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A neutral hydrogen distance limit to the relativistic binary PSR J1141−6545

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ABSTRACT

We have obtained an HI absorption spectrum of the relativistic binary PSR J1141−6545 and used it to constrain the distance to the system. The spectrum suggests that the pulsar is at, or beyond, the tangent point, estimated to be at 3.7 kpc. PSR J1141−6545 offers the promise of stringent tests of General Relativity (GR) by comparing its observed orbital period derivative with that derived from other relativistic observables. At the distance of PSR J1141−6545 it should be possible to verify GR to an accuracy of just a few percent, as contributions to the observed orbital period derivative from kinematic terms will be a small fraction of that induced by the emission of gravitational radiation. PSR J1141−6545 will thus make an exceptional gravitational laboratory.

Key words: pulsars:general – pulsars:individual (PSR J1141 - 6545) – stars:distances

1 INTRODUCTION

An independent confirmation of General Relativity (GR) has recently been obtained using a measurement of the annual orbital parallax of the binary millisecond pulsar PSR J0437−4715 to derive the inclination angle of the binary, thus predicting the shape of the Shapiro delay [van Straten et al. 2001]. In this test, as with those using self-consistency checks, GR has been shown to be a remarkably accurate description of gravity. Measurement of post-Keplerian (PK) orbital parameters in relativistic binary pulsars [Damour & Taylor 1992], have provided the most stringent tests of GR to date. PSR B1913+16 displays a measurable orbital period derivative (\( \dot{P}_b \)), time dilation and gravitational redshift parameter (\( \gamma \)) and an advance of periastron (\( \dot{\omega} \)), which are all consistent with GR [Taylor & Weissberg 1983]. Damour & Taylor 1991 [Taylor 1994]. Unfortunately, at the \( \sim 1\% \) level, these tests cannot be authoritative because of our ignorance of the distance and exact contribution of the Galactic potential to the observed orbital period derivative of the binary system. PSR B1534+12 is a nearby relativistic pulsar which demonstrates all of the above PK phenomena, together with the range (\( r \)) and shape (\( s \)) of Shapiro delay which have been shown to be remarkably self-consistent with GR [Stairs et al. 1998]. As predicted by Bell and Bailes (1996), this pulsar could not be used to verify the emission of gravitational radiation at better than the 15\% level because of the uncertain distance to the pulsar. Instead, Stairs et al. (1998) have used GR to obtain the pulsar distance to a high degree of accuracy.

The relativistic binary pulsar PSR J1141−6545 was recently discovered in the Parkes multibeam pulsar survey (Kaspi et al. 2000). It has a spin period (\( P \)) of 394 ms, a very narrow pulse (0.01\( P \)) and is in an eccentric, 4.7 hr orbit. The measured \( \dot{\omega} \) is 5.3 degrees yr\(^{-1} \) and it has a predicted \( \dot{P}_b \) of \(-3.85 \times 10^{-13} \), which is twice that observed for PSR B1534+12, but nearly an order of magnitude less than that observed for PSR B1913+16. Tests of GR using PSR J1141−6545 would nicely complement those already made using the other relativistic systems because it is thought to contain a neutron star and a white dwarf, rather than two neutron stars, as in the PSR B1534+12 and PSR B1913+16 systems. Within a few years, the orientation and component masses should be known to high
accuracy from measurements of the advance of periastron and \( \gamma \) terms. This will completely specify the orbital geometry of the system and make a specific prediction about the magnitude of the orbital period derivative.

A dispersion measure (DM) of 116 pc cm\(^{-3}\) places this pulsar at a distance of 3.2 kpc using the Taylor and Cordes (1993) model. These estimates can be significantly in error. In individual cases the error in the DM-distance can be as great as a factor of 2. If this distance is correct the kinematic “contamination” of the observed orbital period derivative would be small. Hence, PSR J1141–6545 could be an extremely good gravitational laboratory.

The detection of neutral hydrogen absorption features in the spectrum of a pulsar, together with a detailed neutral hydrogen emission spectrum in the same direction, can be used to place constraints upon its distance. A discussion of the neutral hydrogen distance determination method is given by Frail and Weisberg (1990) and the most recent review is by Weisberg (1996). In this paper we use neutral hydrogen measurements to constrain the distance of PSR J1141–6545 and show that it should be an exceptional laboratory for testing GR.

2 OBSERVATIONS AND METHOD

The observations were carried out over 3 days from the 11th of January to the 13th of January 2001 using the Parkes 64 m radio telescope. The observing system used was the Caltech–Parkes-Swinburne recorder (CPSR)2; a baseband recorder which performs 2-bit sampling on two 20-MHz bands, recording the data onto four parallel DLT 7000 tapes for off-line processing. The observations were centred in frequency at 1413 MHz, which places neutral hydrogen (1420.406 MHz) comfortably in the observing band. The observations were reduced at Swinburne University of Technology on a Beowulf-style cluster of workstations.

In order to examine the structure of the neutral hydrogen absorption and emission features in the pulsar spectrum we employed a software filterbank using standard Fourier techniques. 16384 channels were formed across the 20 MHz observing band. The Stokes I parameter was obtained, by summation of the detected left and right linear polarisations, and then folded at the topocentric period of the pulsar. Due to the high frequency resolution, the time resolution was reduced to 0.8192 ms. Folded profiles with 256 phase bins were formed and individual integrations were summed together using an accurate pulsar ephemeris to produce a single archive consisting of approximately 15.3 hours of data. In order to increase the signal to noise ratio in an individual channel the frequency resolution was reduced by a factor of 7 to 8.5 kHz. This corresponds to a velocity resolution of 1.8 km s\(^{-1}\).

The emission spectrum was formed by calculating the mean level in the off-pulse region and the pulsar spectrum was formed by subtracting the off-pulse spectrum from the on-pulse spectrum. The resultant pulsar spectrum was not completely flat due to interstellar scintillation effects, but nevertheless, two major absorption features are clearly visible in it. The error bars presented in the absorption spectrum were calculated from the root mean square deviation of the off-pulse region of the profile in each frequency channel. This was a direct measure of the error associated with each point in the absorption spectrum.

In transforming the wavelength range into a velocity range account was made of the orbital velocity of the Earth and the velocity of the solar system relative to the local dynamical standard of rest (LSR). The variation of the rotational velocity of the Earth, an effect of maximum magnitude 0.4 km s\(^{-1}\) for a pulsar at this declination (\(\text{\degr}65\)) was neglected, as was the 0.15 km s\(^{-1}\) change in the Earth's orbital velocity during the observations. These contributions are small compared to our presented velocity resolution of 1.8 km s\(^{-1}\).

2.1 Calibration considerations

As a software filterbank was employed, instrumental factors, such as differential gain between channels, which plague analogue filter bank spectrography were not an issue. The software filterbank had uniform response over the entire bandpass. We did not, therefore, employ the technique of frequency switching to ensure instrumental effects were removed in the production of emission spectra. We calibrated the baseline subtracted emission spectrum from the neutral hydrogen survey performed by Kerr et al. (1986). Following Koribalski et al. (1995) we consider the error in the peak value of the brightness temperature to be 5 K. The structure of the emission spectrum is in good agreement with that presented by Kerr et al. (1986).

The absorption spectrum is shown in Fig. 1 as both a ratio of the measured absorption to the baseline, and as an optical depth, \( \tau \), where \( I = I_0 \times e^{-\tau} \).

3 DISTANCE DETERMINATION

In order to ascribe a distance to any feature in either the absorption or emission spectrum we transformed the observed velocity into a distance via a Galactic rotation model. The model used was that of Fich, Blitz & Stark (1989). A systematic uncertainty of 7 km s\(^{-1}\) is assumed in the velocity–distance conversion. Even with this error it is clear from Fig. 2 that there is significant emission at velocities forbidden by the rotation model.

The Galactic coordinates of J1141-6545 are \( \ell=295^\circ.77, b=-3^\circ.8 \). This is in the direction of the Carina spiral arm. The emission spectrum clearly shows a peak at approximately 20 km s\(^{-1}\) which is associated with this spiral arm. Other pulsars in this direction also display similar emission at forbidden velocities. It is generally considered that the discrepancy between the model and the observations in this direction is due to the streaming motion of the gas in the Carina spiral arm (Johnston et al. 1999).

A lower distance limit is found by ascertaining the distance of the most distant absorption feature in the pulsar spectrum. Upper distance limits are obtained by a determination of the furthest significant feature in the neutral hydrogen emission spectrum which does not have a corresponding absorption feature. The relative strengths of the emission and absorption features are used to determine not only the significance of the spectral features but can be used to determine the temperature of the neutral hydrogen.
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3.1 Interpretation of features

The important points to consider here are the significance of any absorption feature and the likelihood of a given emission feature appearing in the absorption spectrum. In order to ascribe a level of significance to absorption and emission features we applied the criterion of Weisberg, Boriakoff and Rankin (1979). That is, any emission feature with brightness temperature \( T_B \), greater than 35 K rarely displays an optical depth \( \tau \), less than 0.3. In applying this criterion to the spectra it is clear that although the absorption is not associated with the emission all the way out to the the velocity of the most negative emission feature, there is significant absorption associated with all emission brighter than 35 K. From this we ascribe a lower distance limit to this pulsar of 3.7 kpc which is the distance of the tangent point in this direction using the Fich, Blitz and Stark (1989) model. There is probably a 10 to 15% discrepancy between this distance estimation and the actual distance to the tangent point [Fich, Blitz & Stark 1989].

Obtaining an upper distance limit is not possible as there is no emission feature at positive velocities greater than our chosen 35 K significance level.

3.1.1 Contamination of the Absorption Spectrum

This type of observation is prone to contamination of the absorption spectrum by features in the emission spectrum. This arises as the absorption spectrum is formed by subtracting two profiles of similar amplitude. Any nonlinearities in the digitisation or detection process will appear in the absorption spectrum as inverted emission spectrum features. In order to ascertain the level of this contamination, the observational technique applied to PSR J1141−6545 was also applied to PSR J1644−4559, a bright pulsar with a well known neutral hydrogen spectrum. The absorption spectrum for PSR J1644−4559 is presented in Fig. 2 and is found to be in excellent agreement with that published in the literature (Ables and Manchester 1976; Frail et al. 1991), which validates our experimental technique. We thus consider the presented absorption spectrum of PSR J1141−6545 to be free of any appreciable contamination from features in the emission spectrum.

4 DISCUSSION

The distance ascribed to this pulsar from its dispersion measure is 3.2 kpc. The limit obtained here serves as an independent distance measure and allows a number of consequences to be explored.

4.1 Electron Density

As the DM of the pulsar is known, we can use the neutral hydrogen distance to give an upper limit on the electron density in this direction. The DM of PSR J1141−6545 is approximately 116.2 pc cm\(^{-3}\). A distance limit of greater than 3.7 kpc provides an upper limit to the mean electron density along this line of sight of 0.03 cm\(^{-3}\).
4.2 The Binary Orbital Period Derivative

The secular decrease of binary orbital period, $\dot{P}_b$, has been successfully observed in PSR B1913+16 (Taylor & Weisberg 1989; Damour & Taylor 1991; Taylor 1994) and PSR B1534+12 (Stairs et al. 1998). While the measured value is dominated by the emission of gravitational radiation, unfortunately there are many possible contributions to an observed orbital period derivative (Damour & Taylor 1991). They include: the component predicted by GR; the acceleration of the centre of mass of the binary system with respect to the Sun due to the gravitational field of the Galaxy, and the apparent acceleration induced by the proper motion of the system.

Tauris and Sennels (2000) have predicted that the space velocity of the binary should be greater than 150 km s$^{-1}$ but Kaspi et al. (2000) point out that the age and Galactic latitude of the system suggest its velocity perpendicular to plane must be $\sim 150(d/3.2\text{kpc})$ km s$^{-1}$. It is possible to examine the magnitude of the kinematical contribution to any measured orbital period derivative. For transverse velocities in the range 100 - 200 km s$^{-1}$ the level of the kinematical contribution to $\dot{P}_b$ is just a few percent, but without a measurement of the proper motion, we will be unable to confirm GR. The prospects of making a quick proper motion measurement are not clear. Young pulsars like PSR J1141−6545 have intrinsic timing noise which make proper motion measurements difficult from timing on short baselines. Interferometric observations may be more useful. PSR J1141−6545 has a very narrow pulse and a reasonable flux density at 20 cm wavelength. If a suitable reference could be found, an accurate proper motion should be obtainable via VLBI within a few years.

An upper limit to the distance of PSR J1141−6545 will be more difficult to obtain. The distance method employed by Stairs et al. (1998) for PSR B1534+12 will be less accurate in the case of PSR J1141−6545, because the kinematic terms are a much smaller fraction of the relativistic contribution to the observed orbital period derivative.

5 CONCLUSION

The measurement of the absorption spectrum of this pulsar has allowed a lower limit to be placed upon its distance of 3.7 kpc, the tangent point distance predicted by the Galactic rotation curve. The mean electron density in the direction of this pulsar is therefore at most 0.03 cm$^{-3}$. We have also examined the Galactic and kinematic contribution to the observed $P_b$ and found that it should only be at the few percent level for reasonable pulsar transverse velocities making PSR J1141−6545 an excellent gravitational laboratory. Future measurements of the system’s proper motion will help to further define the level at which this system can be used to test GR.

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