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A VERY LUMINOUS BINARY MILLISECOND PULSAR

JOSÉ NAVARRO
National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801; jnavarro@nrao.edu
A. G. DE BRUYN[1]
Netherlands Foundation for Research in Astronomy, Postbus 2, 7990 AA Dwingeloo, Netherlands; and Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, Netherlands; ger@nfra.nl
D. A. FRAIL
National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801; dfrail@nrao.edu
S. R. KULKARNI
Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Caltech 105-24, CA 91125; srk@astro.caltech.edu
AND
A. G. LYNE
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK; agl@jb.man.ac.uk
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ABSTRACT

We report the discovery of a field binary millisecond pulsar, J0218+4232, with a period of 2.3 ms and in a 2.0 day binary orbit with a $\gtrsim 0.16\ M_\odot$ companion. The new pulsar was serendipitously discovered as a steep-spectrum, highly polarized, compact radio source during imaging observations at Westerbork, and was later confirmed to be a pulsar with observations carried out with the 76 m antenna at Jodrell Bank. With a dispersion measure of 61 pc cm^{-3}, it lies outside the electron layer in the direction $l = 140°$, $b = -18°$. At a distance of more than 5.7 kpc, it is the farthest known field millisecond pulsar and has a radio luminosity L_{400} comparable to that of PSR B1937+21. It appears that a significant fraction of the radio emission is not pulsed. This, together with the extremely broad pulse profile, suggests that we are looking at an aligned rotator.

Subject headings: ISM: structure — pulsars: individual (PSR J0218+4232) — surveys

1. INTRODUCTION

While the majority of pulsars discovered to date have been made in systematic, untargeted searches for pulsations (Manchester 1994; Nice 1994), major developments in pulsar astronomy have often been initiated by discoveries made by targeted imaging surveys. Indeed, the first millisecond pulsar, B1937+21, was identified initially as an interesting compact, steep-spectrum continuum source (Backer et al. 1982). Similarly, the first globular cluster pulsar, B1821−24, was found in a VLA imaging survey of globular clusters (Hamilton, Helfand, & Becker 1985). B1951+32 was first identified as a polarized, steep-spectrum point source in the supernova remnant CTB 80 (Strom 1987), which led to the study of PSR/SNR interactions (Shull, Fesen, & Saken 1989).

Single-dish pulse surveys, while productive, suffer from three major selection effects. First, the period of the pulsar must be at least twice (and in practice 4–8 times) the interval with which each spectral channel is sampled. Second, the smearing of the pulsed signal across each spectral channel sets a limit to DM/P, where DM is the dispersion measure and P is the period of the pulsar. Finally, the periods of pulsars in tight binaries undergo large changes across the integration interval which decrease the sensitivity of ordinary pulsar searches (Johnston & Kulkarni 1991). The real strength of the imaging approach is that a pulsar candidate, once identified (on the basis of high linear polarization and steep spectral index), motivates one to carry out a thorough search of the available parameter space. In this Letter we report the discovery of a millisecond pulsar which was first identified as a potential pulsar candidate by imaging observations. Such a pulsar would have likely been missed in the current generation of millisecond pulsar searches.

2. IMAGING OBSERVATIONS

In a program designed to study the low-frequency spectrum and variability of the radio supernova SN 1986J (Rupen et al. 1987) in the spiral galaxy NGC 891, one of us (A. G. dB. in collaboration with J. M. van der Hulst) acquired a long series of Westerbork Synthesis Radio Telescope (WSRT) observations at frequencies of 325 and 610 MHz. The large field of view synthesized at 325 MHz (2°.7 full width at half-maximum) resulted in the detection of numerous background sources, those at the edge of the field appearing to be polarized as a result of instrumental effects. When testing software to correct for this off-axis polarization, a relatively weak source was discovered with an anomalously high linear polarization, about 50′ west of the galaxy NGC 891. This indicated that the source had to be intrinsically polarized, with an average 40% linear polarization, much higher than the expected instrumental polarization of 5% at that location in the field of view.

Inspection of the 610 MHz observations of the same field, also carried out with the WSRT, revealed the source to have an extremely steep spectrum ($\alpha = -3$, where the radio flux density $S_\nu \propto \nu^\alpha$). Observations from 1986 to 1991 also showed it to be variable from one synthesis to the next. A literature search showed that the source was also in the 6C catalog (Hales, Baldwin, & Warner 1993) with a flux density of 0.66 Jy at 151 MHz, and in a 34.5 MHz survey (Dwarakanath &

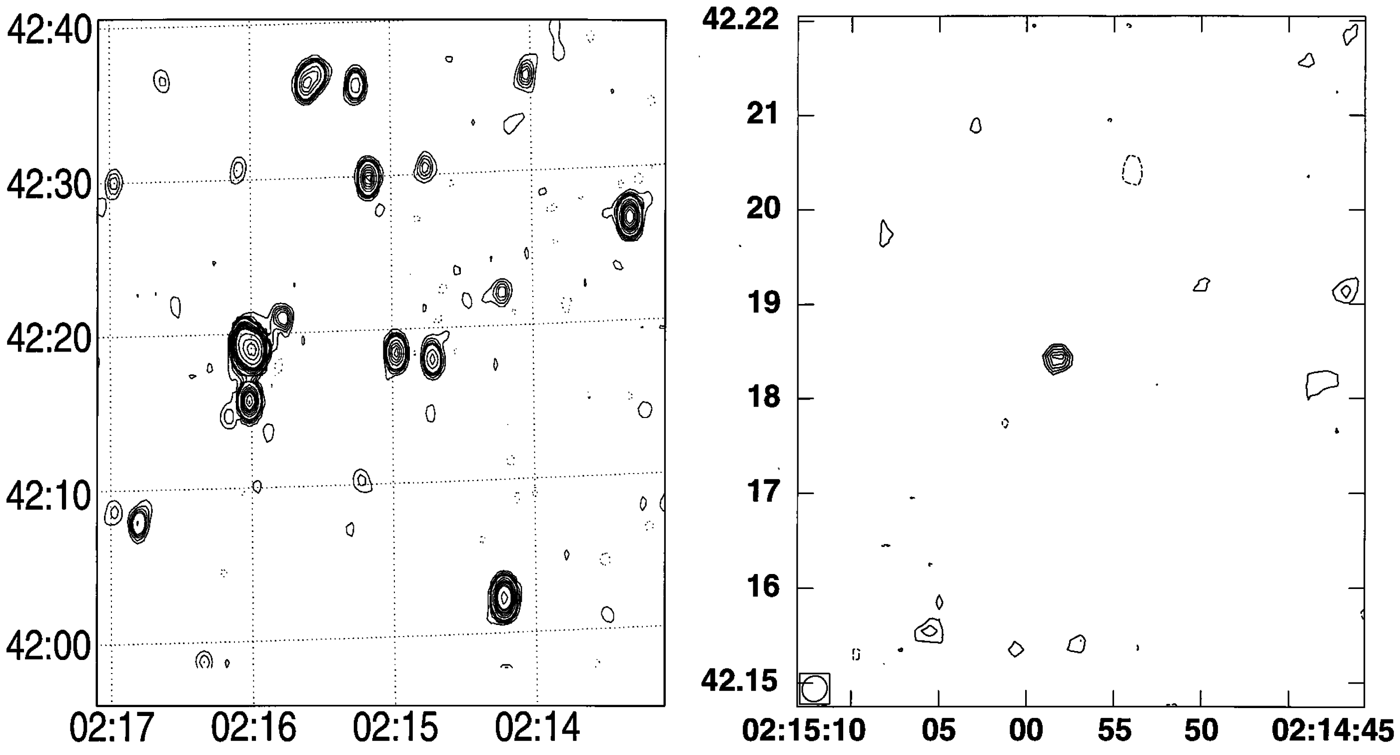

FIG. 1*a*

FIG. 1*b*

FIG. 1.—Two synthesis maps of PSR J0218+4232. The left-hand image is from WSRT at 325 MHz, and the right-hand image is from the VLA in A array, at 333 MHz. PSR J0218+4232 is the left central source in the WSRT image and the central source in the VLA image. In both cases, the apparent size of the candidate source is comparable to the synthesized beam sizes. The fields displayed are 45′ and 7′, respectively. The axes are labeled in B1950 coordinates.

Shankar 1990) with a flux density of 30–50 Jy. These independent observations confirmed the spectral index of −3. In 1992 January we observed and obtained images of the candidate source with the Very Large Array (VLA) at 333 MHz and at 1.4 GHz. The low-frequency WSRT and VLA images are shown in Figure 1.

From the WSRT observations we calculated a rotation measure RM = −61 rad m^{-2} (de Bruyn et al. 1995), similar to the rotation measures of −67 and −81 rad m^{-2} of the two nearby extragalactic sources 3C 66B and 3C 65 at offsets of 1°1 and 2°6 from the source (Simard-Normandin, Kronberg, & Button 1981). This suggested that our source had to be outside the Galactic magnetoionic layer and led us to expect a large dispersion measure, DM ≥ 50 pc cm^{-3} (Taylor & Cordes 1993).

3. SEARCHES FOR PULSATIONS

The steep spectral index and high linear polarization were reminiscent of PSR B1937+21 and made the new source a prime candidate for a millisecond pulsar. Consequently, we mounted a campaign to look for pulsations. In 1992 February we observed the source using the phased VLA with the High Time Resolution Processor (HTRP; see McKinnon 1992). At 333 MHz the HTRP sampled a 1 × 4 × 0.125 MHz (single polarization, 4 channel) filter bank every 0.3 ms, while at 1.4 GHz we used both a 2 × 14 × 2 MHz filter bank sampled every 1.24 ms and a 2 × 14 × 4 MHz filter bank sampled every 0.67 ms. No pulsations were discovered in either configuration, the reasons being dispersion smearing ($\Delta t \sim 1.7$ ms) comparable to the pulsar period at 333 MHz and too little flux from the pulsar at 1.4 GHz.

From the WSRT observation we measured an apparent variation in the RM of the source, and this led us to consider seriously a binary model in which the pulsar might be ablating the companion as in the case of PSR B1957+20 (Fruchter, Stinebring, & Taylor 1988), or perhaps even precessing. The large DM inferred from the failure of the VLA searches, together with the apparent RM variations, led us to conclude that we were dealing with either a very rapidly rotating pulsar or a pulsar in a tight binary. CCD photometry on the Nordic Optical Telescope in 1993 January (P. D. Barthel, private communication) revealed no optical sources brighter than $R = 22.5$ mag at the VLA 1.4 GHz position.

In order to overcome the limitations of the HTRP searches, we decided to observe at low radio frequencies and directly record the electric field (base-band recording), allowing a coherent de-dispersion analysis of the data. For this purpose, the principal author developed special hardware (Navarro 1994) to read VLBI Mk III tapes (Clark & Rogers 1982; Wrobel 1991) as well as an interface to read the data through the Caltech-JPL Block II processor. Data were obtained at both WSRT and the VLA. The effort met considerable technical difficulty, during which time the apparent variable rotation measure was traced back to incorrect polarization calibration. After proper calibration we found that the source had a steady position angle and constant rotation measure. The coherent de-dispersion effort was then abandoned, and we

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TABLE 1

OBSERVED AND DERIVED PARAMETERS FOR PSR J0218+4232

Parameter	Value
Continuum Observations	
Right ascension (J2000)	$02^h18^m06\overset{s}{.}50$ (15)
Declination (J2000)	+42°32′16″ (2)
Flux density at 34.5 MHz (mJy)	30,000–50,000
Flux density at 150 MHz (mJy)	660
Flux density at 325 MHz (mJy)	100–200
Flux density at 608 MHz (mJy)	26
Flux density at 1400 MHz (mJy)	1–2
Rotation measure (rad m^{-2})	−61
Pulsed Observations	
Right ascension (J2000)	$02^h18^m06\overset{s}{.}348$ (1)
Declination (J2000)	+42°32′17″.42 (1)
Epoch of period (MJD)	49,150.6086
Period (s)	0.00232309045631 (1)
Period derivative (10^{-20} s s^{-1})	8.00 (4)
Dispersion measure (pc cm^{-3})	61.2513 (6)
Orbital period (s)	175,292.303 (2)
Projected semimajor axis (lt-s)	1.98444 (1)
Eccentricity	<0.00002
Time of ascending node (MJD)	49,150.608824 (2)
Mass function ($M_\odot$)	0.00203844 (3)
Flux density at 410 MHz (mJy)	30–40
Flux density at 606 MHz (mJy)	3–13
Flux density at 1410 MHz (mJy)	0.7–1.1
Derived Parameters	
Spin-down age (yr)	4.6×10^8
Magnetic field strength (G)	4.3×10^8
Companion mass ($M_\odot$)	0.16/sin i
Galactic longitude	139°.58
Galactic latitude	−17°.72
Distance (kpc)	>5.7
Spin-down luminosity (ergs s^{-1})	2.5×10^{35}
Radio luminosity, L_{400} (mJy kpc^2)	>2700
Spectral index	−3

returned to traditional pulsar search methods, this time convinced that our candidate had a large DM/P ratio.

Using the 76 m Lovell telescope at Jodrell Bank in 1993 January, we recorded data at 411 MHz data in two configurations: a $2 \times 32 \times 31.25$ kHz filter bank sampled every 150 μs (for 20 minutes) and a $2 \times 64 \times 125$ kHz filter bank sampled every 300 μs (for 35 minutes). The data were processed with the Caltech pulsar search software, PSRPACK (Deich 1995). It was in these data that we finally detected pulsations at a period of 2.3 ms in all on-source files and in none of the off-source files. The dispersion measure for this signal was 61.2 pc cm^{-3}, confirming our expectations.

Subsequent timing observations have been conducted at Jodrell Bank with de-dispersing filter banks at 410, 606, and 1410 MHz and have revealed that the pulsar is in a 2 day orbit with a low-mass companion star. The typical uncertainty in the times of arrival is 60 μs. The observations of PSR J0218+4232 now span 2 years and give the timing solution shown in Table 1. No radio eclipses are seen, although at some epochs the pulsar has been barely detectable as a radio source at 1.4 GHz with the VLA, with a rms noise of only 0.25 mJy.

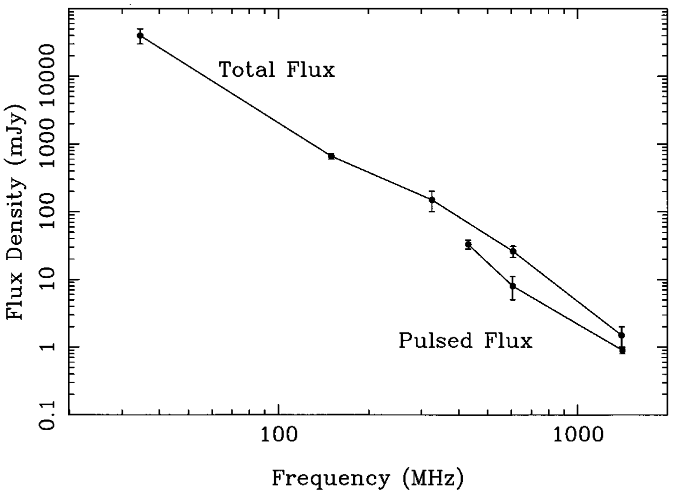

FIG. 2.—Radio spectrum of PSR J0218+4232 showing the total flux density, measured interferometrically, and the pulsed flux density. The latter accounts for only half of the total.

Figure 2 shows the spectrum measured using two techniques. The continuum flux was obtained from images taken at WSRT and the VLA, at 325, 608, and 1400 MHz on several epochs. We regularly measure the pulsed flux at 411, 606, and 1404 MHz at Jodrell Bank using the pulsar flux calibration techniques described in Lorimer et al. (1995b). The derived fluxes can also be found in Table 1. The pulsed flux is systematically only half of the total flux measured interferometrically over the frequency range 400–1400 MHz. It is possible that the additional emission comes from a compact nebula close to the pulsar, but this nebula would then have to have the same steep spectral index. In addition, there is no evidence of an extended nebula near the pulsar in either of the images in Figure 2 (VLA beam size ~16″).

The form of the pulse profile (Fig. 3) also leads us to believe that the additional emission comes from the pulsar. The pulse shape is broad and complex and is essentially the same at 410, 606, and 1400 MHz. There is no flat baseline to the profile at any longitude, which is seen in essentially all other pulsars and which would suggest an absence of emission. We therefore believe that approximately half of the flux from the pulsar is unpulsed. Figure 3 shows all the flux density from the pulsar, including the unpulsed emission.

4. DISCUSSION

The dispersion measure of PSR J0218+4232 places it outside the electron layer suggested by the model of Taylor &

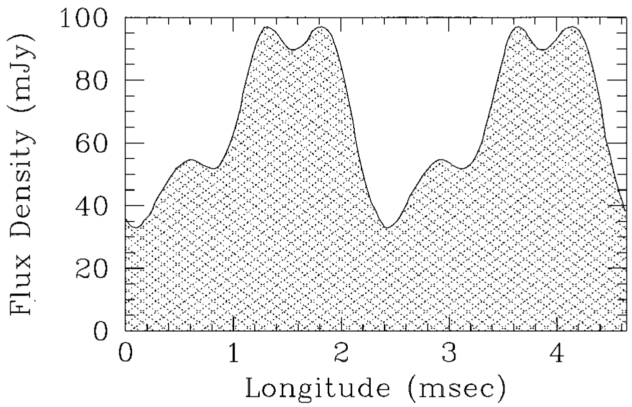

FIG. 3.—Pulse profile of PSR J0218+4232 at 410 MHz. The time resolution is 0.18 ms. The broad pulse shows no clear baseline, and the diagram represents our best estimate of the total flux density from the pulsar at all pulse phases.

Cordes (1993). According to this model, the maximum dispersion measure in the direction of the pulsar ($l = 140°$, $b = -18°$), is only 52 pc cm^{-3}, and as a result the pulsar seems to be farther than 5.7 kpc away and at least 1.75 kpc below the plane of the Galaxy. Such a large Galactic z-height is consistent with current understanding of the velocity and space distribution of millisecond pulsars (Bailes 1989; Phinney & Kulkarni 1994).

The orbital parameters quoted in Table 1 yield the mass function

$$f_1(m_1, m_2, \sin i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$
$$= \frac{4\pi^2}{G}\frac{(a_1 \sin i)^3}{P_b^2} = 0.00204\, M_\odot,$$

where m_1 and m_2 are the pulsar and companion masses, P_b is the binary period, and $a_1 \sin i$ is the length of the orbital semimajor axis projected onto the line of sight. For a typical pulsar mass $m_1 = 1.4\ M_\odot$, the companion mass would be $m_2 = 0.16/\sin i\ M_\odot$, consistent with it being a low-mass white dwarf, the remnant core of the giant star which was probably responsible for the spin-up of the neutron star to millisecond period (Alpar et al. 1982; Phinney & Kulkarni 1994).

We derive an upper limit of 2×10^{-5} to the orbital eccentricity e, consistent with the model of Phinney (1992), in which convection in the companion star responsible for the spin-up limits the circularity of the binary orbit. The wide pulse and low flux density mean that it will be hard to measure e down to the level of 10^{-6} predicted by the Phinney model.

Many of the features of J0218+4232—spin period, orbital period, magnetic field strength, and inferred companion mass—do not distinguish it from the disk millisecond pulsar population. However, there are two outstanding features that single it out and are worthy of further discussion.

First, J0218+4232 is extremely luminous: $L_{400} = S_{400}\, d_{\mathrm{kpc}}^2 > 2700$ mJy kpc^2. This may be compared to the luminosity of millisecond pulsars discovered in recent surveys at Parkes and Arecibo, where the brightest pulsar has $L_{400} \sim 1800$ mJy kpc^2 and the typical pulsar has $L_{400} \sim 10$ mJy kpc^2 (Bailes & Lorimer 1994).

Second, perhaps the most peculiar fact about PSR J0218+4232, is the discrepancy between the pulsed (single-dish) and continuum (interferometric) radio fluxes in Table 1 and Figure 2. Although the continuum flux is variable by as much as 30% (at 325 MHz), probably due to scintillation in the ISM (Rickett 1990), we have no evidence of eclipses (de Bruyn et al. 1995), and there is no indication of substantial scattering in the pulse profile. Multiple measurements have been made of both the pulsed and the continuum fluxes which show that the discrepancy is persistent. A simultaneous measurement of both components would eliminate any uncertainty and is planned for the near future.

In this context, it is significant that this pulsar has one of the broadest profiles of all millisecond pulsars. From the flux discrepancy and the absence of any flat baseline in the profile (Fig. 3), we infer that there is emission at all phases. If so, this is the first pulsar in which a large fraction of the radio emission is not pulsed. We speculate that J0218+4232 is an aligned rotator. Polarization studies of this pulsar would be most interesting.

The system may also permit optical studies of the cooling of low-mass white dwarfs (Kulkarni 1986). Although very distant, the companion is probably somewhat more massive and no older than the companion to PSR J1012+5307 (Lorimer et al. 1995a) which has a magnitude of 19.5. The star should therefore be brighter than about 24.5 mag and clearly visible with a large telescope.

The discovery of such an intrinsically luminous and interesting millisecond pulsar shows the advantage of imaging searches in uncovering unique pulsars and the importance of continuing searches for millisecond pulsars with more powerful pulsar search back ends so as to minimize selection effects.

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