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Non-detection of pulsed radio emission from magnetar Swift J1834.9−0846: constraint on the fundamental plane of magnetar radio emission *

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Abstract The magnetar Swift J1834.9−0846 is observed using the Nanshan 25 m radio telescope. No pulsed radio emission is detected. The upper limit on the pulsed radio emission from this source is $0.5\,\mathrm{mJy}$. According to the "fundamental plane" for radio magnetars, this source should have radio emission. Therefore, our results put constraints on the existence of a fundamental plane of magnetar radio emission. We argue that a magnetar's ability to emit radio emission may have little to do with the spin down luminosity and is related to the magnetar's X-ray luminosity. The only necessary condition is a relatively low X-ray luminosity.

Key words: pulsars: individual (Swift J1834.9−0846) — stars: magnetars — stars: neutron

1 INTRODUCTION

Magnetars are assumed to be neutron stars powered by strong magnetic field decay (Duncan & Thompson 1992). They form a different pulsar population from that of pulsars powered by rotation. Normal pulsars powered by rotation are usually radio emitters, and radio emitting rotation-powered pulsars are commonly known as radio pulsars. However, magnetars manifest themselves mainly as anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) (Tong et al. 2010; Tong & Xu 2011). Until recently, no radio pulsations had been observed from any of the magnetars. The discovery of transient pulsed radio emission from one magnetar has bridged the gap between radio pulsars and magnetars (Camilo et al. 2006). Up to now, more than 20 magnetars have been discovered[1], and three of them are radio-loud magnetars (Camilo et al. 2006, 2007; Levin et al. 2010).

Recently, Rea et al. (2012) tried to understand magnetar radio emission from an empirical point of view. They proposed that magnetars are radio-loud if and only if their quiescent X-ray luminosities are smaller than their rotational energy loss rates: $L_{\rm qui} < \dot{E}$. This is the key point in the "fundamental plane" of magnetar radio emission. Since Rea et al. (2012) published their paper, there have been two new sources: SGR Swift J1822.3−1606 and SGR Swift J1834.9−0846. For the young magnetar

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[1] McGill online catalog: *http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html*

Swift J1834.9−0846, the upper limit of its quiescent X-ray luminosity is lower than its rotational energy loss rate (Kargaltsev et al. 2012). This source should be another radio-loud magnetar if the fundamental plane of magnetar radio emission proposed by Rea et al. (2012) is correct.

1.1 X-ray Observations of Swift J1834.9−0846

According to Kargaltsev et al. (2012), Swift J1834.9−0846 has a rotation period of $2.48\,\mathrm{s}$ and a period derivative of

$$\dot{P} = 0.796 \times 10^{-11}\ \mathrm{s\,s^{-1}}.$$

Its characteristic magnetic field is

$$B = 3.2 \times 10^{19}\sqrt{P\dot{P}} = 1.4 \times 10^{14}\,\mathrm{G}\,.$$

It may also be associated with the supernova remnant W41 (Tian et al. 2007; Kargaltsev et al. 2012). Therefore, Swift J1834.9−0846 is similar to the radio emitting magnetar AXP 1E 1547.0–5408 (Camilo et al. 2007) in that they have a similar rotation period and a similar characteristic magnetic field, and both are young sources associated with supernova remnants. The rotational energy loss rate of Swift J1834.9−0846 is

$$\dot{E} = 3.95 \times 10^{46}\dot{P}P^{-3} = 2.1 \times 10^{34}\ \mathrm{erg\ s^{-1}}\,.$$

According to figure 3 in Kargaltsev et al. (2012), the Swift/XTR observed a declining flux of Swift J1834.9−0846. From their figure 3, the upper limit of the source's quiescent flux is

$$f_{\mathrm{qui}} < 3 \times 10^{-12}\ \mathrm{erg\ cm^{-2}\ s^{-1}}\,.$$

The corresponding upper limit of the source's quiescent luminosity is

$$L_{\mathrm{qui}} = 4\pi d^2 f_{\mathrm{qui}} < 5.7 \times 10^{33} d_4^2\ \mathrm{erg\ s^{-1}}\,.$$

Here, the source distance is chosen as $4\,\mathrm{kpc}$, considering its potential association with the supernova remnant W41 (Tian et al. 2007; Kargaltsev et al. 2012). Furthermore, pre-outburst XMM and Chandra observations showed that the source flux was about 100 and 1000 times smaller, respectively (Section 3.3.2 in Younes et al. 2012; Section 6.2.3 in Kargaltsev et al. 2012). Therefore, the quiescent luminosity of Swift J1834.9−0846 must be smaller than its rotational energy loss rate.

This source meets all the criteria of the fundamental plane of magnetar radio emission from Rea et al. (2012).

(1) Quiescent X-ray luminosity is smaller than the rotational energy loss rate.

(2) There is a high acceleration potential along the pulsar's open field line regions. For Swift J1834.9−0846, the corresponding acceleration potential is

$$\Delta V = 4.2 \times 10^{20}\sqrt{\dot{P}/P^3} = 3.0 \times 10^{14}\,\mathrm{V}\,.$$

(3) A burst/outburst triggers radio emission. Swift J1834.9-0846 showed an SGR-type burst on 2011 August 7 (D'Elia et al. 2011). Its declining flux points to a recent outburst being likely.

(4) It lies relatively nearby. A possible distance of $4\,\mathrm{kpc}$ is obtained considering its potential association with supernova remnant W41.

If the fundamental plane proposed by Rea et al. (2012) was correct, Swift J1834.9−0846 should have radio emission. From previous experience with magnetar radio emission, we should have detected its radio emission in recent years. Therefore, Swift J1834.9−0846 provides us the first opportunity to test the "fundamental plane" of magnetar radio emission.

The radio observations, data analysis and results are presented in Section 2, and the discussions and conclusions are given in Section 3.

2 RADIO OBSERVATIONS, DATA ANALYSIS AND RESULTS

We observed this source for 2×1 hours, with a one hour folding mode and the other a searching mode. Here, we mainly discuss the searching observation and data analysis. The searching data were first checked for the presence of non-dispersed radio frequency interference (RFI). Interference signals above the 5σ threshold level were removed from the raw data prior to our analysis.

2.1 Radio Observations of Swift J1834.9−0846

The observation of Swift J1834.9−0846 was made using the Nanshan 25 m radio telescope (Xinjiang Astronomical Observatory) on 2012 June 24, for 1.0 hour. Data were taken with the cryogenic receiver at a center frequency of 1540 MHz. A bandwidth of 320 MHz was used in our observation, split into 128 continuous channels of 2.5 MHz frequency (Wang et al. 2001). Dual linear polarizations were summed, and the frequency channels were one-bit sampled every 1.0 ms. The data were recorded on a computer disk and transferred from the observatory to a linux computing server for processing. No pulsed radio emission was detected[2].

2.2 The Folding Search

The data were analysed using the pulsar signal processing package SIGPROC[3] (Lorimer et al. 2000). The maximum dispersion measure (DM) detected in the known pulsars is 1456 pc cm^{-3}. According to the NE 2001 model for the galactic distribution of free electrons (Cordes & Lazio 2002), Swift 1834.9−0846 has a DM of 197 pc cm^{-3} assuming a distance of 4 kpc. So the data were de-dispersed using 750 trial DMs ranging from 0 to 1500 pc cm^{-3}. For each DM trial, the full 320 MHz of the bandwidth was de-dispersed.

A barycentric folding period was determined using a measurement from previous X-ray observations of Swift J1834.9−0846. With the reported period and its associated uncertainties from the *RXTE* observations, we extrapolated the period to the 2012 June 24 epoch and determined the barycentric folding period to be 2.48249785(10) s.

Periods ±5 ms (∼0.2%) from the nominal period were searched with a step of 0.01 ms. Each of these folding trials was conducted for DMs between 0 and 1500 pc cm^{-3} with steps of 2 pc cm^{-3}. A total of 375 000 DM and period combinations were tried (750 DM trials, and 500 folds per DM trial), and for each trial the χ^2 significance of the folded profile was recorded. We chose 5σ as a reasonable threshold for the signal, and we found no convincing pulsar candidates at the 5σ significance level or higher in the search. At the same time, we also searched for periodic signals using FFT with the SEEK program at each trial DM. No pulsar candidate was found in this observation.

2.3 Upper Limit on Pulsed Radio Emission

The minimum detectable flux density can be given by the function (Manchester et al. 1996)

$$S_{\rm min} = \frac{\alpha\beta T_{\rm sys}}{G\sqrt{N_{\rm p}\Delta t\Delta\nu}}\sqrt{\frac{W_{\rm e}}{P - W_{\rm e}}}\,. \tag{1}$$

It is affected by system noise $T_{\rm sys}$, telescope gain G, number of polarizations $N_{\rm p}$, integration time Δt, receiver bandwidth $\Delta\nu$, assumed signal to noise ratio α, digitization and other processing losses β, pulsar period P and effective pulse width $W_{\rm e}$. The effective pulse width depends on the intrinsic pulse width W, the sampling time δt, the dispersion smearing time across one sub-channel $\delta t_{\rm DM}$

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[2] We observed this source for 1.0 hour in May 2012 in folding mode, and there were also no detections then.

[3] See *http://sigproc.sourceforge.net*

and the interstellar scattering $\delta t_{\rm scatt}$

$$W_{\rm e} = \sqrt{W^2 + \delta t^2 + \delta t_{\rm DM}^2 + \delta t_{\rm scatt}^2}\,, \tag{2}$$

where

$$\delta t = 1\,{\rm ms},$$

$$\delta t_{\rm DM} = 8.3 \times 10^6\,{\rm DM}\,\nu_{\rm MHz}^{-3}\,B\,{\rm ms} = 1.136\,{\rm ms}\,,$$

$$\delta t_{\rm scatt} = \left(\frac{\rm DM}{1000}\right)^{3.5} \left(\frac{400}{\nu_{\rm MHz}}\right)^{4} 10^3\,{\rm ms} = 0.016\,{\rm ms},$$

with central frequency $\nu = 1540\,{\rm MHz}$, ${\rm DM} = 200\,{\rm cm}^{-3}$ pc, and bandwidth $B = 2.5\,{\rm MHz}$ (Lyne & Graham-Smith 2012). The intrinsic pulse width was assumed to be $0.05\,P$ (Lazarus et al. 2012). The effective pulse width will be $0.05\,P$ when the sum of the three contributions is much less than the intrinsic pulse width. For the Nanshan 25 m radio telescope pulsar observing system ($T_{\rm sys} = 40\,{\rm K}$, $G = 0.1\,{\rm K}$ Jy^{-1}, $N_{\rm p}$ = 2, Δt = 3600 s, $\Delta\nu = 320\,{\rm MHz}$, $\beta = 1.5$), we set α equal to 5. Then, we obtain an upper limit on the pulsed radio emission from Swift 1834.9−0846 of 0.5 mJy.

3 DISCUSSIONS AND CONCLUSIONS

According to Rea et al. (2012), a magnetar will emit radio pulsations if and only if its quiescent X-ray luminosity is smaller than its rotational energy loss rate $L_{\rm qui} < \dot{E}$. Swift J1834.9−0846 meets all the criteria of the fundamental plane of magnetar radio emission. If the proposal of Rea et al. (2012) was correct, then it should have radio emission. However, we detect no pulsed radio emission from this source. It may be that magnetars with $L_{\rm qui} < \dot{E}$ might have radio emission. At the same time, they can also have no radio emission. Despite the original proposal of Rea et al. (2012), $L_{\rm qui} < \dot{E}$ may only be a necessary condition for a magnetar to emit radio pulsations. In Rea et al. (2012), two of the five sources with $L_{\rm qui} < \dot{E}$ have no radio emission. With the addition of Swift J1834.9−0846, a total of six sources have $L_{\rm qui} < \dot{E}$. Three of them have radio emissions (AXP XTE J1810−4197, AXP 1E 1547.0−5408 and PSR J1622−4950), but the other three are not detected in radio (PSR J1846−0258, SGR 1627−41 and Swift J1834.9−0846). It is possible that the three latter magnetars are actually radio emitting sources. Their radio emissions could have been missed because of beaming, absorption due to the environment or large distances, etc (Rea et al. 2012). However, we also want to highlight the possibility that they do not have any radio emission at all.

The X-ray emissions of magnetars are powered by magnetism. They have nothing to do with the rotational energy loss rate (Thompson & Duncan 1996; Thompson et al. 2002). However, the fundamental plane of magnetar radio emission links the magnetar quiescent X-ray luminosity with its rotational energy loss rate. Rea et al. (2012) proposed this relation since they believed that the radio emissions of magnetars are powered by rotation. However, the characteristics of magnetar radio emission are very different from those of radio pulsars (Mereghetti 2008) in that there is a variable flux and pulse profile, a flat spectrum, and most importantly, it is transient in nature. If the radio emissions of magnetars are powered by rotation, the same as in radio pulsars, then we should see similar radio emission properties in radio magnetars and radio pulsars. However, this is not what has been observed (Camilo et al. 2006, 2007; Levin et al. 2010). We find it reasonable to think that the magnetar radio emission comes from a different energy reservoir. In the case of magnetars, the natural energy budget is the magnetic energy. Therefore, the radio emissions of magnetars may be powered by magnetism instead of by rotation. The X-ray emissions of magnetars can vary significantly. Then it is not surprising that their radio emissions are also variable, since they are from the same energy reservoir.

Some magnetars can also have a relatively short period (e.g., AXP 1E 1547.0−5408 has a period of $2.1\,\mathrm{s}$, Camilo et al. 2007). The rotational energy is also very significant. Therefore, we may also expect some activities to be powered by rotation in magnetars (Zhang 2003). For example, radio emissions that are powered by rotation could exist in magnetars and there could be two types of radio emissions in magnetars, those powered by magnetism and those powered by rotation. At present, only transient pulsed radio emissions are observed in magnetars, and they are more likely to be powered by magnetism. In the future, more radio-loud magnetars will be discovered (e.g., by the Five-hundred-meter Aperture Spherical Telescope or the Square Kilometre Array). Among them, we may also see pulsed non-transient radio emissions in some magnetars with properties similar to those of ordinary radio pulsars. These radio emissions may be powered by rotation.

At present, three of the six sources with $L_{\rm qui} < \dot{E}$ have radio emissions. One physical reason is that low luminosity magnetars tend to have a similar magnetospheric structure as that of radio pulsars (section 4.2 in Tong et al. 2013). The coherent radio emission condition is more likely to be fulfilled in magnetars with low luminosity. Only a relatively low X-ray luminosity is required. This property has little relation with the magnitude of rotational energy loss rate. Therefore, the “fundamental plane” of magnetar radio emission (if it exists[4]) should be “low luminosity magnetars are more likely to have radio emissions.” Nothing further can be said. Since the Nanshan telescope is relatively small (25 m in diameter), only a crude upper limit is obtained. Continued monitoring at other radio telescopes is highly recommended[5].

In summary, Rea et al. (2012) previously suggested that the necessary and sufficient condition for a magnetar to emit in radio is $L_{\rm qui} < \dot{E}$ (the quiescent X-ray luminosity is smaller than the rotational energy loss rate), and that the radio emission is powered by the star’s rotational energy. Based on our observation of Swift J1834.9−0846, we want to point out an alternative possibility.

(1) Since Swift J1834.9−0846 is not detected in radio (in contradiction with the prediction of Rea et al. 2012), $L_{\rm qui} < \dot{E}$ may only be a necessary condition.
(2) Considering the differences between the radio emissions of magnetars and normal radio pulsars, it is more reasonable to think that radio emissions of known magnetars are powered by their magnetic energy (instead of rotational energy as proposed by Rea et al. 2012).
(3) If the radio emissions of magnetars are powered by their magnetic energy, and combining theoretical studies of the magnetar’s magnetosphere (Tong et al. 2013), then the necessary condition for a magnetar to have radio emission may have little to do with its rotational energy loss rate. Only a relatively low X-ray luminosity is required.

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[4] See also Ho (2013) for criticisms on the existence of the fundamental plane of magnetar radio emission.

[5] During the submission process of this paper, Esposito et al. (arXiv:1212.1079) reported their GBT radio observations of Swift J1834.9−0846, where it was also not detected. Their observations were made from August 2011 to November 2011. This result is consistent with our analysis here. However, a different explanation is discussed there.

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