Revisiting the double pulsar system PSR J0737-3039 using GBT

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Abstract

Pulsars are highly magnetized, rapidly rotating neutron stars that serve as precise cosmic clocks. There are nearly 3000 known pulsars today but, PSR J0737-3039A/B, a double neutron star system stands out as a unique contender since both the neutron stars are detectable as radio pulsars. This system is therefore a good candidate to explore the important properties of pulsars and understand their evolutionary history. Owing to the fact that PSR J0737-3039A is a millisecond pulsar, this allows us to create very high-precision timing solutions characterizing their rotation, orbital motion, and mass measurements, which in turn enables us to constrain models for the neutron star equation of state. We request 36.75 hours (allowing for 5 full orbital coverage at each frequency) of observation of PSR J0737-3039 using GBT at 400 MHz, 800 MHz and 1.4 GHz to study the properties of this system such as periastron advance, gravitational Redshift and more to better precision and more tightly constrain the mass of the pulsars. Thus, this study combined with the existing data from the Parkes radio telescope promise to greatly increase our knowledge of strong-field gravity and understand the magnetospheric properties of pulsars.

1 Scientific Justification

Double neutron star (DNS) systems are rare cosmic objects that serve as wonderful laboratories for studying relativistic gravity and relativistic plasma physics. The discovery of such systems has been a primary objective of several pulsar survey programs since the discovery of PSR B1913+16, the first DNS system composed of a neutron star and a pulsar, 29 years ago Lyne et al. (2004). These systems are particularly difficult to detect due to the large orbital acceleration experienced by the system, resulting in varying Doppler effects in the observed rotational period.

PSR J0737-3039, a unique DNS system, discovered during a high galactic latitude multi-beam survey using the 64-meter Parkes radio telescope Manchester et al. (2001) is the only known DNS system consisting of two pulsars emitting electromagnetic waves in the radio wavelength. The first of the two pulsars to be discovered was J0737-3039A Burgay et al. (2003), a 22.7-millisecond pulsar (MSP) whose period was seen to change rapidly during the short 4-minute discovery observation. This immediately indicated that it was accelerating in the strong gravitational field of a companion star which was later confirmed to be a pulsar, J0737-3039B. The two pulsars in this system, J0737-3039A and J0737-3039B have orbital periods of $P_A =$ 22.7 ms and $P_B = 2.77$ s and are in a 2.45 hour, 0.088 eccentric orbit. The properties of the system are summarised in table 1. The short orbital period and compactness of this system along with the high timing precision obtainable by the large flux density and narrow pulse

Table 1: Properties of PSR J0737-3039

Pulsar	**PSR J0737-3039A**	**PSR J0737-3039B**
Pulse Period, P_b	22.7 ms	2.77 s
Period derivative, $\dot{P}$	1.74 * 10^{-18}	0.88 * 10^{-15}
Orbital Period, P **(hours)**	2.45	2.45
Projected semi-major axis, x	1.42 s	1.51 s
Eccentricity, e	0.088	
Distance (kpc)	∼0.6	

feature guarantee to make this system an excellent testing ground to bring a new revolution in pulsar astronomy Lyne (2006).

As double pulsar systems (DPS) have significantly strong gravitational fields, they can be uniquely described using the Post-Keplerian (PK) parameters described below. The test for any strong-field gravity theory like general relativity then involves calculating the dependence of each PK parameter on the two pulsar masses and verifying that the allowed families of solutions all intersect in a common region. The dependence of the PK parameters on the masses m_A and m_B are given below Damour and Deruelle (1986)

Periastron advance, the rotation of the line connecting the two pulsars at their closest approach to one another

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T * M)^{2/3}(1-e^2)^{-1} \tag{1}$$

Gravitational redshift, the apparent pulse rate for A will slow down when it is close to B, and vice versa

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T^{2/3}M^{-4/3}m_B(m_A+2m_B) \tag{2}$$

Orbital decay, The rate of decrease of the orbital period, indicting the shrinkage of the orbits of the pulsars

$$\dot{P}_b = \frac{-192\pi}{5}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)(1-e^2)^{-7/2}T^{5/3}m_Am_BM^{-1/3} \tag{3}$$

Shapiro delay, Radiation passing close to a massive body is delayed as its path length is increased by the space-time curvature. This signal delay is a function of s, the shape, and r, the range of the delay experienced by the pulsar pulses.

$$r = T * m_B \tag{4}$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T^{-1/3}m_B^{-1}M^{2/3} \tag{5}$$

By substituting the measured value of each PK parameter into the corresponding equation linking the two masses, we should be able to plot the allowed masses of A and B as a curve in a plot of one mass against the other. Such tests have been carried out for a few DNS systems like PSR B1913+16 and PSR B1534+12 Lyne et al. (2004). The mass-mass diagram for the later system is given in figure 1 where the observational constraints upon the two stellar masses can be inferred Stairs et al. (2002).

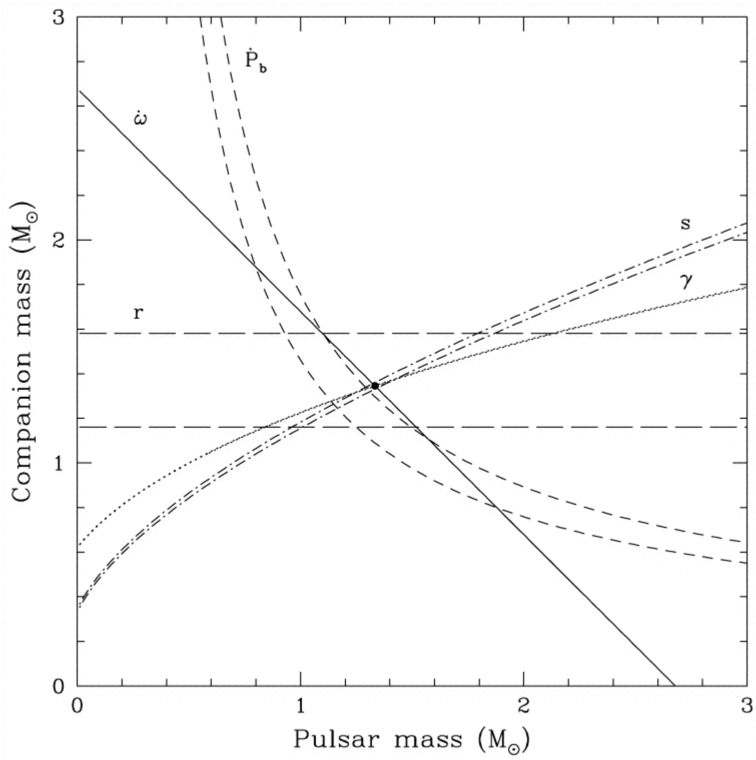

Figure 1: Mass mass diagram of PSR B1534+12 system. The Labeled curves are 68 % confident in their detection range and the filled circle is the region where the allowed families of solutions intersect and is the Component masses

Measuring these PK parameters for the PSR J0737-3039 system would enable us to constrain the mass of the pulsars. However, because both pulsars are visible and we can measure the sizes of their orbits with high precision, we gain an additional parameter, the mass ratio, $R(m_A, m_B) = m_A/m_B = x_B/x_A$ Lyne et al. (2004). Along with the above-mentioned PK parameters, this additional constraint will make this system the most over-determined DNS system to date and a truly unique laboratory to test relativistic gravitational physics. Measuring the PK parameters not only constrains the mass of the pulsar but also helps in determining various other properties of the system such as the characteristic age of the pulsar given by $\tau = P/2\dot{P}$ where $\dot{P}$ is the pulse period derivative.

The double pulsar also provides a novel opportunity to study their magnetospheres - the regions of space around pulsars in which the radio emissions are typically produced. As the pulsars A and B move in their orbits, the line-of-sight from A travels through, and sweeps across, the magnetosphere of B, providing the opportunity to examine its physical properties. The investigation of changes in the radio transmission properties, including the dispersion and rotation measures, will potentially allow the plasma density and magnetic field structure to be probed McLaughlin et al. (2004). Thus, measurements of orbital variations in pulse shapes, amplitudes, polarization, and timing over a range of radio frequencies will give remarkable insights into magnetospheric processes in pulsars. Hence, we conclude that PSR J0737-3039 has the capability to update our understanding of pulsars, and observing this system would have a great impact on the advancement of pulsar astronomy.

2 The Green Bank Telescope

The Green Bank Telescope (GBT) is a 100 meter diameter single-dish radio telescope located in West Virginia, USA. GBT has a fully-steerable antenna that covers 85 % of the celestial

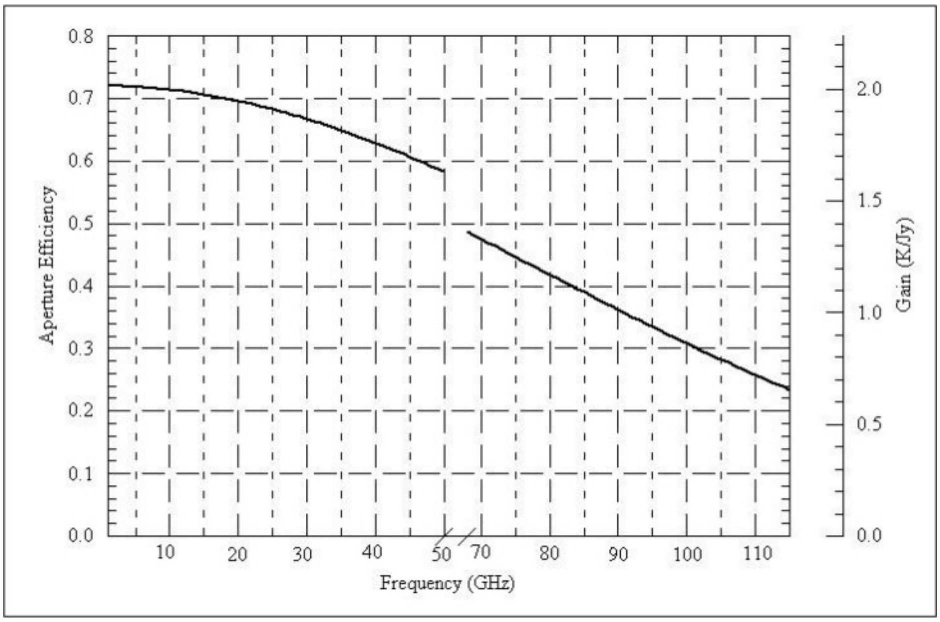

Figure 2: Aperture Efficiency of GBT[1]. The beam efficiencies are 1.37 times the aperture efficiency

sphere and has an elevation range of 5–90 degrees. GBT has frequency coverage of 290 MHz to 115.3 GHz and includes near real-time adjustments to optics and pointing. GBT is a unique resource for Radio Astronomy as it is located in the National Radio Quiet Zone which provides protection from RFI. GBT consists of two receivers, Prime Focus Receivers which cover a frequency range of 290 MHz to 1.23 GHz, and Gregorian Receivers which span over 1.15 to 115.3 GHz.

GBT had a dedicated pulsar backend instrument called Green Bank Ultimate Pulsar Processing Instrument (GUPPI) DuPlain et al. (2008), which was working in conjunction with the existing GBT receiver for observing pulsar timing over a wide band. This instrument has been updated as **VErsatile GBT Astronomical Spectrometer (VEGAS)** Prestage et al. (2015), which can be used in pulsar observing modes. VEGAS consists of 8 CASPER ROACH2 FPGA boards and 8 high-performance computers equipped with Nvidia GTX 780 GPUs. VEGAS is designed with a high dynamic range (8-bit sampling), large bandwidth (800-1000MHz), full polarization capabilities, better RFI immunity, and high time and frequency resolution. Since we are focusing on a high-precision MSP for tests of General Relativity and measurement of other properties, having full polarization data with high dynamic range and significant resistance to RFI in order to measure high quality and high signal-to-noise individual pulses is crucial. As a result, VEGAS seeks to offer enough processing capacity to support these observations for a common user backend on the GBT.

[1]GBT has several cutting-edge design features such as **unblocked aperture** that reduces sidelobes, spectral standing waves, and **active surface** that compensates gravity and thermal distortions. Thus, these characteristics together with its large aperture and the VEGAS pulsar backend, makes GBT the most suitable telescope for our study.

3 Technical Justification

We request to observe PSR J0737-3039, a double pulsar system with a total of 36.75 hours of observation time. The observational requirements and telescope resources are summarised in table 2. We propose to observe the system at 400 MHz, 800 MHz, and 1.4 GHz, each

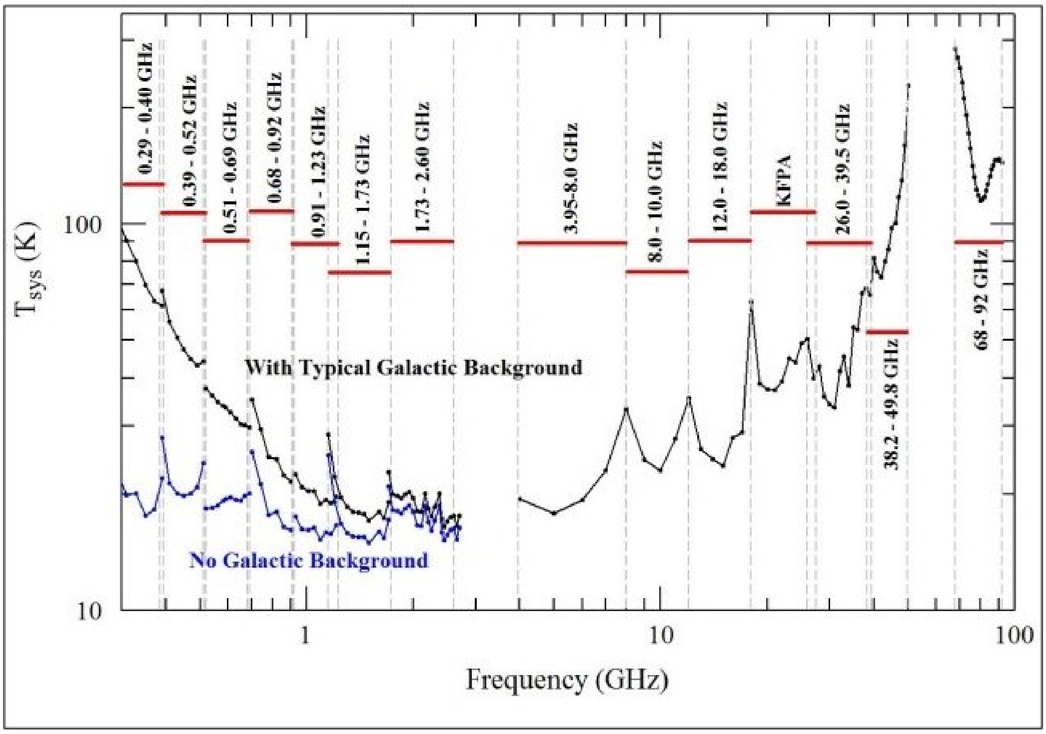

Figure 3: System Temperature of GBT for typical weather conditions[1]

with a bandwidth ($\Delta\nu$) of 200 MHz, as it helps to model the pulsar spectra and measure the pulse shape, amplitude, and polarization as a function of frequency. The system is decided to observe for 12.25 hours at each frequency allowing for 5 full orbital coverage. We intend to use the Prime Focus 1 (PF1) receiver to observe at 400 and 800 MHz, and the Gregorian receiver to observe at 1.4 GHz with VEGAS in pulsar mode for the backend processing. From figures 1 and 2, it is evident that for the frequencies at which we propose to observe, the aperture efficiency (η) is 0.71 and the [2]system temperature (T_{sys}) is around 20 to 50 K with no galactic backgrounds. The gain is calculated as 2 K/Jy using equation 6 where k is the Boltzmann constant and A_{eff} is the effective area. We calculated the noise level/sensitivity of the observations achieved at all the frequencies to be around 0.003 mK (0.0022 mJy) using equation 7 where τ is the integration time, K_1 and K_2 are the [1,2]backend sampling efficiency and [1,2]backend channel weights corresponding to VEGAS ($K_1 = K_2 = 1$) and N_{pol} is the number of independent polarization channels to be averaged which is 2.

$$Gain = \frac{\eta * A_{eff}}{2k} \tag{6}$$

$$dT = \frac{K_1 * T_{sys}}{\sqrt{K_2 * N_{pol} * \Delta\nu * \tau}} \tag{7}$$

The resolution/FWHM of GBT at the observing frequencies is calculated using the formula provided in the [1]GBT Handbook (Equation 8) and is given in table 2. T_e is the edge taper of the feed's illumination of the dish in decibels and it varies with frequency and polarization for all of the GBT feeds. For the PF receivers the edge taper is typically 18 $\pm$ 2 Db and for the Gregorian feed the edge taper is typically 14 $\pm$ 2 Db. [2]Confusion limit is an important term to consider since desired sensitivities in some observing modes are not reachable due to confusion from multiple background sources within the beam . This factor depends upon the observing frequency and the FWHM beam width of the telescope at that frequency and is given by equation 9.

Table 2: Observational Summary

Frequency, f (MHz)	400	800	1400
Integration time, τ (seconds)	44100	44100	44100
Resolution, θ (arcminutes)	30.75	15.37	8.7
Sensitivity (μJy)	2	1	0.8
Confusion Limit (Jy)	1.8	0.2	0.06
Receiver	PF 1	PF 1	Gregorian
[2]**System Temperature, T_{sys} (K)**	56.1	25.6	21.0
Backend	VEGAS - Pulsar mode		
Bandwidth $\Delta\nu$ (MHz)	200		
Source Right Ascension (J2000)	$07^h37^m51^s.247$		
Source Declination (J2000)	$-30°39'40''.74$		

$$\theta = (1.02 + 0.0135 + T_e) * \frac{\lambda}{100} \tag{8}$$

$$\textit{Confusion Limit} = \frac{0.13 * \theta^2}{f^{0.7}} Jy \tag{9}$$

Thus, from the calculated sensitivity, resolution and confusion limit, we conclude that 12.25 hours of observation at each frequency would be sufficient to capture the properties of PSR J0737-3039 and model its spectra. This study can also be a pathfinder for follow up observations on PSR J0737-3039 for pulsar timing applications and search for low-frequency gravitational waves.

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