Low X-ray Efficiency of a Young High-B Pulsar PSR J1208—6238 Observed with Chandra

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Abstract High magnetic field (high-B) pulsars are key sources to bridge magnetars and conventional rotation powered pulsars, and thus to understand the origin of magnetar activities. We have estimated a tight upper limit on the X-ray flux of one of the youngest high-B pulsars PSR J1208—6238 for the first time; a Chandra 10 ks observation shows no significant source. Depending on the emission models, we have the 3σ upper limit on the intrinsic 0.5–7 keV flux to 2.2–10.0×10−14 erg s−1 cm−2. Assuming the distance to the pulsar to be 3 kpc, we suggest that the conversion efficiency from the spin-down energy to the X-ray luminosity of this pulsar is almost the smallest among known high-B pulsars, and even smaller for those for a typical rotation-powered one. We also discuss possible associations of a surrounding pulsar wind nebula and a hosting supernova remnant around this high-B pulsar.

Keywords Pulsars: individual (PSR J1208—6238) · Stars: neutron · Stars: magnetars · Magnetic field · X-rays: stars · ISM: supernova remnants

1 Introduction

It is well known that there are two types of isolated neutron-star emission-mechanism; that amounts to two distinctive populations, the rotation-powered pulsars and the magnetars. Magnetars are strong X-ray emitters with high variabilities (bursts), and it was firstly believed that their properties are caused by the strong dipole magnetic field $B_d$ (larger than $\sim 10^{13}$ G). However, several exceptions make the origin unclear, i.e., the discovery of the low dipole field magnetars, SGR 0418+5729 (Esposito et al. (2010), Rea et al. (2010)), and of the rotation-powered pulsars with large magnetic fields comparable to the magnetars (high-B pulsars) such as PSR J1119—6127 (Camilo et al. 2000). Recent flare detection from this interesting source (Archibald et al. 2016) shows that high-B pulsars are key to clear understanding of the origin of magnetar activities. Another example of magnetar-like bursts on a rotation-powered pulsar would be PSR J1846—0258 (Gavriil et al. 2008). Interestingly, both examples have pulsar wind nebulae (PWNe). Chandra resolved PWN tori and jets from these young pulsar system (Ng and Romani 2004; Kargaltsev and Pavlov 2008; Bamba et al. 2010). Although high-B pulsars are now known, such objects that bridge the two populations, the number of the
sample is still very small, and further X-ray observations of high-B pulsars are strongly required.

PSR J1208–6238 was discovered by Fermi (Clark et al. 2016) in the gamma-ray band on the position of (RA, Dec.) = (12°08′13.96, -62°38′00.02). Radio follow-ups detected no signal, implying that this pulsar is a radio-quiet. The period and period derivative are 0.440590723652(14) s and 3.2695145(10) × 10^{-12} s^{-1} at 56040 MJD, respectively. Its young age (2.14 × 10^5 yrs), large spin-down luminosity (1.5 × 10^{36} erg s^{-1}), and high dipole magnetic field (3.84 × 10^{13} G), suggest that this pulsar is the third youngest with the fourth strongest magnetic field, among 66 pulsars with the dipole magnetic field between 1 × 10^{13} G and 4.4 × 10^{13} G. Actually, these parameters are quite similar to those of the youngest and most energetic high-B pulsar, PSR J1119–6127. The distance is estimated to be 3 kpc, under the assumption that the gamma-ray luminosity is proportional to the square root of spin-down energy (Abdo et al. 2013), which makes this object one of the nearest known high-B pulsars. However, no X-ray observation on this source PSR J1208–6238 was performed so far. Typical rotation-powered pulsars have an X-ray luminosity of a factor of 10^{-3}−4 of the spin-down energy (Shibata et al. 2016), thus this object should have an X-ray luminosity of 10^{32−33} erg s^{-1}.

In this paper, we report on the first X-ray observation result on PSR J1208–6238. Section 2 summarizes the Chandra observation of this pulsar. We show the results (Sect. 3) and discussion (Sect. 4) on the pulsar and its surroundings.

2 Observation and Data reduction

The Chandra Advanced CCD Imaging Spectrometer (ACIS) observed PSR J1208–6238 region on 2019 Dec. 13 in VFAINT mode. We used CIAO 4.11 (Fruscione et al. 2006) and calibration database 4.8.3 for the data reduction and analysis. The net exposure was 9.9 ks. We also used several tools in heasoft 4.11.

3 Results

3.1 PSR J1208–6238

Figure 1 shows the whole band image of the PSR J1208–6238 region. One can see some photons on the position of this pulsar, but it is not distinct. The upper limit was estimated with the srccflux command in CIAO package as follows. We estimated the count rate in the circle of 1.8 pixels, which is the point spread function radius in this detector position. The background region was selected from the annulus region as shown in Fig. 1. The estimated count rate is 1.92 × 10^{-4} cps, which is only 2.7σ significance. The 3σ upper limit is estimated to be 1.0 × 10^{-3} cps. In order to translate these values to the flux, we need spectral assumptions. For the spectral shape of this pulsar, we assumed two models; the first one is an absorbed power-law model. The photon index is assumed to be 2.0, the same value as that in PSR J1119–6127 (Ng et al. 2012). The other one is an absorbed blackbody, which is sometimes observed in high-B pulsars and magnetars (Olausen and Kaspi 2014; Yoneyama et al. 2019). The temperature is assumed to be 0.2 keV, which is the same as that in PSR J1119–6127 (Ng et al. 2012). For the absorption column in both emission models, we have made two assumptions; the first one is 8 × 10^{21} cm^{-2}, from the assumed distance of 3 kpc and the relation between N_H and distance (He et al. 2013). The other assumption is N_H of 1.48 × 10^{22} cm^{-2}, which is the total Galactic column density to the direction of the pulsar (Ben Bekhti et al. 2016). This is the largest (or most pessimistic) assumption. The resultant absorbed and unabsorbed (intrinsic) upper limit with each model is summarized in Table 1.

The assumed photon index and temperature also affect the upper limit. We checked the 3σ upper limit with the assumed photon index of 1.0, 1.5, 2.0, and 2.5, and temperature of 0.1, 0.15, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, and 2.0 keV. The absorption column was fixed to be 8 × 10^{21} cm^{-2} in all cases. The results are summarized in Fig. 2. In both models, a softer spectrum results in a larger upper limit. This can be due to the stronger coupling with the absorption effect.

Some high-B pulsars show burst-like activities so the emission can concentrate on some time interval. We also checked the light curve from the source region. We have done a Kolmogorov–Smirnov test with lcestats in headas and found no significant time variability. Coherent pulsation search was not done, with the lack of statistics and timing resolution.

Fig. 1 Whole band image of PSR J1208–6238 region. The thick circle indicates the source region, whereas the two thin annulus regions indicate the background regions, respectively, for the flux estimation.
Table 1 3σ upper limit with each model†

| Emission model       | \( N_H = 8 \times 10^{21} \) cm\(^{-2}\) | \( N_H = 1.48 \times 10^{22} \) cm\(^{-2}\) |
|----------------------|------------------------------------------|------------------------------------------|
|                      | Absorbed | Unabsorbed | Absorbed | Unabsorbed |
| Power-law model      | 1.2      | 2.2        | 1.4      | 3.0        |
| Blackbody model      | 0.6      | 4.5        | 0.6      | 10.0       |

†: 0.5–7 keV upper limit in units of \(10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\). We assumed \( \Gamma = 2.0 \) for the power-law model, whereas \( kT = 0.2 \) keV for the blackbody model.

Fig. 2 3σ upper-limit dependence on the 0.5–7 keV unabsorbed flux. The top panel shows the dependence on the photon index in the power-law model, whereas the bottom panel shows that on the temperature in the blackbody model. The absorption column was fixed to \(8 \times 10^{21} \) cm\(^{-2}\) in all cases.

3.2 Possible PWN

The region around the pulsar position has several X-ray photons, which would immediately qualify for the PWN candidate powered by PSR J1208–6238. We have made the significance and flux estimation for the possible diffuse emission. Here, we treated the background region for the pulsar analysis shown in Fig. 1 to be the source region. The background region was newly selected from the source free region distant from the possible PWN. The background-subtracted count rate in the 0.5–7.0 keV band was estimated with the srcflux command again, to be 1.28 (0.70–2.04) \( \times 10^{-3} \) cps within 90% error range. The significance is calculated to be on the 4.4σ level. In order to estimate the flux, we assumed the same absorption column as that for PSR J1208–6238 (see Sect. 3.1) and a photon index of 2.0. The estimate of absorbed and intrinsic flux in the 0.5–7.0 keV band is 1.5 (0.8–2.4) \( \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) and 2.5 (1.4–4.0) \( \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), respectively.

3.3 Counterpart SNR search

PSR J1208–6238 is allegedly a very young system. Thus, one would expect to find an associated young supernova remnant (SNR) which still emits thermal X-rays. There is no cataloged SNR in the Green Galactic SNR catalog (Green 2019).

We searched for the possible radio counterpart using online tools Simbad and SkyView. As our target is corresponding to nonthermal radio emission from the possible SNR, we also examined low frequency data and found the Sydney University Molonglo Sky Survey (SUMSS) at 843 MHz (Mauch et al. 2003), the Murchinson Widefield Array 72–231 MHz (Hurley-Walker et al. 2019), and the HI All-Sky Continuum Survey at 408 MHz (Haslam et al. 1982). In all these surveys we can find a faint emission around 75 arcsec northeast of the pulsar position as shown in Fig. 3. Its spectral index is very steep, \( \sim -1 \). However, strong contamination from a bright HII region prevents us from addressing the flux density and spectral index estimate.

There is no X-ray deep observation for this region. Our 10 ks observation is too shallow to find diffuse X-ray emission from the expected SNR. Obviously we need follow-up observations in the X-ray band.

\(^{1}\)https://skyview.gsfc.nasa.gov/current/cgi/titlepage.pl.
4 Discussion

We have made the 3σ tight flux upper limit of PSR J1208−6238, 2.2–10.0 × 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} in the 0.5–7.0 keV band (Table 1). In this section, we discuss the comparison with other high-B pulsars. Here, we treat the power-law model result with the typical absorption (8 × 20^{21} \text{ cm}^{-2}), 2.2 × 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} as “typical upper limit” and the blackbody model result with the large absorption (1.48 × 10^{22} \text{ cm}^{-2}), 10.0 × 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} as a “conservative upper limit”. Watanabe et al. (2019) catalogued X-ray properties of high-B pulsars. To make a comparison with this sample, we converted the derived flux upper limit for PSR J1208−6238 to 0.3–10 keV band one, to be 2.3–13 × 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}. The luminosity upper limit becomes 2.6–14 × 10^{31} d_3^2 \text{ erg s}^{-1}, where d_3 is the distance with the unit of 3 kpc. This is a quite small value compared with the spin-down energy, 1.5 × 10^{36} \text{ erg s}^{-1}. The emission efficiency η, which is the conversion factor of spin-down energy to the X-ray luminosity in the 0.3–10 keV band, is less than 1.7 × 10^{-5} d_3^{-2} for the typical case and 9.3 × 10^{-5} d_3^{-2} for the conservative case, respectively.

There is rather large uncertainty on the upper-limit estimation of η. The assumed parameters such as Γ in the power-law models and kT in the blackbody models affect the results, but Fig. 2 shows that our assumption of Γ = 2.0 or kT = 0.2 keV leads to a rather loose upper limit. The distance uncertainty also results in uncertainty of η. However, the upper limit of η does not exceed ~ 10^{-5} even with a very large distance assumption such as 10 kpc.

In the case that the emission is blackbody, we can estimate the upper limit of the emitting region size. It highly depends on the assumed absorption column, temperature, and distance, but the upper limit of the radius of emitting region is 10 m to 130 km. Considering the possibility that the emitting region is only a part of the neutron star surface, we could not reject any parameters.

Some high-B pulsars show burst activities similar to magnetars (PSR J1846−0258; Kumar and Safi-Harb (2008) PSR J1119−6127; Göğüş et al. (2016), Blumer et al. (2017)). The period and period derivative are quite similar between PSR J1208−6238 and these two sources. Figure 4 shows η vs. the dipole magnetic field. Magnetars have large X-ray luminosity and thus large η, whereas conventional pulsars have η of 10^{-3}–10^{-4}. One can see that PSR J1208−6238 shows different properties from those of magnetar-like high-B pulsar, PSR J1846−0258 and PSR J1119−6127; or, considering the uncertainty of the distance, the small upper limit of η of PSR J1208−6238 is lower than the typical value of those of high-B pulsars, or even lower than those for samples with a smaller magnetic field. Our short exposure does not allow for searching for magnetar-like flare activities. Another interesting feature that needs further investigation is searching for thermal radiation, which is often seen in high-B pulsars (McLaughlin et al. 2007; Zhu et al. 2011; Ng et al. 2012; Rigoselli et al. 2019). Deeper monitoring observations are also encouraged.

Figure 5 shows the summary of X-ray luminosity in the 0.3–10 keV band vs. spin-down energy. Typical spin-down powered pulsars have a positive correlation between these two parameters (Shibata et al. (2016); see also Kargaltsev and Pavlov (2008)), whereas pulsars with magnetar-like activities have a brighter X-ray luminosity, 10^{35}–36 \text{ erg s}^{-1}. This figure shows that PSR J1208−6238 has very faint X-ray luminosity compared with other magnetars and spin-down powered pulsars. It implies that PSR J1208−6238 does not show magnetar-like activities (Shibata et al. 2016).
The line for the X-ray luminosity ($L_{\text{X}}$) = the spin-down luminosity ($L_{\text{rad}}$) is also shown.

While we have large uncertainties of distance, they do not significantly help to address a magnetar-like origin.

PSR J1208−6238 is a GeV gamma-ray emitting pulsar. An interesting fact is that magnetars have not been detected in the GeV band so far, which also would imply that PSR J1208−6238 is not a typical magnetar-like pulsar. Non-detection in the X-ray band shows us that this source has a higher GeV to X-ray flux ratio than other young rotation-powered pulsars and similar to older samples (Coti Zelati et al. 2020). This pulsar can be in the transition phase from young (~ thousand years) to old system (~ a few thousand years).

We have found some signals from its possible PWN with 4.4σ confidence level. Assuming the distance of 3 kpc again, the resultant luminosity 90% upper limit is $4.3 \times 10^{31}$ erg s$^{-1}$. A similar pulsar, PSR J1119−6127, has a faint PWN with a luminosity of $1.9 \times 10^{32}$ erg s$^{-1}$ in the quiescent phase (Blumer et al. 2017), suggesting that the possible PWN of PSR J1208−6238 can be similar to that of PSR J1119−6127. In order to make clear the existence of this possible nebula, deeper observations will be needed.

We found a nearby radio source in 77–231 MHz, 843 MHz and 408 MHz images. As it is a position somewhat further away from the high-B pulsar position and it shows a very steep spectral index, <−1, which is totally different from those for typical SNRs, we place low confidence in it to be considered as its associating SNR shock. The nature of this emission is still unclear. Since the pulsar is very young, ~2000 years old, we also expect thermal and/or non-thermal X-rays from the possible SNR. Unfortunately, our exposure is too short to detect such diffuse emission, and no deep X-ray observation in this region has been performed. Clark et al. (2016) also searched for the host SNR. The nearby gamma-ray emission shows a soft spectrum like other gamma-ray SNRs, but the distance between the emission and the pulsar is too large to consider the offset from the pulsar to be due to the kick-off. Deeper observations in multiwavelength will be needed to study the surrounding environment of this interesting pulsar.

5 Summary

X-ray follow-ups of high-B pulsars give us crucial information on their subclass, such as the magnetars and the conventional rotation-powered pulsars. We have made a 10 ks Chandra observation on one of the youngest high-B pulsars PSR J1208−6238. No significant X-ray emission was found on the pulsar region, although there are some photon excesses. We derived the intrinsic flux and luminosity upper limit of $2.2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in the 0.5–7.0 keV band and $2.6 \times 10^{31}$ d$^{-2}$ erg s$^{-1}$ in the 0.3–10 keV band, respectively, depending on the emission models. The conversion efficiency of the spin-down energy to X-ray emission is less than $1 \times 10^{-4}$ with the typical spectral model, which is quite small compared with magnetar-like high-B pulsars or even conventional rotation-powered cases. We also searched for the hosting supernova remnant in the radio band and found no significant emission.

Deepper observations in multiwavelength are needed to follow up possible flares and setting a deeper upper limit.

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