CHANDRA DETECTION OF THE X-RAY COUNTERPART OF THE HIGH MAGNETIC FIELD RADIO PULSAR J1119-6127 IN THE SUPERNOVA REMNANT G292.2-0.5

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ABSTRACT

We report the Chandra Advanced CCD Imaging Spectrometer detection of the X-ray counterpart of the high magnetic field, ∼1600 year-old, 407 ms radio pulsar J1119–6127 associated with the supernova remnant G292.2–0.5. The powerful imaging capability of Chandra also unveiled, for the first time, a faint 3′′×6′′ pulsar wind nebula (PWN) at energies above ∼1.2 keV. The X-ray emission from the pulsar and its associated nebula is well described by an absorbed power law model with a photon index $\Gamma = 2.2^{+0.3}_{-0.6}$. The corresponding 0.5–10 keV unabsorbed X-ray luminosity is $(5.5^{+10.3}_{-10}) \times 10^{32}$ erg s$^{-1}$ (at 6 kpc). When compared to two other pulsars with similar spin and magnetic properties, J1119–6127 stands out as being the least efficient at turning rotational kinetic energy into X-ray emission. This study shows that high magnetic field radio pulsars can be significant X-ray emitters and Chandra is needed to study the emission properties of the pulsars and associated faint PWNe.

Subject headings: ISM: individual (G292.2–0.5) — pulsars: individual (PSR J1119–6127, AX J1119.1–6128.5) — supernova remnants — X-rays: ISM

1. INTRODUCTION

For over three decades the Crab has been viewed as the paradigm for young pulsars: a fast rotating neutron star with surface dipole magnetic field strength of $10^{15}$ G, injecting a relativistic magnetized wind of particles into its surroundings. The interaction of this wind with the surrounding medium creates a synchrotron nebula, referred to as a pulsar wind nebula (PWN). PWNe provide a unique laboratory that probes the properties of their powering engines, the physics of relativistic pulsar winds and their interaction with the interstellar medium (see e.g. Safi-Harb 2002 for a review). Recent observations have shown that a good fraction of young pulsars exhibits properties unlike the Crab. In spite of their youth, they have much larger spin periods and dipole magnetic fields (see e.g. Camilo et al. 2000). The search for their X-ray counterparts and any PWNe associated with them sheds light on their high-energy properties and the way these pulsars deposit their energies into their surroundings.

The radio pulsar (PSR) J1119–6127 was discovered in the Parkes multi-beam pulsar survey (Camilo et al. 2000). It has a rotation period of 407 ms, characteristic age of 1600 yrs, surface magnetic field strength of $4.1 \times 10^{17}$ G, and spin-down luminosity $\dot{E} \approx 2.3 \times 10^{36}$ erg s$^{-1}$. This is an interesting and unusual object: although it is extremely young, it displays a relatively large period and magnetic field compared to Crab-like pulsars. Furthermore, no radio emission from a PWN was found in spite of the search conducted with the Australia Telescope Compact Array (ATCA). Its observed upper limit is below what might at first be expected from the pulsar’s characteristics (Crawford et al. 2000). The ATCA observation also identified a non-thermal shell of 15′′ in diameter surrounding the pulsar classified as a new supernova remnant (SNR), G292.2–0.5. Previous X-ray observations, performed with the ASCA and ROSAT satellites (Pivovaroff et al. 2001), showed extended emission associated with the radio SNR, as well as a hard point-like ASCA source offset ∼1′′ from the radio pulsar. The large offset made their association uncertain.

In this paper, we report the detection of the X-ray counterpart of the radio pulsar and show the first evidence for a PWN associated with it. In §2, we describe the observation and data analysis. In §3, we derive the distance using our spectral fits to the X-ray source and SNR interior, then discuss the X-ray properties of this system in comparison with other pulsars with similar spin and magnetic field properties. We also show that the previously reported ASCA source is most likely the unresolved counterpart of the radio pulsar, contaminated by emission from its surroundings.

2. OBSERVATION AND DATA ANALYSIS

The field around pulsar J1119–6127 was observed with Chandra on 2002 March 31–April 1. The coordinates of the X-ray source detected with ASCA were positioned at the aimpoint of the back-illuminated S3 chip of the Advanced CCD Imaging Spectrometer (ACIS). The CCD temperature was −120°C with a frame readout time of 3.2 sec in “very faint” mode. We applied the CTICORRECTIT tool to the original event 1 raw data (Townsley et al. 2000) in order to correct for charge transfer inefficiency. The data were then calibrated using standard CIAO 2.2 routines. The resulting effective exposure time was 47 ks.

Figure 1 shows the ASCA (left) and Chandra (right) images of G292.2–0.5. The 2.0–10.0 keV ASCA image has been smoothed using a Gaussian with $\sigma = 45^\prime\prime$. The Chandra image was obtained as follows: the data were divided into individual images in the soft (0.5–1.15 keV, red), medium (1.15–2.3 keV, green), and hard (2.3–10.0 keV, blue) bands. Each image was adaptively smoothed using a Gaussian with $\sigma = 1^\prime\prime$ for significance of detection $>5$ and up to $\sigma = 10^\prime\prime$ for significance down to 3. A broadband (0.5–10.0 keV) background image was produced using the blank-sky datasets available in CALDB v2.12. The resulting background image was divided into the same energy bands and then subtracted from its corresponding (source + background) image. The individual background-subtracted images were finally combined to produce the image shown in Figure 1. This image shows several resolved X-ray sources surrounded by diffuse emission from the interior of the remnant.

2.1. PSR J1119–6127

In Figure 2 (left) we show a close-up image of the ACIS field around the radio pulsar J1119–6127. We find an X-ray source

1 See Pivovaroff et al. (2001) for a detailed analysis of the ASCA data
at $\alpha_{2000} = 11^h19^m14.4^s$ and $\delta_{2000} = -61^\circ27'49.7''$, with a 90% error radius of 1.7%. This source is the brightest one in the field and it lies 0.7 away from the coordinates of the radio pulsar ($\alpha_{2000} = 11^h19^m14.3^s$ and $\delta_{2000} = -61^\circ27'49.5''$, 0.3'' error, Camilo et al. 2000). From the positional coincidence of the X-ray source with the radio pulsar, the low probability of a chance alignment ($\sim1 \times 10^{-4}$), the evidence of a PWN associated with it and the nature of its spectrum (see below), we believe this source to be the X-ray counterpart of PSR J1119–6127.

Within a radius of 30'' centered at the X-ray coordinates and including the point source and extended component, we obtained 285 background subtracted events in the 0.5–10.0 keV band translating to a count rate of $(6.0 \pm 0.4) \times 10^{-3}$ cts s$^{-1}$. Pile-up effects are then negligible. We fit the spectrum with XSPEC$^{2}$ in the 0.5–10.0 keV band, using a minimum of 15 counts per bin. An absorbed power law model provided a better fit than thermal models. The best-fit spectral parameters are summarized in Table 1 and the spectrum is shown in Figure 2 (right). The corresponding absorbed fluxes are $(1.4_{-0.8}^{+2.6}) \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (0.2–2.4 keV) and $(1.3_{-0.8}^{+2.4}) \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–10.0 keV). All errors throughout the paper are at the 90% confidence level unless otherwise specified. We note that by examining Figure 2 (right), we find residuals at $\sim1.4$ keV indicating that the spectrum could be partly thermal. However, these residuals become insignificant when extracting a spectrum from a smaller region. The poor statistics did not allow us to fit multi-component models. A detailed investigation of this emission will have to await a deeper exposure.

As shown in Figure 2 (left), the pulsar has an associated extended X-ray component aligned nearly north-south. In order to compare its spatial characteristics with Chandra’s point-spread-function (PSF), we performed a 2-D spatial fit to the data using the GAUSS2D function in Sherpa v2.2. First, images of the source in the soft (0.5–1.15 keV), medium (1.15–2.15 keV) and hard (2.15–10.0 keV) energy bands were created. The number of counts in these energy images was 25, 170, and 90, respectively. Corresponding normalized PSF images at an off-axis angle of 1/28 and energies characteristic of the source’s energy histogram (0.85 keV, 1.7 keV and 3.0 keV) were made and used as convolution kernels when fitting. From this fit, the low energy image yielded a FWHM value fully consistent with the PSF ($\sim0.8''$), while the medium band image had a slightly larger value ($\sim0.9''$). The hard band image was best described by an elliptical gaussian function with FWHM of $\sim0.9'' \times 1''/2$, confirming the extended nature of the source. We rule out trailing in the S3 chip as an origin for this feature since the read-out direction is at an angle of $\sim35^\circ$ measured counter-clockwise from the almost north-south direction of the extended emission.

In order to further characterize the morphology of this extended emission, we smoothed the above energy images using a Gaussian with $\sigma = 0.5''$ and then normalized them. The contamination by the surrounding SNR in these images is small (<7% of total). We then subtracted the normalized soft image (consistent with a point source) from the normalized hard image. Figure 3 shows the resulting image, which reveals structures that appear to be consistent with torus- and jet-like features surrounding the pulsar. Such features have been observed around young rotation-powered pulsars (e.g. Lu et al. 2002) and are believed to be associated with the deposition of the pulsar’s energy into its surroundings.

We estimate a total of 41 background-subtracted counts from an annulus centered at the X-ray coordinates with radius 1''2–3''/4 (see Fig. 3, right). (The inner radius was chosen to be $\sim1.5$ times the PSF so the contamination from the point source would be less than 15%. The outer radius includes the emission detected from the extended component.) This corresponds to a significance of detection $\sim5.5$ and contributes $\sim14\%$ to the total count rate from the point source and extended component. From the 41 counts quoted above, 14 are present in the medium energy band (1.15–2.15 keV) and 25 in the high energy band (2.15–10.0 keV). A spectral analysis of the extended emission is not possible with the available number of counts and has to await a deeper exposure. We note however that, unlike the point source, the extended emission is not detected in the soft band (see Fig. 3, left). This leads us to conclude that the extended emission appears to be harder than the point source (assuming both have the same column density).

### 2.2. SNR G292.2–0.5

We defer a detailed study of the emission from the SNR and the newly identified point sources to a follow-up paper. Here, we briefly summarize the results of our spectral fits targeted to derive the column density needed to constrain the distance to the system (see §3.1). A spectrum of the SNR’s interior was extracted from the S3 chip. The point sources were excluded and source-free regions were used as background. A single component non-equilibrium

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**Table 1**

| Parameter | Value ($\pm 90\%$) |
|-----------|----------------------|
| $N_H$ (10$^{21}$ cm$^{-2}$) | 9$^{+5}_{-3}$ |
| Photon index, $\Gamma$ | 2.3$_{-0.6}^{+0.3}$ |
| Normalized photon flux (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) | $(3.1^{+0.2}_{-0.2}) \times 10^{-5}$ |
| $f_{abs}$ (0.5–10.0 keV, ergs cm$^{-2}$ s$^{-1}$) | $(6.6^{+3.4}_{-3.8}) \times 10^{-14}$ |
| $f_{unabs}$ (0.5–10.0 keV, ergs cm$^{-2}$ s$^{-1}$) | $(1.3^{+0.4}_{-0.3}) \times 10^{-13}$ |
| $\chi^2$/dof | 0.57 (16) |

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$^{a}$Includes point source and extended component, see §2.1 for details.

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2 http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html
ionization (NEI) model provided an acceptable fit. The spectral parameters derived from our best fit VPShock model are: \(N_{H}=(5.8 \pm 1.0) \times 10^{21} \) cm\(^{-2}\), \(kT=36 \pm 10 \) keV and \(n_{e}=5.1 \pm 1.0 \times 10^{3} \) cm\(^{-3}\), with a \(\chi^2_{\text{red}}=1.04\) (278). A two-component NEI thermal and non-thermal model provided an equally acceptable fit, with the non-thermal model well described by a power law with a hard photon index (\(\Gamma \leq 1\)). Regardless of the model, we found an \(N_{H}\) value similar to the one quoted above. This value is consistent with, but better constrained than, the one derived for the pulsar and its PWN (see Table 1). It is also intermediate between the ASCA values derived for the eastern and western sides of the remnant, \(\sim 14 \times 10^{21}\) cm\(^{-2}\) and \(\sim 2 \times 10^{21}\) cm\(^{-2}\), respectively (Pivovaroff et al. 2001).

3. DISCUSSION

3.1. Distance

The extinction per unit distance in the direction of the system can be estimated to be \(E_{B-V}/D \sim 0.2 \) mag kpc\(^{-1}\) (Lucke 1978). We can then use the relation \(N_H/E_{B-V}=5.55 \times 10^{21} \) cm\(^{-2}\) mag\(^{-1}\) to estimate the distance. From our \(N_H\) values from Table 1 and §2.2, we obtain a distance of 5.4–12.6 kpc for the pulsar and 4.0–6.3 kpc for the remnant. A distance of 4–8 kpc was then adopted for the system. The upper limit is determined from the location of the source with respect to the Carina spiral arm (Camilo et al. 2000).

3.2. PSR J1119–6127 and its PWN

The analysis described in §2.1 allowed us to identify the X-ray counterpart of PSR J1119–6127 and its PWN. Using the spectral model outlined in Table 1, we derive a 0.5–10.0 keV X-ray luminosity for the point source and PWN of \(L_X = (5.5^{+10.0}_{-3.3}) \times 10^{32} \) ergs s\(^{-1}\), where \(D_h\) is the distance in units of 6 kpc. The conversion efficiency of \(\dot{E}\) into \(L_X\) is then \(\epsilon_{\text{pwr-pwn}} = (L_X/\dot{E}) \sim (2.4^{+4.5}_{-1.5}) \times 10^{-4} D_h^2\). This value is somewhat on the low end of the efficiencies exhibited by other pulsars associated with SNRs (e.g. Safi–Harb 2002).

In Table 2, we summarize the properties of J1119–6127 and two other pulsars with similar spin properties. PSR J1846–0258 lies within 1° of the center of SNR Kes 75 and PSR B1509–58 lies close to the center of SNR G320.4–1.2. All three pulsars spin slowly (\(P > 100\) ms) and have large inferred magnetic fields (\(B > 1 \times 10^{13}\) G) compared to other young, Crab-like pulsars. However, their observed X-ray properties are different from those of J1119–6127. While PSR J1846–0258 exhibits the highest X-ray efficiency (even when compared to all other Crab-like pulsars, it has one of the highest \(\epsilon\) values), J1119–6127 exhibits the lowest value (\(\epsilon_{\text{pwr-pwn}} \lesssim 0.001\), using the upper limits on the luminosity and distance). Furthermore, both J1846–0258 and B1509–58 exhibit very similar spectral properties, with the measured photon indices of the X-ray pulsars being flatter than those of their associated PWNe. On the other hand, as noted above, our analysis of PSR J1119–6127 suggests the opposite trend, with the photon index of the point source being steeper than that of the extended feature. (We here caution the reader that this conclusion is based on the small number of counts available). Therefore, it seems that their peculiar spin properties and high magnetic fields cannot account in an obvious way for the differences in their X-ray properties.

3.3. Relation to AX J1119.1–6128.5

The nature of the X-ray source AX J1119.1–6128.5, detected with ASCA’s Gas Imaging Spectrometer (GIS), is also of interest. This source does not have a Chandra point-source counterpart (see Fig. 4). The coordinates of AX J1119.1–6128.5 were reported to be \(\alpha_{J2000}=11^{h}19^{m}03^{s}34\) and \(\delta_{J2000}=-61^\circ 2830^\prime\prime\), with an error radius of 24" (Pivovaroff et al. 2001). This represents an offset of 87" from PSR J1119–6127. We have re-examined the ASCA data and found a similar offset. Using an aperture of 2.5° centered on the ASCA source, a background-subtracted count rate of \(\sim 0.004\) s\(^{-1}\) in the 3.0–10.0 keV range was reported with the GIS. The count rate obtained with Chandra using the same region, which includes emission from the pulsar, PWN and surrounding SNR, is consistent with the above GIS count rate. We then conclude that AX J1119.1–6128.5 represents the unresolved pulsar counterpart contaminated by its surrounding emission. Finally, the large offset between AX J1119.1–6128.5 and the pulsar can be attributed to a combined effect of ASCA’s limited resolution and additional positional errors (e.g. Ueda et al. 2000 and Gotthelf et al. 2000).

4. CONCLUSIONS

| Parameter                  | J1119–6127 | J1846–0258 | B1509–58 |
|----------------------------|------------|------------|----------|
| Spin period, \(P\) (ms)    | 408        | 324        | 150      |
| Period derivative, \(P^2\) | \(4 \times 10^{-12}\) | \(7.1 \times 10^{-12}\) | \(1.5 \times 10^{-12}\) |
| Surface magnetic field, \(B\) (G) | \(4.1 \times 10^{13}\) | \(4.8 \times 10^{13}\) | \(1.5 \times 10^{13}\) |
| Characteristic age, \(\tau_c\) (yr) | 1600     | 980–1700   | 1700     |
| Spin-down luminosity, \(\dot{E}\) (erg s\(^{-1}\)) | \(2.3 \times 10^{36}\) | \(7.9 \times 10^{36}\) | \(18 \times 10^{36}\) |
| Braking index, \(n\)        | 2.91       | 1.86–2.48  | 2.8      |
| Distance \(\sim 6\) kpc     | \(\sim 19\) kpc | \(\sim 5\) kpc |
| \(N_H\) (10\(^{22}\) cm\(^{-2}\)) | \(0.9\)   | \(< 4\)     | \(< 1\)   |
| Photon index                | no / yes   | yes / yes  | yes / yes|
| Radio/X-ray PWN?            | this work  | Helfand et al. 2003 | Gaensler et al. 2002 |
| 0.5–10.0 keV efficiency, \(\epsilon\) (\(L_X/\dot{E}\)) | \(< 0.001\) | \(< 0.016\), \(< 0.065\) | \(< 0.001\), \(< 0.009\) |

Table 2: Observed parameters for PSRs J1119–6127, J1846–0258 and B1509–58.
Thanks to the sensitivity and resolution offered by Chandra, we have detected the X-ray counterpart of PSR J1119–6127 as-
associated with G292.2–0.5, and resolved a $3'' \times 6''$ extended dif-
fuse emission that represents the first evidence for its PWN. Ad-
ditional deep observations of this system are needed to: 1) bet-
ter constrain the pulsar parameters, 2) study in detail the m-
orfology of the PWN, 3) determine its spectral properties in-
dependently from the point source, and 4) address the nature of the hard X-ray emission from the interior of G292.2–0.5.
A timing observation will also allow the search for pulsations from the X-ray source. Our observation illustrates the need for Chandra to unveil small PWNe that could be associated with high-magnetic field radio pulsars and to resolve their powering engines. In addition, our study suggests that the X-ray prop-
erties of PSR J1119–6127 are different from those of other pul-
sars with similar spin and magnetic field properties, and there-
fore this class of pulsars merits further study.

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Fig. 1.—Left: 2.0–10.0 keV ASCA image of SNR G292.2–0.5. The superimposed regions mark the locations of Chandra’s S3 chip (white box), the radio coordinates of PSR J1119–6127 (white cross) and the radio boundary of G292.2–0.5 (black circle, 15′ diameter). Right: Chandra ACIS-S3 image of the interior of the remnant. Individual images in the soft (0.5–1.15 keV, red), medium (1.15–2.3 keV, green), and hard (2.3–10.0 keV, blue) bands were combined. Resolution ranges from 1″-10″ and black regions represent non-significant detection. The arrow marks the location of the detected counterpart of PSR J1119–6127.

Fig. 2.—Left: The X-ray counterpart of PSR J1119–6127. This ‘truecolor’ image combines the soft (0.5–1.15 keV, red), medium (1.15–2.15 keV, green), and hard (2.15–10 keV, blue) bands. The images were smoothed with a Gaussian with σ=0″.5. Right: Spectrum and best fit power-law model (see Table 1). A minimum significance of 3σ was chosen in rebinning the data for display.
FIG. 3.—Left and Center: Normalized soft (0.5–1.15 keV, left) and hard (2.15–10.0 keV, center) energy images of PSR J1119–6127 smoothed with a Gaussian with $\sigma=0''5$. Right: subtracting the soft (left) from the hard (center) band image makes the underlying structure surrounding the pulsar visible. A logarithmic display scale was used. See §2.1 for details.

FIG. 4.—0.5–10.0 keV Chandra image of the region around the ASCA source AX J1119.1–6128.5. The small box marks the position of PSR J1119–6127 (error much less than displayed size), the ellipse shows a nearby IRAS source, J11169–6111 (error of 53'' $\times$ 3''), and the circle shows the location of AX J1119.1–6128.5 (error radius of 24''). See §3.3 for details.