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A RADIO-LOUD MAGNETAR IN X-RAY QUIESCENCE

Lina Levin[1,2], Matthew Bailes[1], Samuel Bates[3], N. D. Ramesh Bhat[1], Marta Burgay[4], Sarah Burke-Spolaor[1,2], Nichi D'Amico[4,5], Simon Johnston[2], Michael Keith[2], Michael Kramer[3,6], Sabrina Milia[4,5], Andrea Possenti[4], Nanda Rea[7], Ben Stappers[3], and Willem van Straten[1]

[1] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H39, P.O. Box 218, VIC 3122, Australia
[2] Australia Telescope National Facility–CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
[3] Jodrell Bank Centre for Astrophysics, University of Manchester, Alan Turing Building, Oxford Road, Manchester M13 9PL, UK
[4] INAF/Osservatorio Astronomico di Cagliari, localitá Poggio dei Pini, strada 54, 09012 Capoterra, Italy
[5] Dipartimento di Fisica, Universitá degli Studi di Cagliari, Cittadella Universitaria, 09042 Monserrato (CA), Italy
[6] Max Planck Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[7] Institut de Ciéncies de l'Espai (CSIC-IEEC), Campus UAB, Facultat de Ciéncies, Torre C5-parell, 08193 Barcelona, Spain
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ABSTRACT

As part of a survey for radio pulsars with the Parkes 64 m telescope, we have discovered PSR J1622−4950, a pulsar with a 4.3 s rotation period. Follow-up observations show that the pulsar has the highest inferred surface magnetic field of the known radio pulsars ($B \sim 3 \times 10^{14}$ G), and it exhibits significant timing noise and appears to have an inverted spectrum. Unlike the vast majority of the known pulsar population, PSR J1622−4950 appears to switch off for many hundreds of days and even in its on-state exhibits extreme variability in its flux density. Furthermore, the integrated pulse profile changes shape with epoch. All of these properties are remarkably similar to the only two magnetars previously known to emit radio pulsations. The position of PSR J1622−4950 is coincident with an X-ray source that, unlike the other radio pulsating magnetars, was found to be in quiescence. We conclude that our newly discovered pulsar is a magnetar—the first to be discovered via its radio emission.

Key words: pulsars: individual (1E 1547.0−5408, PSR J1622−4950, XTE J1810−197) – stars: magnetars – stars: neutron

1. INTRODUCTION

Magnetars are slowly rotating neutron stars that, in contrast to ordinary pulsars, are not powered by their spin-down energy losses, but by the energy stored in their extremely large magnetic fields, typically $\gtrsim 10^{14}$ G (Duncan & Thompson 1992). They are divided into two groups, soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs), whose relation to each other and to other kinds of neutron stars is still a matter of debate (Mereghetti 2008). SGRs were discovered as sources emitting short repeating bursts in the hard X-ray/soft γ-ray band, while AXPs were first detected in the soft X-ray band. Recently, sources have been found that show properties of both groups, suggesting that AXPs and SGRs belong to the same family (Rea et al. 2009; Mereghetti et al. 2009). Many attempts have been made to find pulsed radio emission from magnetars (see, e.g., Kriss et al. 1985; Gaensler et al. 2001; Burgay et al. 2006), but it was not until 2006 that the first detection was reported (Camilo et al. 2006). To date, only two AXPs have confirmed radio pulsations, namely XTE J1810−197 (Camilo et al. 2006) and 1E 1547.0−5408 (Camilo et al. 2007a). Both of these sources are transient AXPs, a subgroup of magnetars that occasionally undergo very bright X-ray outbursts. Their pulsed radio emission was discovered in connection with these outbursts.

Here, we report on the discovery of PSR J1622−4950, the first magnetar discovered in the radio band, and discuss its properties in relation to the two magnetars previously known to emit radio pulsations.

2. OBSERVATIONS AND HISTORICAL DATA

2.1. Parkes Observations

The High Time Resolution Universe (HTRU) survey for pulsars and fast transients is currently being carried out at the Parkes 64 m radio telescope (Keith et al. 2010), using the 20 cm multibeam receiver (Staveley-Smith et al. 1996). In brief, an effective bandwidth of 341 MHz, centered around 1.35 GHz, is divided into 874 frequency channels and sampled using 2 bits every 64 μs. In 2009 April (MJD = 54939), a bright radio pulsar, PSR J1622−4950, was discovered. It has a period (P) of 4.326 s and a dispersion measure (DM) of 820 cm^{-3} pc, corresponding to a distance of ~9 kpc, if the Cordes–Lazio model for the distribution of the electrons in the interstellar medium is assumed (Cordes & Lazio 2002).

After the HTRU discovery, we embarked on a timing campaign, observing PSR J1622−4950 a total of 110 times at 1.4 GHz and 10 times at 3.1 GHz, obtaining polarimetric information on most occasions. The digital filterbank system (DFB3) used to create the folded profiles first converts the analog voltages from each polarization channel of the linear feeds into digital signals. It then produces 1024 polyphase filterbank frequency channels that are folded at the apparent topocentric period of the pulsar into 1024 pulsar phase bins, and written to disk every 20 s. Four Stokes parameters are recorded. To determine the relative gain of the two polarization channels and the phase between them, a calibration signal is injected at an angle of 45° to the feed probes. The data are analyzed off-line using the psrchive package[8] (Hotan et al. 2004) and corrected for parallactic angle and the orientation of the feed. The position angles are also corrected for Faraday rotation through the interstellar medium using the nominal rotation measure.

2.2. Archive Mining

The area of sky containing PSR J1622−4950 was previously covered by the Parkes Multibeam Pulsar Survey (Manchester et al. 2001) but, somewhat surprisingly given its large apparent

[8] See http://psrchive.sourceforge.net.

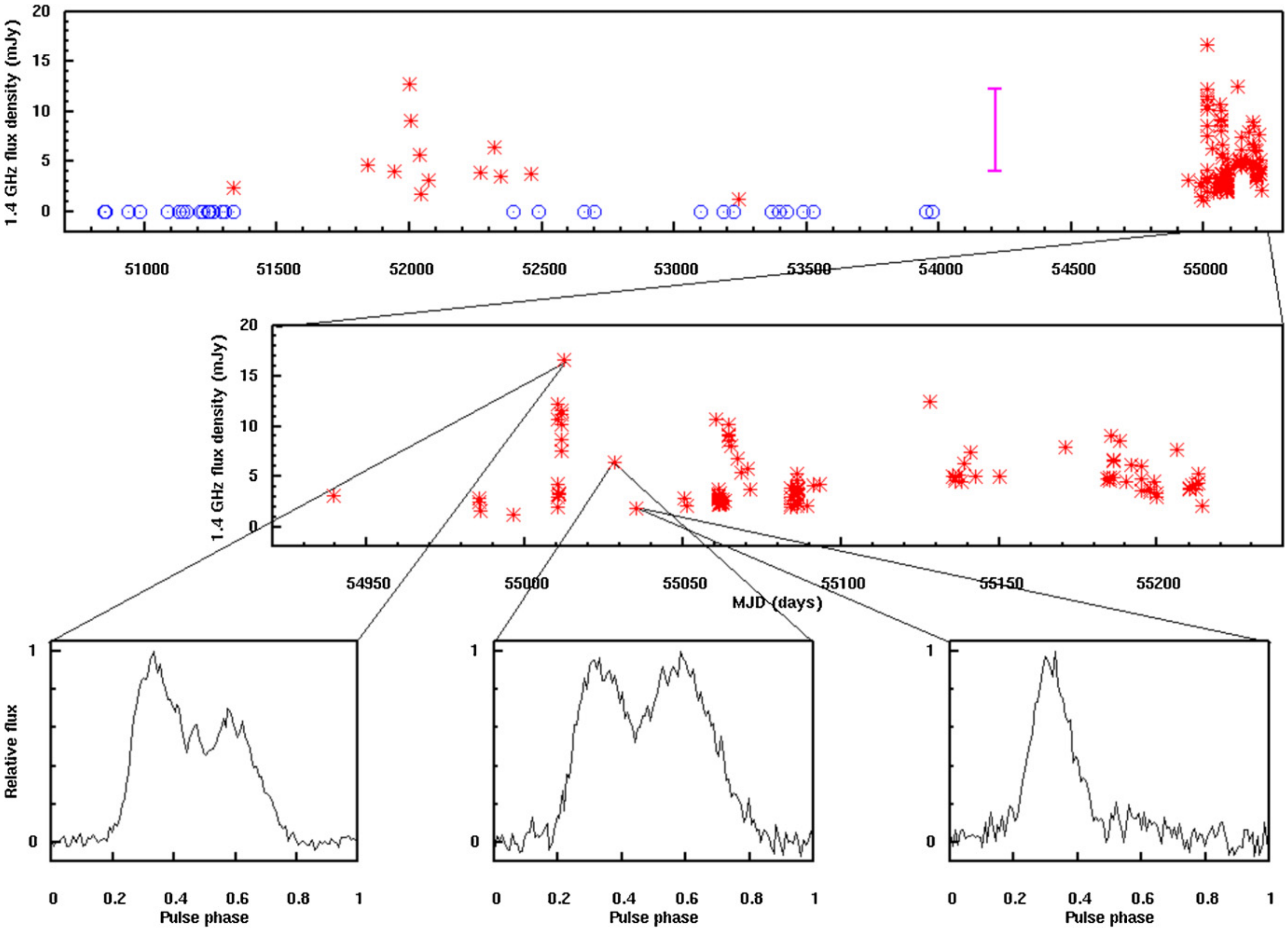


Figure 1. Light curve and profile variations for PSR J1622−4950. The top plot shows the temporal variation of flux density at 1.4 GHz. Archival timing data collected within the framework of the Parkes Multibeam Survey ends just before MJD = 54000, and the discovery of PSR J1622−4950 by the HTRU pulsar survey was made on MJD = 54939. The red asterisks show the detections (with errors smaller than the size of the points), and the blue circles indicate observations during which PSR J1622−4950 was not detected (down to a limiting flux density of 1.2 mJy). The purple error bar indicates the observation centered at 6.3 GHz from the Methanol Multibeam survey that detected PSR J1622−4950. When converted into a 1.4 GHz flux density, the large error is dominated by the uncertainty in the spectral index; the top value of the bar corresponds to a flat radio spectrum, and the bottom value is derived from our best estimate of the spectral index. The bottom plots show three different pulse profiles from three consecutive observations, taken on 2009 June 30, 2009 July 16, and 2009 July 23.

flux density and DM, the pulsar was not detected in these data. However, that survey did find two other radio pulsars in close proximity to PSR J1622−4950 and monitored them for a number of years, namely PSRs J1623−4949 and J1622–4944 at an angular separation of 11′ and 7′, respectively. These archival data were reprocessed using the period and DM of PSR J1622−4950. The first detection was made in observations recorded in June 1999 (MJD = 51334), and it was then detected in 11 observations between 2000 October (MJD = 51844) and 2002 July (MJD = 52458; see the top panel of Figure 1). However, in the 14 subsequent observations preceding 2006 August (MJD = 53975), the pulsar was detected only once. No further archival data of the two nearby pulsars were available after that date. The Methanol Multibeam pulsar survey at 6.3 GHz (S. Bates et al. 2010, in preparation) also covered the part of the sky containing PSR J1622−4950, and by reprocessing the relevant data, the pulsar was detected in an observation taken in 2007 April (MJD = 54211).

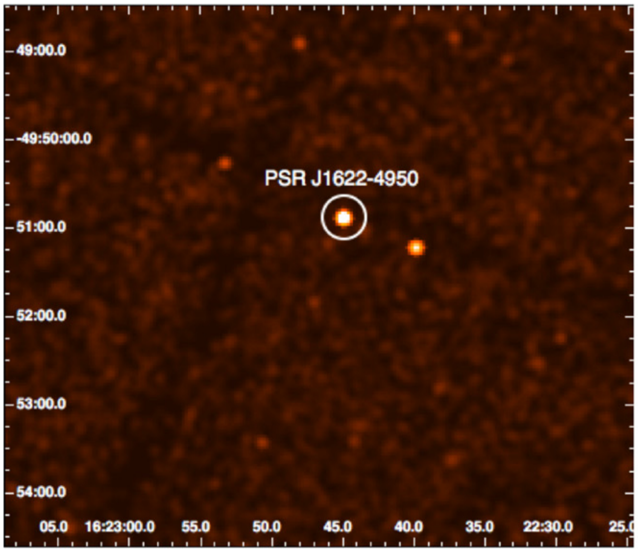
2.3. *ATCA and Chandra Observations*

Observations of the pulsar were made on 2009 December 8 and 2010 Feburary 27 with the Australia Telescope Compact Array (ATCA), an east–west synthesis telescope located near Narrabri, NSW, which consists of six 22 m antennas on a 6 km track. The observations were carried out simultaneously at 5.5 and 9.0 GHz with a bandwidth of 2 GHz at each frequency subdivided into 2048 spectral channels, and full Stokes parameters. The source was tracked for 12 hr in each of the EW352 and 750B array configurations.

Initial data reduction and analysis were carried out with the MIRIAD package[9] using standard techniques. After flagging bad data, the primary calibrator (PKS 1934−638) was used for flux density and bandpass calibration and the secondary calibrator (PKS J1613−586) was used to solve for antenna gains, phases, and polarization leakage terms.

We also obtained a 20 ks *Chandra* observation performed with ACIS-I on 2009 July 10 to search for an X-ray counterpart. Figure 2 shows the resultant radio and X-ray images. Although there are a number of radio and X-ray sources present in the field of view, a highly polarized radio point source is coincident with the brightest X-ray source, CXOU J162244.8−495054, which is also the counterpart of a source seen in archival *ASCA* data, AX J162246−4946. We note that CXOU J162244.8−495054 was one of only two X-ray sources in the field without an

[9] See http://www.atnf.csiro.au/computing/software/miriad.



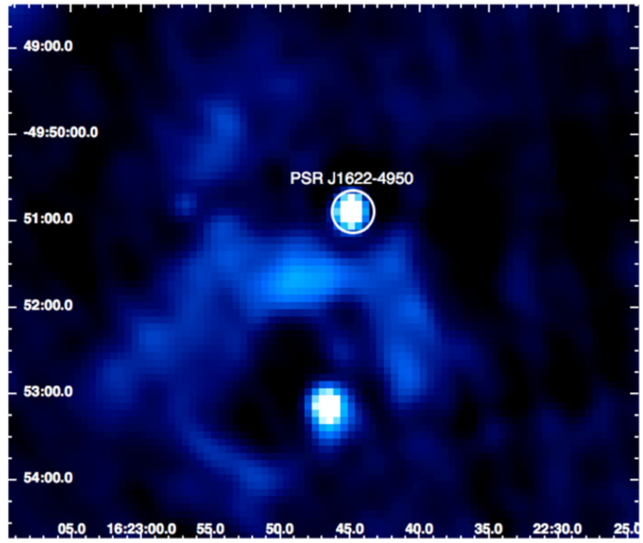


Figure 2. Left: *Chandra* X-ray observations of the region around PSR J1622−4950. The source encircled with a 15″ marker, CXOU J162244.8−495054, is coincident with the radio point source in the ATCA image. Right: ATCA radio observations at 5.5 GHz. The encircled source is PSR J1622−4950. South of the magnetar is a faint ring of extended emission that appears to be non-thermal and may be a supernova remnant (see the text for details).

optical/infrared counterpart. We are therefore confident that the polarized source seen in the radio is indeed the pulsar and that it has an X-ray counterpart.

3. ANALYSIS, RESULTS, AND DISCUSSION

3.1. Radio Light Curve

Throughout the HTRU timing campaign, the pulsar was detected in every observation with a greatly varying flux density, which fluctuated by as much as a factor of $\sim$6 within a 24 hr period. These flux variations cannot be attributed to interstellar scintillation and must be intrinsic to the source, as at 20 cm wavelengths, pulsar flux densities are reasonably stable at such large DMs (Stinebring et al. 2000). The pulse profile averaged over each observation (typically 5–10 minutes) also changes shape on short timescales, often from day to day. Although such variability in both the integrated profile and the flux density is very uncommon in pulsars, it is a distinctive feature of the two magnetars whose pulsed emission has been detected in the radio band (Camilo et al. 2007a; Serylak et al. 2009; Kramer et al. 2007). The light curve for PSR J1622−4950 and three representative pulse profiles are shown in Figure 1.

3.2. Timing

To attain a stable timing solution of a source that is changing its pulse profile from observation to observation, special care needs to be taken in the timing procedure. In conventional pulsar timing, a standard profile is created and used to calculate each pulse's time of arrival (TOA) at the telescope. In the case of PSR J1622−4950, each pulse profile is different, but we noticed that all profiles seem to consist of the same components, only differing by their amplitudes (and sometimes the amplitude for a specific component was indistinguishable from zero). Software from the PSRCHIVE package (Hotan et al. 2004) was used to fit Gaussians to one of the profiles that showed all the different components and a model was made to describe how the components buildup the profile. This model was then used to calculate TOAs, by letting the amplitudes of the different components vary.

When TOAs for all our observations were calculated, the TEMPO software[10] was used to analyze the rotational history of PSR J1622−4950. The resultant fit requires at least nine period derivatives to obtain reasonable phase connection for all of our data, which is not uncommon for magnetars (Camilo et al. 2008). To monitor variations of the period derivative with time, we have also measured P and $\dot{P}$ over several time intervals separately. The time spans were chosen to be as long as possible while keeping phase connection without adding higher period derivatives. This usually resulted in groups of TOAs spanning about 40 days each. It appears that $\dot{P}$ is fluctuating within a factor of $\sim$2 in time. From this analysis, we derived an average period derivative, $\dot{P} = 1.7 \times 10^{-11}$ s s^{-1}. The parameters from the timing analysis are listed in Table 1.

The timing solution for PSR J1622−4950 implies a very high surface magnetic field strength of $B \equiv 3.2 \times 10^{19}$ G $\sqrt{P\dot{P}} \approx 2.8 \times 10^{14}$ G and a characteristic age of $\tau_c \equiv P/(2\dot{P}) \approx$ 4000 years (e.g., Lorimer & Kramer 2005). This is the highest surface magnetic field of any radio pulsar known to date. Figure 3 shows an extract of the P–$\dot{P}$ diagram, where the currently known magnetars are clustered in the upper right corner, with $P \gtrsim 2$ s and $\dot{P} \gtrsim 5 \times 10^{-13}$ s s^{-1}. The two radio emitting magnetars are found in the lower parts of the magnetar group, with periods that are short in comparison to the other AXPs and inferred magnetic field strengths in the lower half of the magnetar range, adjacent to the ordinary radio pulsars with the highest surface magnetic fields. The gap between these two groups of pulsars is narrowing with new discoveries, such as the detection of magnetar-like X-ray bursts from PSR J1846−0258 (Gavriil et al. 2008), which was previously thought to be solely rotation-powered. PSR J1622−4950 is found in the same region of the plot as the two radio emitting magnetars.

3.3. Polarization

The emission from the magnetar is often highly linearly polarized, typically with greater polarization at 3.1 GHz than at 1.4 GHz (see Figure 4). The pulsar also intermittently shows significant circular polarization. The Faraday rotation measure

[10] See http://www.atnf.csiro.au/research/pulsar/tempo/.

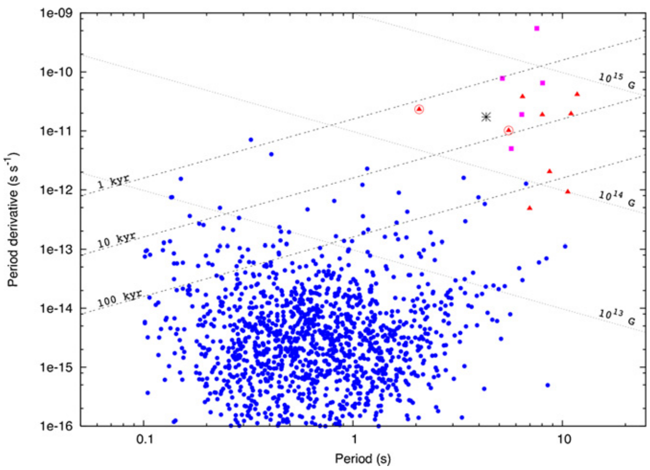


Figure 3. Extract of the P–$\dot{P}$ diagram, showing the longer period pulsars and those with higher inferred magnetic field strengths. Blue dots represent ordinary pulsars, red triangles are AXPs, purple squares are SGRs, and the black asterisk represents PSR J1622−4950. The two encircled AXPs are the magnetars that are observed to emit radio pulsations. Dashed lines correspond to lines of constant characteristic age, and dotted lines correspond to constant magnetic field strength. PSR J1622−4950 has a slightly higher magnetic field strength than the AXPs that are pulsating in the radio band, but clearly higher than that of any of the ordinary pulsars.

Table 1
Parameter Summary of PSR J1622−4950

Parameter	Value
Observed	
Right ascension (J2000)[a]	$16^{\mathrm{h}}22^{\mathrm{m}}44\overset{\mathrm{s}}{.}80(3)$
Declination (J2000)[a]	$-49°50'54\overset{''}{.}4(5)$
Galactic longitude[a]	333.85
Galactic latitude[a]	−0.10
Epoch	MJD 55080
Spin period (P)	4.3261(1) s
Period derivative ($\dot{P}$)	$1.7(1)\times10^{-11}$ s s^{-1}
Dispersion measure (DM)	820(30) cm^{-3} pc
Flux density at 1400 MHz (S_{1400})	4.8(3) mJy
Rotation measure (RM)	−1484(1) rad m^{-2}
Derived	
Distance[b]	≈ 9 kpc
Surface magnetic field (B)	2.8×10^{14} G
Characteristic age (τ_c)	4 kyr
Spin-down luminosity ($\dot{E}$)	8.5×10^{33} erg s^{-1}
X-ray luminosity (L_X)[c]	2.5×10^{33} erg s^{-1}

Notes.
[a] The position refers to the coordinates of the X-ray source.
[b] The distance is calculated from the DM with the Cordes–Lazio model.
[c] Assuming the DM derived distance.

derived from these observations is very large, RM $= -1484 \pm 1$ rad m^{-2}. A detailed analysis of these polarization data will be reported elsewhere but we note the similarity between the polarization properties of PSR J1622−4950 and the other radio pulsating magnetars 1E 1547.0−5408 (Camilo et al. 2008) and XTE J1810−197 (Kramer et al. 2007; Camilo et al. 2007b).

3.4. Radio Spectrum

We combined the various flux density measurements to estimate the spectral index of the pulsar in the radio band. The average flux density at 1.4 GHz is $\langle S_{1400}\rangle = 4.8$ mJy (with standard deviation $\sigma_{S_{1400}} = 2.8$ mJy) and at 3.1 GHz is $\langle S_{3100}\rangle = 4.9$ mJy ($\sigma_{S_{3100}} = 2.5$ mJy). The ATCA measurements yield $\langle S_{5500}\rangle = 13 \pm 1$ mJy and $\langle S_{9000}\rangle = 14.3 \pm 0.8$ mJy, similar to the flux density of 12 ± 2 mJy obtained from the Methanol Multibeam pulsar survey at a center frequency of 6.3 GHz. The spectrum therefore appears to have a positive spectral index, highly unusual for pulsars which have a mean spectral index of about −1.6 (Lorimer et al. 1995). Again, this peculiar spectral behavior is observed in the other two radio pulsating magnetars, which both have a flat (or inverted) radio spectrum (Camilo et al. 2007c, 2008; Lazaridis et al. 2008).

3.5. X-ray Emission

For ordinary rotation-powered pulsars, the X-ray luminosity (L_X) is much smaller than the spin-down luminosity, $\dot{E} \equiv 4\pi^2 I\dot{P}P^{-3}$; on average $L_X \approx 10^{-3}\dot{E}$ (Becker & Trümper 1997). In contrast, magnetars are observed to have $L_X \gtrsim \dot{E}$. An estimate of the unabsorbed 0.3–10 keV flux for CXOU J162244.8−495054 gives 2.6×10^{-13} erg cm^{-2} s^{-1}, assuming a Galactic hydrogen column density in that direction of $N_H = 2\times10^{22}$ cm^{-2} (Dickey & Lockman 1990) and a blackbody spectrum with $kT = 0.4$ keV, typical of a quiescent magnetar. This implies $L_X(0.3\text{–}10\ \text{keV}) \approx 2.5\times10^{33}$ erg s^{-1} at the estimated distance of

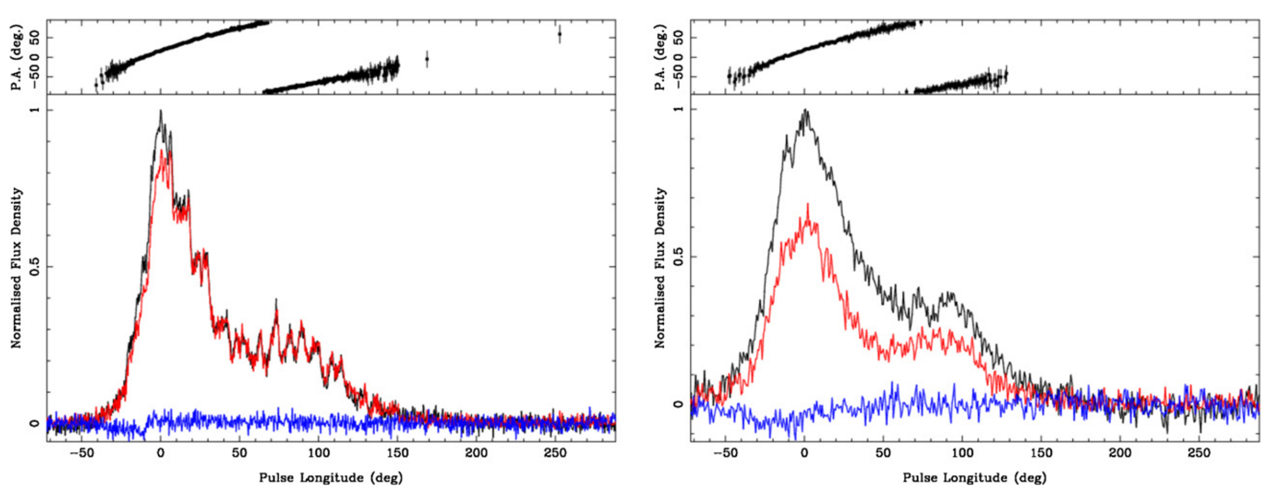


Figure 4. Polarimetric profiles of PSR J1622−4950 at 3.1 GHz (left) and 1.4 GHz (right) observed at Parkes on the same day (MJD = 55197). The blue and red lines represent circular and linear polarizations, respectively, while the black lines represent the total intensity. The full 360° view of pulse rotation is shown, with the zero point of the pulse longitude set at the peak value of the flux density. Absolute position angles at infinite frequency are shown after correction for a rotation measure of −1484 rad m^{-2}.

9 kpc and, given $\dot{E} \approx 8.5 \times 10^{33}$ erg s^{-1} for this magnetar, $L_X \sim 0.3\,\dot{E}$. Since the distance calculated from the DM has a large uncertainty and is known only to within a factor of two or so, the derived X-ray luminosity may be in error by up to a factor of four. Even within these errors, the ratio is significantly higher than for ordinary pulsars, but well within the range for the magnetars 1E 1547.0−5408 and XTE J1810−197 which have $L_X \sim 0.1\,\dot{E}$ and $L_X \sim 4\,\dot{E}$ (Mereghetti 2008; Camilo et al. 2007a; Halpern et al. 2005) in quiescence and larger ratios in outburst.

The radio emission from XTE J1810−197 was discovered following a strong X-ray outburst. It has since faded, both in the radio and the X-ray band, and the radio pulsations are no longer visible. For 1E 1547.0−5408, the radio emission is also highly variable. PSR J1622−4950, on the other hand, has had at least two episodes of non-detections in the radio band lasting hundreds of days followed by periods of bright radio emission (see Figure 1). In addition to the new *Chandra* observation, we searched archival data from *Chandra*, *XMM Newton*, *ROSAT*, *ASCA*, *Beppo-SAX*, *Rossi-XTE*, and *Swift* for an outburst, however no evidence for X-ray flux variability and no X-ray outburst at the level of the outbursts seen in XTE 1810−197 and 1E 1547.0−5408 ($\gtrsim 10^{35}$ erg s^{-1}) were found since at least as early as 2005. It is possible therefore that an enhancement of X-ray activity is not a requirement for pulsed radio emission by magnetars, however, given the duty cycle of sensitive X-ray observations of the field containing PSR J1622−4950, we cannot constrain the occurrence of fainter X-ray enhancements of the source. What is instead certain is that the observed X-ray emission from PSR J1622−4950 is at variance with what is observed for the other two radio pulsating magnetars.

3.6. *Possible SNR Association*

If the true age of PSR J1622−4950 is similar to its characteristic age of 4 kyr, we might expect to see a supernova remnant (SNR) surrounding the pulsar. Indeed, five of the nine AXPs and at least one of the five SGRs are located within SNRs (Mereghetti 2008; Gaensler et al. 2001). Inspecting the ATCA image in Figure 2, we see a ring of emission centered $\sim 2'$ south of the pulsar location. This ring lacks an infrared counterpart and appears to be non-thermal, whereas the extended radio source to the south of the ring is clearly thermal in nature. Could the ring be the SNR, with the pulsar having escaped its bounds? If we assume a distance of ∼9 kpc to the magnetar and further assume it was born in the center of the ring, the magnetar would need a velocity of ∼1300 km s^{-1} to reach its current location whereas the ring itself would have a lower expansion velocity. Such a velocity is high (though not impossible) for pulsars but rather low for expanding SNRs. Although the link between the ring and the magnetar is a possibility, we consider it unlikely.

4. CONCLUSIONS

The HTRU survey has discovered a radio-luminous pulsar, which is highly polarized, has an inverted spectrum, and is highly variable in both its pulse profile and flux density. The radio pulsar has a faint X-ray counterpart that appears to be stable in flux, with a value that is typical of a quiescent magnetar. The pulsar shares many of the properties of the two known radio magnetars and we therefore conclude that PSR J1622−4950 is indeed a magnetar, the first discovered through its radio emission. This discovery not only adds a new member to the magnetar family, but also highlights unprecedented features of the emission of the magnetars across the electromagnetic band. At odds with what is observed in other sources, PSR J1622−4950 indicates that bright radio emission can be present even when a magnetar displays an X-ray luminosity typical of a quiescent state. Moreover, PSR J1622−4950 shows that *pulsed* radio emission can either exist without the occurrence of a strong X-ray outburst, or occur a long time ($\gtrsim$5 years) after the outburst. Alternatively, the radio pulsations could be triggered by a modest increment of X-ray activity that escaped detection in this case. We finally note that the extreme variability in the flux density of PSR J1622−4950 also demonstrates the advantages of surveying the radio sky at regular intervals with even modest sensitivity. This highlights the potential of the upcoming radio facilities like the LOFAR, ASKAP, or SKA which promise to characterize the dynamic radio sky at an unprecedented level.

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Facilities: Parkes, ATCA, CXO (ASIS-I)

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