DO RADIO MAGNETARS PSR J1550−5418 AND J1622−4950 HAVE GIGAHERTZ-PEAKED SPECTRA?

J. Kijak, L. Tarczewski, W. Lewandowski, and G. Melikidze

Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265 Zielona Góra, Poland; kijak@astro.ia.uz.zgora.pl

Received 2013 March 14; accepted 2013 May 21; published 2013 July 2

ABSTRACT

We study the radio spectra of two magnetars, PSR J1550−5418 and J1622−4950. We argue that they are good candidates for pulsars with gigahertz-peaked spectra (GPS), as their observed flux density decreases at frequencies below 7 GHz. We suggest that this behavior is due to the influence of the pulsars’ environments on radio waves. Both of the magnetars are associated with supernova remnants and thus are surrounded by hot, ionized gas, which can be responsible for the free–free absorption of radio waves. We conclude that the GPS feature of both magnetars and typical pulsars are formed by similar processes in the surrounding media rather than by different radio-emission mechanisms. Thus, the radio magnetars PSR J1550−5418 and J1622−4950 can be included in the class of GPS pulsars.

Key words: ISM: general – pulsars: general – pulsars: individual (J1550−5418, J1622−4950) – stars: winds, outflows

1. INTRODUCTION

Most radio pulsars are observed to have simple spectra that can be described by a power-law function with an average spectral index of −1.8 (Maron et al. 2000). Some sources, moreover, show a low-frequency turnover, normally observed at frequencies below a few hundred megahertz (Sieber 1973). On the other hand, few pulsars have been observed whose spectra peak above 1 GHz and then have an otherwise typical high-frequency spectrum (Kijak et al. 2011b). At frequencies below 1 GHz, the observed flux decreases and the corresponding spectral index becomes positive. In order to describe the pulsars showing these features, Kijak et al. (2011b) suggested the term gigahertz-peaked spectra (GPS) pulsars. Recently, while analyzing a distribution of spectral indices, Bates et al. (2013) concluded that the fraction of GPS pulsars might be less than 10% of the whole population. It seems that the appearance of this type of spectrum is related to the peculiar environments (such as pulsar wind nebulae (PWNe), Hii regions, etc.) of these neutron stars. Kijak et al. (2011b) also indicated that the GPS pulsars are relatively young objects and may coincide with X-ray sources from the third EGRET catalog or HESS observations. Thus, they suggested that the GPS does not occur due to the radio emission mechanism but due to the influence of the pulsars’ environments on radio waves. Perhaps the most convincing evidence of this statement is the unique binary system of PSR B1259−63 and Be star LS 2883 recently studied by Kijak et al. (2011a). They showed that the spectral shape depends on the orbital phase, which proves that the Be star environment is the main reason for the spectral evolution of PSR B1259−63. The spectrum of PSR B1259−63 at various orbital phases mimics the spectrum of GPS pulsars. Kijak et al. (2011a) considered two mechanisms that might influence the observed radio emission: free–free absorption and cyclotron resonance.

A periodic signal from PSR J1550−5418 with a rotation period of 2.069 s was first detected on 2007 June 8 by the Parkes telescope in Australia at 1374 MHz (Camilo et al. 2007). It has a characteristic age of 1.4 kyr and a surface magnetic field of $2.2 \times 10^{14}$ G. The dispersion measure $DM = 830$ cm$^{-3}$ pc and the corresponding distance is 9.74 kpc. However, Deller et al. (2012), using the very long baseline interferometry measurements, estimated a likely distance of 6 ± 2 kpc to this pulsar. PSR J1550−5418 is also the X-ray source 1E 1547.0−5408 that was identified as a magnetar candidate by Gelfand & Gaensler (2007) and later confirmed to be a magnetar by Camilo et al. (2007). Its period (2 s) and spin-down luminosity $\dot{E} = 1 \times 10^{35}$ erg s$^{-1}$ show that PSR J1550−5418 has the shortest $P$ and highest $\dot{E}$ among known magnetars. It also has a peculiar environment (see details in Gelfand & Gaensler 2007). Camilo et al. (2008) analyzed the spectrum of PSR J1550−5418 in a wide frequency range (1.4–45 GHz) and suggested that the spectrum could be described as approximately log parabolic with a peak at $\approx 6$ GHz. Later, Bates et al. (2011) inscribed PSR J1550−5418 in the list of pulsars with positive spectral index in a frequency range between 1.4 and 7 GHz. Therefore, PSR J1550−5418 seems to be a natural candidate to be classified as a GPS pulsar.

PSR J1622−4950, a radio magnetar with a period of 4.3 s and spin-down luminosity of $\dot{E} = 8.5 \times 10^{33}$ erg s$^{-1}$, was discovered by Levin et al. (2010). The integrated column density of free electrons is $DM = 820$ cm$^{-3}$ pc, therefore the corresponding distance to this pulsar is about 9.14 kpc, and thus its parameters are similar to those of PSR J1550−5418. This radio magnetar is also a young (4 kyr), highly magnetized neutron star (> $10^{14}$ G) and is referred to as an anomalous X-ray pulsar. Anderson et al. (2012) suggested that the object G333.9+0.0 is a supernova remnant physically associated with PSR J1622−4950. Having analyzed the spectrum between 1.4 and 9 GHz, Levin et al. (2010) claimed that the spectral index might be positive. However, Keith et al. (2011) combined the flux density measurements up to 24 GHz and concluded that the spectral index of PSR J1622−4950 is very close to zero.

Here we analyze spectral shapes of two radio magnetars, PSR J1550−5418 and J1622−4950, and suggest that these magnetars are good candidates for objects with GPS.

To trace the origin of GPS, we need to assume that the radio emission mechanisms for both magnetars and normal pulsars share the same coherent curvature radiation (Melikidze et al. 2000; Gil et al. 2004; Mitra et al. 2009; Rea et al. 2012).
The average spectra of magnetars and normal pulsars should have some similar features too, e.g., power-law spectra with a turnover at low frequencies. Generally, the radio-emission features of pulsars and magnetars differ significantly, e.g., the profiles of magnetars are not stable or the position angle varies in a different way. According to the observations they have at least one common feature—highly linearly polarized single pulses with the position angle locally following the mean position angle traverse are observed for both normal pulsars and magnetars (Levin et al. 2012; Melikidze et al. 2011; Kramer et al. 2007). We believe that this detail is of great importance. It points to the curvature radiation as the main mechanism for the radio emission (Melikidze et al. 2000; Gil et al. 2004; Mitra et al. 2009). The difference can be explained by the relaxation of the twisted magnetosphere, which in general does not have a simple dipolar geometry responsible for both the stable shape of profiles and the rotation vector model of the position angle (Melikidze et al. 2011).

2. RADIO MAGNETARS WITH GPS

2.1. GPS and Turnup in PSR J1550−5418

The flux density measurements of PSR J1550−5418 have been obtained using ATCA and the Parkes radio telescope (Camilo et al. 2007, 2008; Bates et al. 2011), and the spectrum of this magnetar is presented in Figure 1. The collected data of the integrated flux density gathered from the available published data. This spectrum looks like GPS and, in addition, at high frequencies it might be showing a turnup, as is observed in the spectra of normal pulsars (Wielebinski et al. 1993; Kramer et al. 1996). Let us note once again that Camilo et al. (2008) suggested that the spectrum of this pulsar could have a turnover with the maximum at 6 GHz.

2.2. PSR J1622−4950

For the frequency ranges 1.4–9 GHz and 17–24 GHz, we have used data obtained by Levin et al. (2010) and Keith et al. (2011), respectively. The values at 1.4 and 3.1 GHz are statistical averages, whereas all the values at higher frequencies are obtained from single observations. Anderson et al. (2012) presented the fluxes at 5 and 8 GHz from ATCA observations in 2008 November and December. These measurements are greater by a factor ~2.5 than those presented in Figure 1. The flux measurements at 5 and 9 GHz presented in Figure 1 were obtained between 2009 and 2010 (Levin et al. 2010). This discrepancy is caused by the strong radio variability, which may be a direct result of the X-ray outburst that occurred in 2007 (Anderson et al. 2012). Since the discovery of this radio magnetar in 2009 April, the same phenomenon has been observed at 1.4 GHz by the Parkes telescope.

The collected data of the integrated flux density gathered since the discovery are plotted in the bottom panel of Figure 1 in Levin et al. (2012). Simply fitting a line to the data points results in a slight slope, showing a decline in the average flux density of ~2 mJy for the 700 days of observing (see Figure 1 in Levin et al. 2012), which suggests an intrinsic long-term decay of the flux density. That is why we present the spectrum when the pulsar flux achieves stability.

2.3. The Fitting Procedure and Data Analysis

To analyze spectral shapes, we use the fitting method previously used by Kuzmin & Losovsky (2001) for pulsar spectra with a turnover at low frequencies. The same method was used by Kijak et al. (2011a) in the case of GPS pulsars and PSR B1259−63. Based on the data of flux measurements with errors for these two radio magnetars, we have characterized the spectral shapes as

\[ F(\nu) = 10^{(ax^2 + bx + c)}, \quad \text{where } x \equiv \log_{10} \nu. \]  

(1)

Here, \( \nu \) is the observed frequency and \( a, b, \) and \( c \) are the fitting parameters. In order to fit the data, we used an implementation of the nonlinear least-squares Levenberg–Marquardt algorithm. Table 1 summarizes the results of fitting Equation (1) to the spectra of radio magnetars with peak frequencies. Table 1 also quotes the obtained values of the normalized \( \chi^2 \), which show that the fit to the PSR J1622−4950 spectrum is better than the fit to the PSR J1550−5418 spectrum. Thus, both radio magnetars clearly show GPS features with peak frequencies at 5.0 and 8.3 GHz, respectively (see Table 1).
Pulsed radio emission from a magnetar was first detected in 2006 by the Parkes telescope while observing the position of PSR J1810–197 (Camilo et al. 2006). Its radio spectrum in the range of frequencies between 1.4 and 32 GHz is described by a single, flat power law with a spectral index $\alpha = 0.0 \pm 0.5$ (Lazaridis et al. 2008). Only two other radio-emitting magnetars (PSR J1550–5418 and J1622–4950), which are the subjects of our study, have been found. Both of them are probably associated with supernova remnants. Radio observations reveal that both magnetars are located in the center of radio shells emitting a faint diffuse radio emission (Anderson et al. 2012; Gelfand & Gaensler 2007). This environment, consisting of hot, ionized gas, should influence the magnetar radio emission. Therefore, we can expect that the spectra of radio magnetars can be subject to the same kind of changes as the spectra of the GPS pulsars. It is also possible that the spectrum of PSR J1622–4950 is influenced by a nearby H II region (Anderson et al. 2012). The typical GPS pulsar PSR B1054–62 lies behind or within a dense H II region (Koribalski et al. 1995) and its spectrum shows somewhat less power at low frequencies (Kijak et al. 2011b). A similar effect can be seen while comparing the spectra of PSR J1550–5418 and J1622–4950, and the difference between these spectra can be caused by a H II region (see Figure 2 in Anderson et al. 2012).

Table 2 summarizes the results of peak frequency estimations for the following sources: the isolated GPS pulsars, PSR B1259–63 for three orbital phase ranges (for a full list see Kijak et al. 2011a), and two radio magnetars. As can be seen, the peak frequency for the regular radio pulsars ranges from 0.7 to 2.3 GHz, while for PSR B1259–63 it reaches 3.5 GHz, close to the periastron passage. We note that the spectrum evolves to a regular power-law pulsar spectrum for those orbital phases where the pulsar is far from its companion star. The values of $v_p$ that we have obtained for the radio magnetars are much higher: 5 and 8 GHz. But the question arises, why do we not observe regular radio pulsars with a turnover at such high frequencies? This question seems natural, since we suggest that for both regular pulsars and radio magnetars the GPS appearance is due to the environmental conditions around the neutron stars.

There are two possible explanations: either the magnetar environments are even “more extreme” than those for the GPS pulsars or, more plausibly, pulsars with turnovers at such high frequencies have not been discovered yet. Most of the regular pulsar search surveys were conducted at low frequencies, usually 1.4 GHz or below. A pulsar with a peak frequency of a few gigahertz would be extremely weak at these frequencies, and hence probably undetectable. The radio emissions of the two magnetars were found only after the sources had been identified by other means. Obviously, the detection of pulsed radio emission is much easier when the period of rotation is already known than when detecting it in a blind survey.

### Table 1

| PSR       | $a$  | $b$  | $c$  | $\chi^2$ | $v_p$ (GHz) |
|-----------|------|------|------|----------|-------------|
| J1550–5418| $-1.0 \pm 0.2$ | $1.4 \pm 0.3$ | $0.35 \pm 0.08$ | 1.85 | 5.0 |
| J1622–4950| $-1.8 \pm 0.3$ | $3.3 \pm 0.6$ | $-0.35 \pm 0.32$ | 0.91 | 8.3 |

**Note.** $v_p$ is the peak frequency estimated using our fitting procedure (see Equation (1)).

### Table 2

**Pulsars with GPS and Radio Magnetars, and the Case of PSR B1259–63**

| PSR       | DM (pc cm$^{-3}$) | Age (kyr) | $E$ (erg s$^{-1}$) | $v_p$ (GHz) |
|-----------|------------------|-----------|-------------------|-------------|
| B1054–62  | 320              | 1870      | 1.9e+33            | 0.7 (1.0)   |
| J1809–1917| 197              | 51        | 1.8e+36            | 2.3 (1.7)   |
| B1822–14  | 357              | 195       | 4.1e+34            | 1.4 (1.4)   |
| B1823–13  | 231              | 21        | 2.8e+36            | 1.7 (1.6)   |
| B1828–11  | 161              | 107       | 3.6e+34            | 0.7 (1.2)   |

**Notes.** $v_p$ is estimated using different spectral fit methods (Kijak et al. 2011a, 2011b), i.e., the values of the peak frequency quoted in parentheses are from a two-power-law-model fit, and the other values are from the nonlinear function fit (see Equation (1)). For PSR B1259–63, we quote the value of $v_p$ for three different ranges of orbital phases (expressed as the days prior to/past the periastron passage).

Additionally, the pulse broadens due to interstellar scattering, which is severe for high DM pulsars (see Kijak et al. 2011b).

Only a few pulsar surveys have been conducted at higher frequencies, where it is easier to find “the missing link” —a pulsar with a turnover at the frequency of a few GHz. Two of the most recent surveys, conducted at 3 GHz (Keith et al. 2008) and 6 GHz (Bates et al. 2011), yielded a few promising discoveries of pulsars that can be potential candidates for GPS sources. Of course, these pulsars, and especially their spectra, still require further investigation, which we intend to do in our future observing projects for GPS pulsar candidates.

At present, it is difficult to construct a detailed theory of the turnover spectra, as we lack observational data, especially for the GPS sources. However, from the available observational data we can still draw a general conclusion about the main factors that influence the observed spectra. It is generally known that absorption at low frequencies is caused by means of thermal absorption in the hot stellar wind (Sieber 1973; Slee et al. 1986). Preliminary estimations show that free–free absorption in PWNe and H II regions can be responsible for this effect. The optical depth $\tau_v$ of the free–free absorption can be expressed as (Rybicki & Lightman 1979)

$$\tau_v = 0.4 \times T_3^{-3/2} v_{GHz}^{-2} \int n_e^2 dl_{AU},$$

(2)

where $n_e$ is the electron density in cm$^{-3}$, $T_3$ is the temperature in 10$^3$ K, $v_{GHz}$ is the frequency in GHz, and $d_{AU}$ is the distance in AU, or, according to Rohlfs & Wilson (1996) and Wilson et al. (2009)

$$\tau_v = 8.235 \times 10^{-2} \left( \frac{T_e}{K} \right)^{-1.35} \left( \frac{v}{GHz} \right)^{-2.1} \left( \frac{EM}{pc \ cm^{-6}} \right) a(v, T),$$

(3)
where the correction \(a(\nu, T)\) is usually \(\sim 1\) and the emission measure (EM) is given by

\[
\left( \frac{\text{EM}}{\text{pc cm}^{-6}} \right) = \left( \frac{N_e}{\text{cm}^{-3}} \right)^2 \int_0^{l/\text{pc}} d \left( \frac{l}{\text{pc}} \right) .
\]

When the frequency is given in units of \(\nu_0\), where \(\nu_0\) is the frequency at which the optical depth is unity, we have, from Equation (3),

\[
\frac{\nu_0}{\text{GHz}} = 0.3045 \cdot \left( \frac{T_e}{K} \right)^{-0.643} \left( \frac{a(\nu, T)\text{EM}}{\text{pc cm}^{-3}} \right)^{0.476}.
\]

Thus, we can conclude that the GPS feature can be caused by external factors in the same way it occurs in the environment of normal GPS pulsars. The GPS pulsars are apparently surrounded by an environment that can affect the spectra of those pulsars in the same way that the stellar wind affects the PSR B1259−63 spectrum. For example, PSR B1823−13 is surrounded by a compact PWN (Pavlov et al. 2011) and PSR B1054−62 lies behind or within a dense H\(\text{II}\) region (Koribalski et al. 1995).

4. CONCLUSIONS

A described in Section 3, the average spectra of two radio magnetars, PSR J1550−5418 and J1622−4950, possess characteristic features of GPS. In the Introduction, we discussed whether the coherent curvature radiation should be the mechanism of radio emission for both magnetars and normal pulsars. Despite a substantial difference between the observed radio features of magnetars and normal pulsars, both of them emit highly linearly polarized individual pulses. We believe that this essential feature unambiguously points to similar emission mechanism. Therefore, we conclude that the GPS feature of the magnetars is caused by their environment, and the radio magnetars PSR J1550−5418 and J1622−4950 can join the class of GPS pulsars.

We are grateful to the anonymous referee for useful comments. This paper was supported by the grant DEC-2012/05/B/ST9/03924 of the Polish National Science Centre. We thank M. Margishvili for the language editing of the manuscript.

REFERENCES

Anderson, G. E., Gaensler, B. M., Slane, P. O., et al. 2012, ApJ, 751, 53
Bates, S. D., Johnston, S., Lorimer, D. R., et al. 2011, MNRAS, 411, 1575
Bates, S. D., Lorimer, D. R., & Verbiest, J. P. W. 2013, MNRAS, 431, 1352
Camilo, F., Ransom, S. M., Halpern, J. P., & Reynolds, J. 2007, ApJL, 666, L93
Camilo, F., Ransom, S. M., Halpern, J. P., et al. 2006, Nat, 442, 892
Camilo, F., Reynolds, J., Johnston, S., Halpern, J. P., & Ransom, S. M. 2008, ApJ, 679, 681
Deller, A. T., Camilo, F., Reynolds, J., & Halpern, J. P. 2012, ApJL, 748, L1
Gelfand, J. D., & Gaensler, B. M. 2007, ApJ, 667, 1111
Gil, J., Lyubarsky, Y., & Melikidze, G. I. 2004, ApJ, 600, 872
Keith, M. J., Johnston, S., Kramer, M., et al. 2008, MNRAS, 389, 1881
Keith, M. J., Johnston, S., Levin, L., & Bailer, M. 2011, MNRAS, 414, 346
Kijak, J., Dembska, M., Lewandowski, W., Melikidze, G., & Sendyk, M. 2011a, MNRAS, 418, L114
Kijak, J., Lewandowski, W., Maron, O., Gupta, Y., & Jessner, A. 2011b, A&A, 531, A16
Koribalski, B., Johnston, S., Weisberg, J. M., & Wilson, W. 1995, ApJ, 441, 756
Kramer, M., Stappers, B. W., Jessner, A., Lyne, A. G., & Jordan, C. A. 2007, MNRAS, 377, 107
Kramer, M., Xilouris, K. M., Jessner, A., Wielebinski, R., & Timofeev, M. 1996, A&A, 306, 867
Kuzmin, A. D., & Losovsky, B. Ya. 2001, A&A, 368, 230
Lazaridis, K., Jessner, A., Kramer, M., et al. 2008, MNRAS, 390, 839
Levin, L., Bailes, M., Bates, S., et al. 2010, ApJ, 721, L33
Levin, L., Bailes, M., Bates, S. D., et al. 2012, MNRAS, 422, 2489
Maron, O., Kijak, J., Kramer, M., & Wielebinski, R. 2000, A&A, 147, 195
Melikidze, G., Gil, J., & Szary, A. 2011, in AIP Conf. Proc. 1379, Astrophysics of Neutron Stars 2010: A Conference in Honor of M. Ali Alpar, ed. E. Göğüş, T. Benö, & U. Ertan (Melville, NY: AIP), 144
Melikidze, G. I., Gil, J., & Pataraya, A. D. 2000, ApJ, 544, 1081
Mitra, D., Gil, J., & Melikidze, G. I. 2009, ApJL, 696, L141
Pavlov, G. G., Chang, C., & Kargaltsev, O. 2011, ApJ, 730, 2
Rea, N., Pons, J. A., Torres, D. F., & Turrolla, R. 2012, ApJL, 748, L12
Rohls, K., & Wilson, T. L. 1996, Tools of Radio Astronomy (Berlin: Springer)
Rybicki, G. P., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley-Interscience)
Sieber, W. 1973, A&AS, 28, 237
Slee, O. B., Alurkar, S. K., & Bobra, A. D. 1986, ApJPh, 39, 103
Wielebinski, R., Jessner, A., Kramer, M., & Gil, J. A. 1993, A&A, 272, L13
Wilson, T. L., Rohls, K., & Hüttemeister, 2009, Tools of Radio Astronomy (Berlin: Springer)