>962.7(7)</td>
<td>1456(3)</td>
<td>1088</td>
</tr>
<tr>
<td>Age (Myr)</td>
<td>0.013</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B (G)</td>
<td>3.8 \times 10^{13}</td>
<td>2.8 \times 10^{12}</td>
<td></td>
</tr>
<tr>
<td>( \dot{E} ) (erg/s)(^a)</td>
<td>4.24 \times 10^{34}</td>
<td>1.47 \times 10^{32}</td>
<td></td>
</tr>
<tr>
<td>( W_{8.9} ) (50%,ms)(^b)</td>
<td>50</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>( W_{4.8} ) (50%,ms)</td>
<td>45</td>
<td>130</td>
<td>54</td>
</tr>
<tr>
<td>( W_{1.5} ) (50%,ms)</td>
<td>100</td>
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<tr>
<td>( S_{8.9} ) (mJy)</td>
<td>0.4</td>
<td>0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>( S_{4.8} ) (mJy)</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>( S_{1.95} ) (mJy)</td>
<td>0.8</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Spectral index ( \alpha )</td>
<td>-0.3</td>
<td>-1.1</td>
<td></td>
</tr>
<tr>
<td>( S_v \propto v^{\alpha} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Assuming a 1.4 M\(_{\odot}\) neutron star with a 10 km radius and moment of inertia \( I = 10^{45} \text{ g cm}^{-3} \).

\(^b\) Subscripts refer to observing frequencies in GHz.

including sky background contributions in the Galactic center direction of 12 K at 1.4 GHz scaled as \( \nu^{-2.5} \) (Reich & Reich, 1988). The gains \( G \) are 2.0 K Jy\(^{-1}\), 1.9 K Jy\(^{-1}\), 2.0 K Jy\(^{-1}\), 1.8 K Jy\(^{-1}\), respectively at the four frequencies. The number of bins in the pulse profile \( n_{\text{bins}} = 128 \). The total bandwidth \( \Delta \nu = 600 \text{ MHz} \) at 1.4 and 2 GHz, and 800 MHz at 4.8 and 9 GHz.

No isolated dispersed pulses were detected above a \( 5\sigma \) threshold in any of the 2 GHz survey pointings. For a 100 ms pulse width (comparable to the observed pulse widths from Table 5.1), we derive an upper limit on the flux density
of single pulses

\[ S_{\text{max}} = \frac{mT_{\text{sys}}}{G \sqrt{N_{\text{pol}} \Delta v W}} \approx 6.5 \text{ mJy} \quad (5.2) \]

### 5.3.1 PSR J1746–2850I

A timing solution for J1746-2850I was obtained from observations with the GBT made at 24 epochs between June 2008 and August 2009 and fitted for period \( P \), period derivative \( \dot{P} \), DM, and sky coordinates. The long period and large period derivative indicate that this is a young object with a characteristic age \( \tau_c = P/2\dot{P} = 13 \text{ kyr} \) and large surface magnetic field, \( 3.8 \times 10^{13} \text{ G} \). Assuming a power-law spectrum \( S_\nu \propto \nu^\alpha \), we found that J1746-2850I has a relatively flat spectrum, with \( \alpha = -0.3 \). The mean spectral index for normal pulsars is \(-1.5\) and fewer than 10% have \( \alpha > -0.5 \) (Lorimer et al. 1995). Of the two currently known radio-emitting magnetars, XTE1810–197 has \( \alpha = -0.5 \) in the frequency range \( 0.7 - 42 \text{ GHz} \) (Camilo et al., 2006), and 1E1547.0–5408 exhibits a flat or rising spectrum over \( 1.4 - 6.6 \text{ GHz} \) (Camilo et al., 2007). The flat spectrum of PSR J1746–2850I in addition to its spin parameters suggest that this object belongs to a class of young neutron stars bridging the gap between magnetars and canonical radio pulsars.

### 5.3.2 PSR J1746–2850II

J1746–2850II was timed simultaneously with J1746–2850I because the two pulsars are contained within the same beam of the GBT at 1.4 and 2 GHz. It has the highest dispersion measure of any pulsar known to date, indicating that of the
fifth pulsars currently known within 1 of Sgr A*, J1746-2850II is likely closest to Sgr A* in radial distance. It is an old pulsar, with a characteristic age $\tau_c = 2$ Myr. While most of the timing observations were made at 2 GHz, the receiver was unavailable in July and August 2008 so observations were made at 1.5 GHz. J1746–2850II is significantly scattered at this frequency (Fig. 5.2). While it was detected during a 2.25 h observation in June 2008, it was too weak to detect in our routine 1-hr observations at 1.5 GHz. Consequently, its timing solution has a larger position uncertainty than that of J1746-2850I.

The pulse profile of J1746–2850II at 4.8 GHz is symmetric and Gaussian-like without a discernible scattering tail (Fig. 5.2). We simulate the effect of scattering broadening by convolving a Gaussian matching the 4.8 GHz profile with an exponential depending on the scattering time, $\tau_{sc}$. We compare the results to the 1.5 and 2 GHz profiles using least-squares fitting and obtain $\tau_{sc} \approx 140$ ms at 2 GHz and 266 ms at 1.5 GHz.

### 5.3.3 PSR J1745–2910

PSR J1745–2910 has a period of 0.982 s and DM of 1088 pc cm$^{-3}$. Its nominal position is 12′ from Sgr A* and ~ 8′ from J1745–2912. Due to the large uncertainties in the positions of both pulsars, they may be between 3′ – 14′ apart. Using Eqn. 5.1, we estimate the flux density of J1745–2910 to be ~ 0.2 mJy at 2 GHz.
5.3.4 PSR J1746–2856 and PSR J1745–2912

The two pulsars discovered at 3.1 GHz by Johnston et al. (2006) are in our 2 GHz search area (Fig. 5.1). PSR J1746–2856 was blindly detected at up to $\sim 6'$ from its position. PSR J1745-2912 was not detected either blindly or by folding data from search pointings near its position with its period of 187 ms. The reported scattering time for this pulsar is $25 \pm 3$ ms at 3.1 GHz. If we assume a Kolmogorov scattering spectrum with a dependence of the scattering time on frequency of $\tau_{sc} \propto f^{-4.0}$, the scattering time for PSR J1745-2912 at 2 GHz is 144 ms. This is close to its period and therefore we attribute the non-detection to scattering broadening.

5.4 The Galactic Center Environment

Scattering from the dense region near Sgr A* has been modeled as both a thin screen and as an extended scattering volume. Lazio & Cordes (1998) estimate that the scattering screen around the Galactic center is $133^{+200}_{-80}$ pc from Sgr A*. The NE2001 model (Cordes & Lazio, 2003) uses an ellipsoidal scattering volume with a scale height of 26 pc and characteristic radius of 145 pc that is slightly offset from Sgr A*. The expected DM of a pulsar at the location of Sgr A* is $\sim 1600$ pc cm$^{-3}$ with a corresponding pulse-broadening time $\sim 400$ s or $\sim 2000$ s at 1 GHz for the screen or extended models, respectively. Pulsars on the near side of Sgr A* will have smaller values of DM and much smaller pulse broadening times.

All five pulsars within 1° of Sgr A* have high DMs that are too large to be
accounted for by the Galactic disk components of the NE2001 electron density model. If the pulsars are part of a disk population in the foreground of Sgr A*, the large DMs might be due to an unmodeled excess of intervening ionized gas associated with foreground HII regions. However, the two Johnston et al. (2006) pulsars are far in angular separation from one another and from the three pulsars we have found, making unlikely the possibility of a single HII region contributing to their large DMs. Similarly unlikely is the coincidence of five out of five pulsars being affected by separate HII regions.

In the absence of any unmodeled HII regions, the NE2001 model places all five pulsars within $\sim 100$ pc of Sgr A* using the DM values (Fig. 5.3). However the predicted pulse broadening times for the pulsars are several orders of magnitude larger than the measured value for J1746–2850II and the upper bounds on the other objects. This signifies that the near-side boundary and/or density of the idealized Galactic-center component of the model are incorrect or that the scattering volume is patchy, as suggested by Lazio et al. (1999). In either case, like any distance calculated using DM, the distances of the five pulsars from Sgr A* are highly model dependent and cannot be refined to better than $\sim \pm 100$ pc. However, unless there is an electron density component in the foreground disk (or spiral arm) of the Galaxy, the large DMs imply that the pulsars are no more than about 200 pc from Sgr A*. Galactic center pulsars will be key for improving the Galactic center component of the next electron density model, NE2008 (Cordes et al., in preparation).
Figure 5.2: Pulse profiles at 1.5, 2, 5, and 9 GHz for J1746-2850I (left), J1746-2850II (middle), and J1745-2910 (right). Scattering broadening results in an exponential tail to the pulse profiles at 2 and 1.5 GHz. J1746-2850II is scattered most severely of the three pulsars due to its high DM.

5.4.1 The Arches and Quintuplet Clusters

Could J1746–2850I have been born in either the Arches or Quintuplet cluster? Both clusters contain numerous massive stars, which are neutron star progenitors. Kim et al. (2006) find the present day mass function of the Arches cluster to extend to at least 40 M☉, while Figer et al. (2002) find the Arches cluster to contain stars exceeding 100 M☉ with the age of the cluster estimated to be 2 ± 1 Myr,
old enough for neutron stars to have formed. Current estimates for the maximum progenitor mass that will produce a neutron star are $20 \, M_{\odot}$ for solitary progenitors and as high as $50 - 80 \, M_{\odot}$ for binary progenitors due to mass loss in Roche lobe overflow (Belczynski & Taam, 2008). The Quintuple cluster has an estimated age of $\sim 4$ Myr (Figer et al., 1999) but contains the Pistol Star, whose mass of $150 \, M_{\odot}$ points to an age no larger than 2 Myr. These estimates indicate that the Quintuplet cluster is also old enough to have already formed neutron stars.

The current position estimate for J1746–2850I places it within 2′ of the Quintuplet cluster (Fig. 5.1). If the cluster and the pulsar are roughly 8.5 kpc from Earth, this angle corresponds to a distance of 5 pc. A transverse velocity of 375 km/s would have allowed the pulsar to reach its present location from the Quintuplet cluster within 13 kyr. Our double discovery in a single pointing suggests that the Arches and Quintuplet region may have a relative excess of pulsars.

### 5.4.2 Galactic Center Pulsar Population

We show here that the pulsar detections within 15 arcmin of Sgr A* imply the existence of a Galactic center subpopulation of pulsars and that this population may be quite sizable. First, given the small solid-angle coverage of our survey, $\Delta \Omega \approx 10^{-4.2} \, sr$, we do not expect to find any pulsars from the Galactic disk population. Integrating either a simple disk model with a uniform density or using the spatial distribution reported by Lorimer et al. (2006b), we find that only 1 to 2 disk pulsars beamed toward us are expected in the volume between Earth
Figure 5.3: Expected dispersion measure vs. distance for several lines of sight in the inner Galaxy based on the NE2001 model of Galactic ionized gas (Cordes & Lazio, 2003). The inset shows expected DM vs. distance for the lines of sight to the five known pulsars within $1^\circ$ of Sgr A*. The expected DM for objects physically near Sgr A* is $\gtrsim 1500$ pc cm$^{-3}$. The vertical part of the curve for a line of sight towards the Galactic center corresponds to a dense scattering screen around Sgr A* which makes detection of pulsars in this region difficult (Lazio & Cordes, 1998).
Figure 5.4: Likelihood contours based on the Poisson probability of detecting on average $\langle N \rangle$ pulsars of the simulated population in a survey beam where there are $k$ actual detections. Contours from left to right and in order of increasing thickness correspond to $L = (0.1, 1, 2, 4, 6, 8) \times 10^{-6}$.

and Sgr A*. When we include the survey sensitivity, which depends on the pulsar period, and the luminosity and period distributions, the expected number of detected pulsars $\ll 1$.

To assess the rough parameters of a Galactic center pulsar population, we employed a simple modeling approach. We used an ellipsoidal distribution with characteristic radius in the plane of the Galaxy $R_{GC}$ that contains $N_{GC}$ pulsars. The scale height of the population was fixed at $H_{GC} = 0.026$ kpc, equal to that of the scattering region in the NE2001 model. Through Monte Carlo, we generated pulsars consistent with this spatial distribution and drawn from pop-
ulations with the period and luminosity distributions of Lorimer et al. (2006b). Detection criteria were applied using the GBT observation parameters reported earlier and the Parkes survey parameters reported by Johnston et al. (2006), and taking into account the effects of pulse broadening from both residual dispersion smearing and scattering on the harmonic sum. As a test statistic we used the likelihood function $L = \prod_i P(l_i, b_i, \langle N_i \rangle, k_i)$. A term in the product corresponds to the Poisson probability of detecting on average $\langle N \rangle$ pulsars of the simulated population in the $i$-th survey beam, where there are $k$ actual detections, $P(\langle N \rangle, k) = \langle N \rangle^k e^{-\langle N \rangle} / k!$. The population was generated 1000 times for each $N_{GC}, R_{GC}$ pair. Figure 5.4 shows contours of $L$, which indicate that $N_{GC} \gtrsim 2000$ and $R_{GC} \gtrsim 0.3$ kpc are lower bounds on parameter values.

Extending our grid up to $N_{GC} = 10^4$ and $R_{GC} = 5$ kpc, we found no upper bounds on the parameters. We expect such bounds from a more comprehensive analysis that includes other survey results over a larger region, which we defer to another paper.

### 5.5 Conclusions

We have discovered three pulsars within 12’ of Sgr A*. The low ($\ll 1$) number of detectable disk pulsars in our survey volume and the high dispersion measures of the new pulsars indicate that they are within the dense scattering region surrounding Sgr A* and part of a neutron star population associated with the Galactic center. Based on a Monte Carlo simulation of this population which incorporates our survey results as well as those of Johnston et al. (2006), we conclude that there are $N_{GC} \gtrsim 2000$ active pulsars associated with the Galac-
tic center. Based on the average lifetime of canonical pulsars, \( \sim 10 \) Myr, we obtain a rough estimate of the radio pulsar birth rate in the Galactic center of \( \gtrsim 2 \times 10^{-4} \) yr\(^{-1}\). Considering that this is a lower limit, and that not all supernovae produce radio pulsars, this result is consistent with the rate of Galactic center supernovae (\( \sim 10^{-3} \) yr\(^{-1}\)) based on a survey of compact radio sources (Lazio & Cordes, 2008) and observations of soft X-ray emitting plasma (Muno et al., 2004).
CHAPTER 6
MODELLING THE GALACTIC CENTER PULSAR POPULATION

In Chapter 5 we presented the discovery of three pulsars from a Galactic center population in a 2 GHz survey with the Green Bank telescope. Here we explore two types models of the spatial distribution of this population based on the survey results: a spheroid and an ellipsoid. We employ a $\chi^2$ minimization and a likelihood maximization method to constrain the total number of Galactic center pulsars, $N_{GC}$, and the characteristic radius of the population, $R_{GC}$. Finally, we discuss the implications of the results for future pulsar searches near Sgr A* and for star formation in the Galactic center.

6.1 Introduction

The center of our Galaxy is an unusual environment for several reasons. It is believed to harbor a massive black hole whose location is marked by the compact radio source Sgr A*. Its relative proximity to us affords the unique opportunity to study an example of a class of exotic objects and their interaction with spacetime, which gives rise to observable relativistic effects. Ghez et al. (2000) estimated the mass of the black hole to be $M_{BH} \sim 2.6 \times 10^6 \, M_\odot$ based on the significant accelerations of stars near Sgr A*. After an additional near-decade of astrometric measurements, Ghez et al. (2008) update their estimate to $M_{BH} = (4.5 \pm 0.4) \times 10^6 \, M_\odot$ and $R_{BH} = 8.4 \pm 0.4$ kpc for the black hole distance. Gillessen et al. (2009) provide an independent estimate of $M_{BH} = (4.31 \pm 0.42) \times 10^6 \, M_\odot$ and $R_{BH} = 8.33 \pm 0.35$ kpc. As outlined in Chapter 4, Sgr A* is a prime target for pulsar searches because the discovery of a pulsar in a tight orbit around the central black hole would allow a more accurate mass measurement and even a
spin estimate. Since such a discovery has not yet been made and all five known pulsars within a degree of the Galactic center are \( \geq 10' \) from Sgr A* (Figure 5.1), we focus on what we can learn from those objects about the Galactic center pulsar population as a step towards solving the mystery of star formation in the region.

The Galactic center has three stellar clusters: the central cluster surrounding Sgr A*, the Arches, and the Quintuplet cluster. Figer (2008) point out that the clusters are all young \((2 - 7 \text{ Myr})\), massive \((\geq 10^4 M_\odot)\), and have central stellar mass densities of \( \sim 10^6 M_\odot \text{ pc}^{-3} \), exceeding the central densities of globular clusters. Lu et al. (2009) present evidence that there is a disk of young stars orbiting Sgr A* within 0.15 pc. Bartko et al. (2009a) suggest that there are two warped disks of young stars orbiting Sgr A* in the opposite sense to each other, and Bartko et al. (2009b) present observations indicating that the initial mass function (IMF) of the stellar population in the disks is unusually top-heavy. In Chapter 5 we showed that the three highly dispersed pulsars we discovered within 15’ of Sgr A*, as well as the two pulsars discovered by Johnston et al. (2006) at similar angular distances from the Galactic center, belong to a Galactic center pulsar population. One of the unsolved problems about the history of the region is whether the Galactic center has been a site of continuous star formation throughout the lifetime of the Galaxy or the young stars we observe today are products of a recent starburst event. If pulsar lifetimes are \( \leq 10 \text{ Myr} \), the pulsar population is in essence a fossil record of recent star formation history in the Galactic center. A combination of deep pulsar surveys and models of the pulsar population in the region based on the results of those surveys will ultimately allow us to reconstruct its past. Here we focus on several models of the spatial distribution and total number of the Galactic center pulsar population.
6.2 Monte Carlo Simulation

We model the Galactic center pulsar population using two different spatial distributions assuming a total number of pulsars $N_{GC}$. The first model uses a Gaussian spheroid spatial distribution with a characteristic radius $R_{GC}$ so that the pulsar number density

$$n_{GC}(r) \propto \exp \left( -\frac{r^2}{R_{GC}^2} \right).$$

(6.1)

The spheroid is centered 8.5 kpc from the observer in the direction $(l, b) = (-0.06^\circ, -0.04^\circ)$, corresponding to the location of Sgr A*. The centroid location of the scattering region in the NE2001 model of ionized gas in the Galaxy (Cordes & Lazio, 2003) is slightly offset at $(l, b) = (-0.06^\circ, -0.15^\circ)$ based on the observed temporal and angular broadening of Galactic and extragalactic sources, respectively.

The second model uses a Gaussian ellipsoid of the form

$$n_{GC}(r) \propto \exp \left[ -\frac{r^2}{H_{GC}^2} \right] \exp \left[ -\frac{r^2}{R_{GC}^2} \right],$$

(6.2)

where $H_{GC} = 0.026$ kpc is a fixed scale height equal to the scale height of the scattering region in the NE2001 model. We discuss the rationale for this choice below. The free parameters we want to fit based on the results of our 2 GHz Galactic center pulsar survey (Chapter 5) are $R_{GC}$ and $N_{GC}$. Individual pulsar parameters that our model depends on are the spectral index $\alpha$, the period-averaged luminosity $L_p$, the period $P$, and the period-dependent intrinsic pulse width $W_{int}$.

The probability density function of pulsar spectral indices was estimated from a least-squares fit to the spectral index distribution of canonical pulsars in the ATNF catalog (Manchester et al., 2005). We find that it is well described by
a Gaussian:

\[ f_{\alpha} \propto \exp \left[ -\frac{(\alpha - \mu_\alpha)^2}{2\sigma_\alpha^2} \right], \]  

(6.3)

where \( \mu_\alpha = -1.74 \) and \( \sigma_\alpha = 0.31 \). Spectral indices of pulsars in the simulated population are assigned in the range \( \alpha = -3.29 - 0.19 \), corresponding to \( \mu_\alpha - 5\sigma_\alpha \) to \( \mu_\alpha + 5\sigma_\alpha \).

We adopt the luminosity, period, and pulse width probability density functions of Lorimer et al. (2006b), who derived these PDFs from fits to the properties of the observed Galactic disk pulsar population. Period-averaged pulsar luminosities at 1.4 GHz are assigned according to the PDF \( f_{L_p} \propto L_p^{-1.77} \) in the range \( 0.1 - 1000 \) mJy and then scaled to 2 GHz using the pulsar spectral indices and assuming a power-law spectrum of the form \( S_\nu \propto \nu^\nu \). Pulsar periods are assigned in the range \( 0.5 \) ms - 15 s according to the PDF

\[ f_{\log P} \propto \exp \left[ -\frac{(\log P - \mu_{\log P})^2}{2\sigma_{\log P}^2} \right], \]  

(6.4)

with \( \mu_{\log P} = 2.7 \) and \( \sigma_{\log P} = 0.34 \). Instead of a full beaming model, Lorimer et al. (2006b) use an empirical approach in describing the dependence between period and intrinsic pulse width. With this approach, pulse broadening effects are taken into account for the known Galactic pulsar population, and a family of \( W_{\text{int}} - P \) relations examined to determine the best fit with respect to the observed distribution of pulse widths. Following their result, we assign intrinsic pulse widths according to the PDF

\[ \log W_{\text{int}} = \log \left[ 0.06 \left( \frac{P}{\text{ms}} \right)^{0.09} \right] + \Gamma, \]  

(6.5)

where \( \Gamma \) is a Gaussian distribution with a mean of zero and standard deviation of 0.3.
Galactic center pulsars are heavily scattered by a region of dense ionized gas surrounding Sgr A*. The observed pulse width

\[ W_{\text{obs}} = \sqrt{W_{\text{int}}^2 + \Delta t_{\text{DM}}^2 + \tau_{\text{sc}}^2 + \Delta t_{\text{samp}}^2}, \]  

(6.6)

where \( \Delta t_{\text{samp}} \) is the sampling time, \( \Delta t_{\text{DM}} \) is the dispersion smearing over a channel bandwidth (Eqn. 2.5), and \( \tau_{\text{sc}} \) is the scattering broadening. While dispersion depends only on the total amount of intervening ionized gas, scattering also depends on the density and size of the scattering region, and on its distance to the observer. We obtain \( \tau_{\text{sc}} \) for an observing frequency of 1 GHz for each of the pulsars in the simulated population from the NE2001 model, which includes a dense Galactic center ionized gas component. We then scale this scattering time estimate to 2 GHz based on a Kolmogorov scattering spectrum \( \tau_{\text{sc}} \propto f^{-4.0} \).

After generating the model Galactic center population for a certain pair of values \( R_{\text{GC}} \) and \( N_{\text{GC}} \), we retain the subset of pulsars that are within our survey field. For our 2 GHz survey, \( \Omega_{\text{tot}} \approx 7.8 \times 10^{-5} \) ster. In order for pulsars from that subset to be detected, they must pass three tests. We define a single-harmonic detection threshold

\[ S_{\text{min},1} = \frac{m T_{\text{sys}}}{\sqrt{N_{\text{pol}}} \Delta v T_{\text{obs}}}, \]  

(6.7)

where \( m = 6 \). Since \( N_h \) harmonics are summed during periodicity pulsar searches and a smaller duty cycle results in more harmonics, the detection threshold becomes \( S_{\text{min}} = S_{\text{min},1}/\sqrt{N_h} \), where \( N_h \approx P/2W \) (McLaughlin & Cordes, 2003).

First, a pulsar must be bright enough to be detected at its distance \( D \) if there is no pulse broadening, therefore we discard all pulsars that do not fulfil the condition \( L_p/D^2 > S_{\text{min},1} \sqrt{2W_{\text{int}}/P} \). If the pulse broadening exceeds the pulsar period, the pulsar would also be undetectable and so we discard pulsars that do not ful-
fil \( W_{\text{obs}} > P \). Pulse area corresponds to integrated flux density and is preserved if the pulse is broadened. However, broadening reduces the pulse amplitude and therefore we discard pulsars that do not fulfil \( L_p/D^2 > S_{\text{min,1}} \sqrt{2W_{\text{obs}}/P} \).

### 6.3 A Least-Squares Fitting Approach

As a first approximation, we try to find the \( R_{\text{GC}}, N_{\text{GC}} \) pair that results in the same or similar number of total pulsar detections as our 2 GHz survey. While information about the position of simulated pulsars is used to determine whether they are detected, with this approach we treat the entire survey area at once as a single “beam” of radius 20′ and we ignore the fact that data from some beams were not usable due to technical problems (Figure 5.1). We loop over a grid of \( R_{\text{GC}}, N_{\text{GC}} \) values and calculate the quantity

\[
\chi^2(N_{\text{GC}}, R_{\text{GC}}) = (1/n) \sum_i (N_{i,\text{det}} - N_{\text{det, survey}})^2,
\]

where \( n \) is the number of population realizations per parameter pair, and \( N_{i,\text{det}} \) is the number of pulsars detected for the \( i \)-th realization. \( N_{\text{det, survey}} = 4 \) is the number of pulsars detected by the survey, which include the new discoveries J1746–2850I, J1746–2850II, and J1745–2910, and the Johnston et al. (2006) discovery J1746–2856. The values assigned to the two free parameters were \( R_{\text{GC}} = 0.01 \text{ to } 1 \text{ kpc} \) at 0.06 kpc intervals and \( N_{\text{GC}} = 100 \text{ to } 5000 \text{ kpc} \) at intervals of 250.

Figure 6.1 shows contours of \( \chi^2 \) vs. \( N_{\text{GC}} \) and \( R_{\text{GC}} \). While \( N_{\text{GC}} \) is generally constrained between 1000 – 2500 and to a fraction of this interval for a fixed value of \( R_{\text{GC}} \), we can only obtain a lower limit \( R_{\text{GC}} \gtrsim 0.06 \text{ kpc} \). We next examine the
Figure 6.1: Contours in increasing order of thickness denote $\chi^2 = 4, 5, 10, 15$ and 20 for a Gaussian spheroid model of the Galactic center pulsar population based on results of the 2 GHz GBT survey. The population was generated 1000 times for each $N_{GC}, R_{GC}$ pair.

spatial distribution of detected pulsars in these simulated populations with respect to Sgr A* and the scattering volume surrounding it for two $N_{GC}, R_{GC}$ pairs at the bottom of the $\chi^2$ minimum trough shown in Figure 6.1. For $N_{GC} = 1100$ and $R_{GC} = 0.06$ kpc, the top panel of Figure 6.2 shows an observer’s view in Galactic coordinates of the positions of detected pulsars from 1000 population realizations. The panel size is equal to the diameter of our 2 GHz survey region, and there is a noticeable excess of detections in the North part of the field. The bottom panel of the figure reveals the reason: since our survey field is centered
Figure 6.2: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of a spheroidal population with $N_{GC} = 1100$ and $R_{GC} = 0.06$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
Figure 6.3: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of a spheroidal population with $N_{GC} = 2600$ and $R_{GC} = 0.91$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
on Sgr A* and the scattering volume is offset from it, we preferentially detect pulsars to the North of the densest part of the scattering volume. There are just a few detections to the South or in front of the scattering region. Also since the region’s North edge is $\sim 0.01$ kpc from Sgr A*, a spheroidal population centered on Sgr A* with $R_{GC} < 0.01$ kpc would be completely within the scattering volume and rendered undetectable due to scattering.

Figure 6.3 shows the same plots of detected pulsars from 1000 realizations of a less compact but more numerous population, with $N_{GC} = 2600$ and $R_{GC} = 0.91$ kpc. Because of the large $R_{GC}$, a larger part of the population is now in front of the scattering volume and there are more detections in that area. The detections are more uniformly distributed in the survey field, although still with a slight excess in the North part of the field. However, all four of the real pulsars detected by the survey are within 15' from Sgr A* and close to the plane of the Galaxy while a Gaussian spheroid model favors detections to the North of Sgr A*. Next we examine an ellipsoidal population model using the same least-squares approach and free parameters $N_{GC}$ and $R_{GC}$, where the latter now refers to the characteristic radius of the spatial distribution in the Galactic plane. One reason why we have not detected any pulsars in the North half of the survey field could be that the population’s scale height is similar to that of the scattering volume around Sgr A*, which Cordes & Lazio (2003) estimate to be $H_{GC} = 0.026$ kpc. We adopt this fixed scale height for our ellipsoidal model and repeat the simulation for the same $N_{GC}, R_{GC}$ grid and using again 1000 iterations per parameter pair.

Figure 6.4 shows $\chi^2$ contours for the ellipsoidal spatial distribution with a fixed scale height. Now there is no apparent lower limit on $R_{GC}$, unlike for the
Figure 6.4: Contours in increasing order of thickness denote $\chi^2 = 4, 5, 10, 15$ and 20 for a Gaussian ellipsoid model of the Galactic center pulsar population based on results of the 2 GHz GBT survey. The scale height of the population is fixed at $H_{GC} = 0.026$ kpc. Here $R_{GC}$ denotes the characteristic radius of the spatial distribution in the plane of the Galaxy. The population was generated 1000 times for each $N_{GC}, R_{GC}$ pair.

spheroidal version (Figure 6.1). If we plot the positions of the detected pulsars for a model from the low-$R_{GC}$ end of the $\chi^2$ minimum trough, with $R_{GC} = 0.01$ and $N_{GC} = 600$, we see that the spatial distribution is spindle-shaped since $R_{GC} < H_{GC}$ (Figure 6.4). The population is compressed radially and even for very low $N_{GC}$ there are enough pulsars to the North and South of the scattering volume to yield a total of four detections per realization. For a population in the high-$R_{GC}$ end of the $\chi^2$ trough, with $R_{GC} = 0.96$ and $N_{GC} = 2850$ (Figure 6.6), the result is
Figure 6.5: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of an ellipsoidal population with $N_{GC} = 600$ and $R_{GC} = 0.01$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
Figure 6.6: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of an ellipsoidal population with $N_{GC} = 2850$ and $R_{GC} = 0.96$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
similar to the spheroidal version in Figure 6.3.

6.4 A Maximum Likelihood Approach

The drawback of the $\chi^2$ minimization approach described above is that it is agnostic about the positions of the four actual pulsar detections. This leads to $N_{GC}, R_{GC}$ pairs corresponding to the lowest $\chi^2$ values producing models of the Galactic center pulsar population spatial distribution that are statistically at odds with observations. In the models selected by this method, pulsars are more likely to be detected to the North of the Galactic plane, while three of the four pulsars detected at 2 GHz have $-0.1^\circ < b < 0^\circ$, and for the fourth, $b \sim -0.2^\circ$.

Alternatively, we can treat each pointing in the 2 GHz survey as an independent measurement of the spatial distribution of the Galactic center pulsar population. We want to construct the survey likelihood function

$$L(N_{GC}, R_{GC}) = \prod_i L(l_i, b_i, \langle N_i \rangle, k_i, N_{GC}, R_{GC}),$$

where $k$ is the number of real pulsar detections in the $i$-th pointing and $\langle N_i \rangle$ is the average number of pulsar detections in the same pointing over $n$ realizations of the population. For an individual pointing, the likelihood is the Poisson probability of detecting on average $\langle N \rangle$ pulsars of the simulated population where there are $k$ actual detections

$$P(\langle N \rangle, k) = \frac{\langle N \rangle^k e^{-\langle N \rangle}}{k!}.$$ 

We have 26 beams with no detections, one beam with two real detections, and two beams with one detection each. If the average number of simulated pulsars
Figure 6.7: Likelihood contours based on the Poisson probability of detecting on average $\langle N \rangle$ pulsars of a simulated spheroidal population in a survey beam where there are $k$ actual detections. Contours from left to right and in order of increasing thickness correspond to $L = (0.01, 0.05, 0.1, 0.5, 1) \times 10^{-6}$.

detected in the latter two cases is $\langle N_{2\text{det}} \rangle$ and $\langle N_{1\text{det},i} \rangle$, the log-likelihood for the survey is

$$
\ln L = - \sum_i \langle N_i \rangle + \ln \left( \frac{\langle N_{2\text{det}} \rangle^2 \langle N_{1\text{det},1} \rangle \langle N_{1\text{det},2} \rangle}{2} \right).
$$

(6.11)

Figures 6.7 and 6.8 show likelihood contours vs. $R_{\text{GC}}$ and $N_{\text{GC}}$ for a spheroidal and an ellipsoidal population, respectively. For the spheroidal case, $L$ declines steeply for $R_{\text{GC}} \lesssim 0.15$ kpc and $N_{\text{GC}} \lesssim 1000$. For the ellipsoidal case, the decline is more gradual is occurs for $R_{\text{GC}} \lesssim 0.3$ kpc and $N_{\text{GC}} \lesssim 2000$. The general shape of the likelihood function in both cases is similar, and $L$ appears to approach a maximum for the largest parameter values in our $R_{\text{GC}}, N_{\text{GC}}$ grid. However,
Figure 6.8: Likelihood contours based on the Poisson probability of detecting on average $\langle N \rangle$ pulsars of a simulated ellipsoidal population in a survey beam where there are $k$ actual detections. Contours from left to right and in order of increasing thickness correspond to $\mathcal{L} = (0.1, 1, 2, 4, 6, 8) \times 10^{-6}$.

extending the parameter grid up to $R_{GC} = 5$ kpc and $N_{GC} = 10000$ did not reveal upper bounds on the two parameters. Such bounds may emerge if the results of other surveys, both of the Galactic center and the Galactic disk, are included in the simulation.

Figure 6.9 shows an observer’s view and a side view of the distribution of detected pulsars for 1000 realizations of a spheroidal population with $N_{GC} = 4850$ and $R_{GC} = 0.96$ kpc, the largest values for the two free parameters used in our standard $R_{GC}, N_{GC}$ grid. Figure 6.10 shows the same views for an ellipsoidal population with the same $R_{GC}$ and $N_{GC}$ values. In both cases there is an excess
Figure 6.9: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of a spheroidal population with $N_{GC} = 4850$ and $R_{GC} = 0.96$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
Figure 6.10: Detected pulsars (dots) in the 2 GHz survey field for 1000 realizations of an ellipsoidal population with $N_{GC} = 4850$ and $R_{GC} = 0.96$ kpc. Sgr A* is denoted by a cross and the positions of the four real pulsars detected by the survey are shown as circles. The top panel shows an observer’s view of the detections in Galactic coordinates. The bottom panel shows a side view in linear spatial coordinates with the observer to the far left.
of detections to the North of the Galactic plane since pointings in that direction skirt the densest part of the scattering volume around Sgr A* and the search volume per pointing is larger.

6.5 Discussion

Based on Monte Carlo simulations of Gaussian spheroid and ellipsoid models of the Galactic center pulsar population that use results from our 2 GHz Sgr A* survey, we find that the total number of pulsars in the region (including those not beamed towards Earth) $N_{GC} \gtrsim 1000 – 2000$. Lazio & Cordes (2008) estimate the rate of pulsar-producing supernovae in the Galactic center based on detections of steep-spectrum, pulsar-like sources in a VLA survey of a field around Sgr A*. Assuming a recent starburst in the Galactic center, they arrive at a lower limit of $\lesssim 10^5$ pulsar-producing supernovae within the past 10 Myr (a canonical pulsar lifetime). For continuous star formation in the Galactic center, the estimated number of pulsar-producing supernovae is $\lesssim 10^4$ in the past 10 Myr. In terms of supernova rates, our result translates to $\gtrsim 10^{-4}$ yr$^{-1}$, consistent with the Lazio & Cordes (2008) estimate of $\lesssim 10^{-2} – 10^{-3}$ yr$^{-1}$.

Figer (2003) and Figer et al. (2004) argue that continuous star formation rather than a recent starburst is more consistent with the current Galactic center luminosity function. The star formation density rate they derive for the central 50 pc around Sgr A* corresponds to a supernova rate of roughly $10^{-2}$ yr, which is an upper limit on the rate of pulsar-producing supernovae. Muno et al. (2004) present observations of soft X-ray emitting plasma in the Galactic center, which is believed to be produced by supernova shock waves, and derive a supernova
rate of $10^{-5}$ yr$^{-1}$ for the central 20 pc of the Galaxy. Extending that estimate for the central 100 pc results in a rate of $\sim 10^{-3}$ yr$^{-1}$.

While our simulation results for the number of pulsars in the Galactic center agree with estimates from the literature, the population models that best fit our observations also predict an excess of pulsar detections to the North of the Galactic plane, which is not observed. Several effects may contribute to this inconsistency. First, our model populations and our 2 GHz survey field were centered on Sgr A* and therefore are offset from the centroid of the dense scattering volume by an amount $\Delta$. If for the scale heights of the population and the ionized gas $H_{GC} + \Delta > H_{gas}$, there is always an excess of detections to the North of the Galactic plane because the search volume per pointing per unit observation time is larger in that area. Since we have not observed an excess of pulsar detections in that area, we must explore the possibility that the centroid of the pulsar population is offset from Sgr A* and closer to the centroid of the scattering ionized gas volume. In addition, three of our four actual pulsar detections at 2 GHz are (at least in projection) close to the Galactic center Radio Arc, and two of the four detected pulsars are close to the Arches and Quintuplet clusters. In adjusting our models, we have to also take into account the possibility that there may be localized sub-populations of pulsars near these structures, even as the pulsars are part of the overall population associated with the Galactic center. Finally, our models are a first step relying on a limited number of pointings and actual detections. Future pulsar surveys and discoveries near Sgr A* will allow us to better constrain the parameters of the Galactic center pulsar population.
Multiple directions for future projects emerge from the results presented in this thesis. In addition, the building of new and better facilities as well as the upgrade of existing ones promise improved sensitivity for future observations. The PALFA survey will likely be expanded to latitudes $|b| > 5^\circ$, and made deeper for latitudes $|b| < 1^\circ$ by increasing the observation time per pointing to 10 minutes. This will undoubtedly yield more discoveries, both periodic and intermittent. In the case of intermittent objects, increasing the known sample will help with classifying the causes of intermittency, and also with estimates of the Galactic population of neutron stars that emit only occasional pulses and are therefore easily missed in one-pass surveys. Long-term timing of intermittent pulsars is also crucial for unraveling the properties of these elusive objects, with the goal of describing the mechanism of intermittent emission and the differences, if any, from the emission mechanism of steady emitters. The extended sky and temporal coverage of PALFA will also increase the probability that we detect radio transients caused by objects other than neutron stars, even powerful transients at intergalactic and cosmological distances.

Our Galactic center results show that some areas near Sgr A* may warrant special pulsar search attention. In particular, the apparent excess of pulsars and pulsar-like steep-spectrum sources near the Arches and Quintuplet clusters and the Radio Arc has led us to propose a deep pulsar search in those regions with the Green Bank telescope. The results of this search will be incorporated into our model of the Galactic center pulsar population. They will allow us to distinguish between models that include a single population associated with
Sgr A* and models that also include localized sub-populations of pulsars in the Arches, Quintuplet, and/or the Radio Arc.

The Expanded Very Large Array (EVLA) is a project that is updating the VLA to modern antenna and correlator electronics and will improve sensitivity by an order of magnitude by the time it is completed in 2013. The available bandwidth will increase by a factor of up to 80, allowing us to go to higher frequencies, where scattering in the Galactic center is not as severe but pulsars are weaker. Lazio & Cordes (2008) surveyed the inner 2° around Sgr A* with the VLA at 1.4 GHz and detected 170 sources, 29 of which likely have steep-spectra, a hallmark of pulsars. With the EVLA, we will be able to survey the Galactic center at frequencies as high as 5 GHz, measure the spectral indices of sources found in the 1.4 GHz survey, probe the properties of ionized gas in the region by comparing angular broadening at the two frequencies, and discover sources that were missed at 1.4 GHz because of scattering. Regular imaging of the region around Sgr A* will allow us to measure the proper motions and parallaxes of any new pulsars, as we have already proposed to do for the magnetar-like object J1746−2850I during the EVLA upgrade.

The Square Kilometer Array (SKA) is an interferometer currently in the design and site selection stage. Its sensitivity will be ~ 50 times better than that of the EVLA and its completion will revolutionize the fields of pulsar searching, timing, and population modelling. Searching for pulsars in the Galactic center is a major science incentive for the SKA. In addition, it is expected to make ~ 10⁴ new pulsar discoveries in the Galactic plane, amounting to a near-complete census of pulsars in the Galaxy.
In this Appendix we present single pulse search results for a 6.5 h observation of Sgr A* at 5 GHz. Because of the length of the observation and the large number of events the output is divided into ten pages, each spanning 2500 s of the observation. A page is divided into five panels, each spanning 500 s of the observation. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM values in the range $50 - 2550 \text{ pc cm}^{-3}$ is illustrated in Figure 4.6. Event statistics for the entire observation are also given in Figure 4.6. In each panel, events are denoted by circles, with larger circles corresponding to higher S/N.

While there is no noticeable excess of events at a particular trial DM indicating a possible sporadic source, several weak events are detected at various ranges of DMs away from $DM = 0 \text{ pc cm}^{-3}$. They may be caused by dispersed pulses or swept-frequency RFI. These events (at $t \sim 20, 4870, 5090, 6160, 6730, 7360, 7500, 13400, 13470, 15360 \text{ s}$) are generally too weak to be visible as frequency sweeps in the time-frequency plane and their origin remains unverified. At $t \sim 19100 - 21060 \text{ s}$, strong RFI visible as multiple bright events at low DM dominates the search results. Very bright RFI blasts are above the single pulse search threshold at most or all trial DMs.
Figure A.1: Single pulse search output for $0 < t < 2500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.2: Single pulse search output for $2500 < t < 5000$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.3: Single pulse search output for $5000 < t < 7500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.4: Single pulse search output for $7500 < t < 10000$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.5: Single pulse search output for $10000 < t < 12500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.6: Single pulse search output for $12500 < t < 15000$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.7: Single pulse search output for $15000 < t < 17500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.8: Single pulse search output for $17500 < t < 20000$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.9: Single pulse search output for $20000 < t < 22500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure A.10: Single pulse search output for $22500 < t < 23500$ s of a 6.5 h 5 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
APPENDIX B

SINGLE PULSE SEARCH OUTPUT: SGR A* AT 9 GHZ

In this Appendix we present single pulse search results for a 6.5 h observation of Sgr A* at 9 GHz. Because of the length of the observation and the large number of events the output is divided into ten pages, each spanning 2500 s of the observation. A page is divided into five panels, each spanning 500 s of the observation. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM values in the range 50 – 2550 pc cm\(^{-3}\) is illustrated in Figure 4.7. Event statistics for the entire observation are also given in Figure 4.7. In each panel, events are denoted by circles, with larger circles corresponding to higher S/N.

For most of the observation, RFI events dominate the search results and make distinguishing any legitimate dispersed pulses difficult. Bright RFI blasts are above the single pulse search threshold at most or all trial DMs.
Figure B.1: Single pulse search output for $0 < t < 2500$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.7.
Figure B.2: Single pulse search output for $2500 < t < 5000$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.3: Single pulse search output for $5000 < t < 7500$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.4: Single pulse search output for $7500 < t < 10000$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.5: Single pulse search output for $10000 < t < 12500$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.6: Single pulse search output for $12500 < t < 15000$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.7: Single pulse search output for $15000 < t < 17500$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.8: Single pulse search output for $17500 < t < 20000$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.9: Single pulse search output for $20000 < t < 22500$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
Figure B.10: Single pulse search output for $22500 < t < 25000$ s of a 6.5 h 9 GHz observation of Sgr A*. The DM channel on the vertical axis of each panel is the sequence number of a trial DM in the DM list. The mapping of DM channel to DM value is illustrated in Figure 4.6.
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