QUALIFYING EXAM RESEARCH REPORT
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Topics in Radio Astronomy

Summary:

In the past year I have gained research experience while working on three projects in radio astronomy:

- The timing of 13 pulsars in 4 globular clusters, including the relativistic binary PSR B2127+11C in M15. We will use the data to determine the masses of the two neutron stars (NS), while studying cluster dynamics and gas distribution.
- The searching of 3 globular clusters for undiscovered pulsars. A new pulsar backend recently came online at the Green Bank Telescope (GBT) that is an incredible asset in the area of pulsar searching. Over the summer we obtained three data sets that will be thoroughly searched for millisecond pulsars (MSPs) in the near future.
- The development of a pipeline for the rapid reduction of large quantities of spectral line and continuum data from the Very Large Array (VLA). The code is powerful, easy to use, and is already being put to use by myself and members of the GRB group.

In the sections below, I give the details of each project.

Globular Cluster Pulsar Timing

Globular cluster pulsars have proven to be interesting objects of study since the discovery of a 3 millisecond pulsar (MSP) in M28 (Lyne et al., 1987). They can be used to test General Relativity (GR), probe cluster dynamics, and have the potential to constrain the equation of state for matter at nuclear densities.

ARECIBO TIMING:

In the spring I joined Rick Jenet and Bryan Jacoby in timing 8 pulsars in M15. Of particular interest is the double neutron star system PSR B2127+11C, which is essentially a copy of the Hulse-Taylor binary (Anderson, 1993). We have combined results from timing of the M15 pulsars in the early 1990s with 35 epochs of Caltech Baseband Recorder data obtained at Arecibo between 1999 and 2001. Using code provided by my collaborators, I synthesized a coherently dedispersed filterbank, folded each pulsar in the cluster, and cross-correlated the individual profiles with a high signal-to-noise template to generate an average time-of-arrival (TOA) for 33 of the new epochs. This process should have taken $\sim$ 5 weeks, but we suffered several setbacks due to Center of Advanced Computing Research (CACR) becoming unavailable for long periods of time. However, all the data has been processed with the exception of 2 epochs due to CACR's tape robot continuing to be unavailable.

Compact binaries such as B2127+11C can be considered ideal orbiting point masses from the point of view of GR. The problem of determining the individual NS masses is overdetermined when

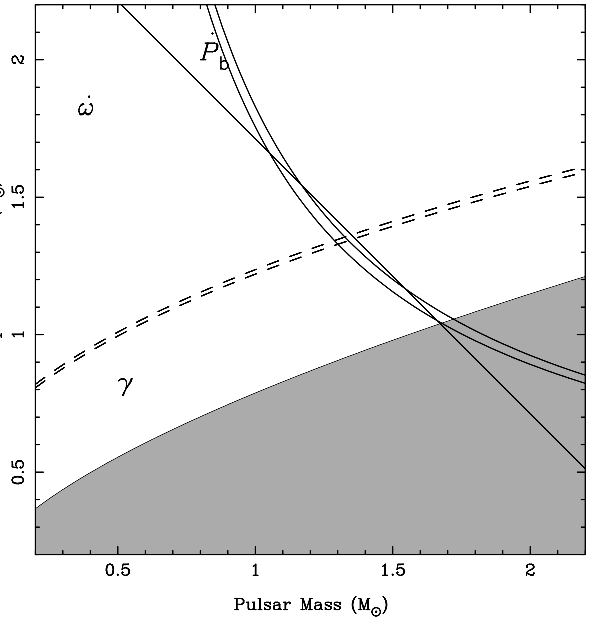

Figure 1: Preliminary mass-mass plot for B2127+11C. The constraints on the neutron star masses come from the orbital shrinkage due to gravitational wave radiation $\dot{P}_B$, the gravitational redshift γ, and the advance of the periastron of the orbit $\dot{\omega}$. At present we do not fully understand the uncertainties in the TOAs from the early data, so our three constraints do not overlap.

Name	P (ms)	$\dot{P}$ (sec/sec)	DM (cm^{-3} pc)	P_B (d)	$a \sin i$ (lt sec)	$M_{2,min}$ ($M_\odot$)	Cluster
PSR J1701-3006D	3.418	?	114.46	1.12	0.98	0.12	M62
PSR J1701-3006E	3.234	?	113.36	0.16	0.07	0.03	M62
PSR J1701-3006F	2.295	?	113.75	0.2	0.06	0.02	M62
PSR J1807-2459B	4.186	?	134.0	?	?	?	NGC 6544
PSR B1820-30C	405.9	?	87.0	–	–	–	NGC 6624

Table 1: Parameters of pulsars currently being timed with the GBT (Chandler, 2003).

3 or more relativistic corrections to the well-known Keplerian orbital parameters are measured. It is at this point that GR can be tested. In the case of B2127+11C we are able to determine the advance of periastron $\dot{\omega}$, the gravitational redshift γ, and decay of the binary orbit due to gravitational wave radiation $\dot{P}_B$. A preliminary mass-mass plot is shown in Figure 1. As is evident in the figure, our constraints do not overlap. We need to understand the TOA uncertainties in the old Arecibo data before we can begin to make quantitative statements about the individual NS masses or the accuracy of GR's predictions.

GBT Timing

Upon arriving last fall I joined another ongoing effort lead by Bryan Jacoby to time globular cluster pulsars with the GBT. We have been following up pulsars discovered in M62, NGC 6544, and NGC 6624 during the thesis work of Adam Chandler. The known properties of these pulsars can be found in Table 1.

Collectively these pulsars may allow study of globular cluster dynamics (Phinney, 1992). Many cluster pulsars have been found with negative period derivatives, which suggests they lie on the far side of the cluster and are being accelerated toward the Sun. In the case of 47 Tuc this allowed for the placement of a lower limit on the cluster core mass (Camilo et al., 2000). I cannot be sure of the utility of these pulsars in probing the cluster dynamics, since I have only completed the preliminary tasks of dedispersing, and folding the known pulsars in each observing run. However, phase connected timing solutions should be available in the next few months.

I have also refined the dispersion measures (DM) of the M62 pulsars. Measuring this quantity precisely is important since DM differences of pulsars within a given cluster allows us to study the intracluster medium.

Finally, I made the modest discovery that PSR J1701-3006C is actually a 7.6 ms pulsar, which is twice the period (3.8 ms) claimed by Possenti et al. (2001). As can be seen in Figure 2, the pulsar has a small interpulse that is 180° out of phase with the main pulse, which is seen at multiple epochs. It is not hard to see why this may have been confused with the main pulse in lower signal-to-noise, single epoch data.

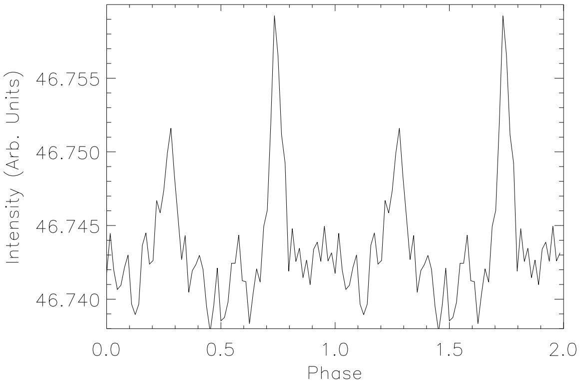

Figure 2: Two pulse profiles of J1701-3006C showing pulse and interpulse 180°. The interpulse lead to an incorrect period determination.

Globular Cluster Pulsar Searching

The data collected for timing above can also be searched for new pulsars. Globular clusters appear to be factories for producing binary MSPs. There are currently 80 known pulsars in 24 clusters, with a binary fraction $> 50\%$, and only 6 pulsars have $P > 100$ms (Freire). Consequently, globular clusters are a logical place to search for a much sought after prize in pulsar astronomy, a NS with a spin period shorter than 1.5 ms. Measurements of neutron star (NS) masses and radii imply that these objects are comprised of more than a solar mass of material at nuclear densities. However, the characteristics of this exotic matter are not well understood. That is, the equation of state (EOS) of neutron stars is not known. The EOS determines the mass-radius relationship for the NS. A softer (more compressible) EOS will lead to a smaller radius for a given mass. The star will be disrupted if the rotational speed at the pulsar's equator exceeds the escape velocity; therefore equations of state which predict smaller radii for a given neutron star mass allow for shorter pulsar spin periods. Only the hardest equations of state are ruled out by the fastest known pulsars. The discovery of a neutron star spinning faster than 1 ms would help rule out a large portion of the EOS parameter space for neutron stars (Lattimer & Prakash, 2001). Our GBT Spigot (discussed below) data will be quite sensitive to fast pulsars, as can be seen in Figure 3.

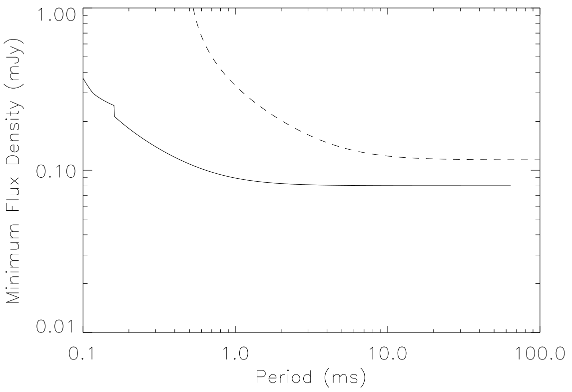

Figure 3: Sensitivity of the old backend (Berkeley Caltech Pulsar Machine, dotted) versus the new backend (Spigot, solid) in a simulated 3 hour GBT observation of M62 (DM = 114.4) at 825 MHz. We will have very good sensitivity to sub-millisecond pulsars.

Pulsars in tight binary orbits are another target of our pulsar searching. However, a major challenge in the detection of binary MSPs is the modulation of the signal by orbital motion. Even a small acceleration during the observation can greatly reduce the sensitivity of traditional search methods (Johnston & Kulkarni, 1991). A great deal of progress has been made in recent years toward developing algorithms to detect binary MSPs (Chandler, 2003 and Ransom, 2001). The new pulsar backend at the GBT, called the Spigot system, is a hardware development that complements those in software. The Spigot uses the extremely flexible, powerful Digital Spectrometer at the GBT to perform auto-correlations of the data very rapidly, and will be an invaluable tool for MSP searching. The best Spigot modes for searching became available this past summer, so searching of this cluster data, along with that of M15, has just recently begun. In preparation, I have been studying the various search techniques, and familiarizing myself with the search software by using it on old data sets and to achieve the DM refinement described above.

A Pipeline for VLA Data Reduction

This past summer I attended the Summer School in Synthesis Imaging at NRAO, and spent 8 weeks at the VLA. During my stay, I developed software for the rapid reduction of large quantities of VLA continuum and spectral line data. The task of producing an image from raw visibilities has three parts: the initial editing of the data (known as flagging), the calibration of the data to obtain complex gain solutions for each antenna, and Fourier inversion and deconvolution of the calibrated data to make an image. There is a great deal of interest in producing software that performs the above reduction steps quickly and easily on large amounts of raw data, because the development of the 3TB NRAO Data Archive has become a recent point of emphasis at the VLA..

The basis of the pipeline was a pre-existing piece of code called vlarun. It consists of procedures written by Lorant Sjouwerman for the Astronomical Image Processing System (AIPS) which can quickly accomplish robust calibration, and simple imaging of a single raw data file. It uses the standard AIPS reduction techniques that can accommodate $\sim 80\%$ of VLA observations (Sjouwerman, private communication). However, I needed to add several features to vlarun in order to make it a stand alone reduction tool. The first of these was simple automated flagging. This has proven to be a very difficult, yet crucial step, and was accomplished with the help of Eric Greisen. But, as shown below, very little flagging can yield excellent results at the majority of VLA observing frequencies. My second addition to vlarun was the ability to use models of flux calibrators at high frequency (> 15GHz). During calibration, it is assumed that the amplitude calibrator is a point source, but at higher frequencies and long baselines these objects are often resolved. Therefore, it is critical to use reliable source models to calibrate high frequency data. Ideally this should be done at all frequencies, so the longer wavelength models are currently under development. I also added other minor features, such as various diagnostics for determining the success of calibration, and options for more control over the imaging step.

The heart of the package consists of the python PIPELINE script that drives VLARUN through numerous data sets. I designed PIPELINE to require almost zero input while keeping the user informed of progress and possible problems. It accomplishes this task by gathering all of the information relevant for reduction from the raw data header and various VLA calibrator manuals, then calculating or looking up the relevant settings, and delivering the information to AIPS. Normally, the user combs through these headers and manuals to determine the correct inputs for each AIPS procedure. This, along with automated flagging, results in roughly a factor of 30 reduction in the time it takes to image VLA data.

As a demonstration, Figure 4 shows the early 8.4 GHz light curve of GRB 030329 (Berger et al., 2003). The data set consisted of many bands that likely took ∼ 20 hours to reduce. However, we are able to cut this number down to roughly 30 minutes with the pipeline software. The biggest bottleneck in the typical data reduction scheme is flagging bad data by hand. However, the small (< 2%) residuals in light curve prove that excellent results can be obtained with simple automated flagging. This consists of discarding huge outliers in otherwise clean data sets (which is usually the case above 4 GHz), but the algorithm does not deal well with heavy or persistent interference, which is common at lower frequency bands.

This tool will be used by myself and members of the GRB group to work on a variety of projects. Additionally, the scientific staff at NRAO was enthusiastic about the pipeline's development, and intends to refine it to the point that it can be released to the public as a tool for use with the data archive.

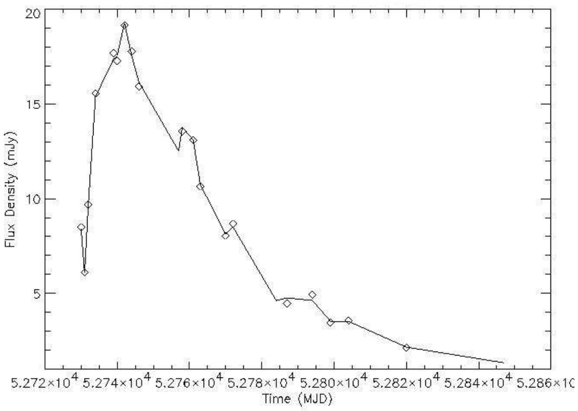

Figure 4: Comparison of the published (line) and the pipeline produced (symbols) light curve of GRB 030329 at 8.4 GHz. The residuals are < 2%, and the data reduction time was decreased by a factor of ∼ 30.

Future

My future plans regarding the above research are:

1. I intend to author a paper for PASP regarding the VLA pipeline in the next month.
2. The timing paper of PSR B2127+11C will be completed within the next month (on which I will be a co-author).
3. I intend to author a paper on the timing of the other pulsars in M15 before the spring quarter.
4. The last of the GBT observing runs for timing will be completed in November, so the paper (on which I will be a co-author) regarding the timing of these objects will be completed during the winter quarter.
5. I intend to author a paper on the results of the pulsar searching of the globular clusters before the spring quarter.

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