CHANDRA AND XMM-NEWTOWN OBSERVATIONS OF THE VELA-LIKE PULSAR B1046–58

M. E. Gonzalez1,2, V. M. Kaspi1,3, M. J. Pivovaroff4, and B. M. Gaensler5,6

Draft version October 18, 2006

ABSTRACT

We present results from Chandra and XMM–Newton observations of the radio pulsar B1046–58. A high-resolution spatial analysis reveals an asymmetric pulsar wind nebula (PWN) ~6″×11″ in size. The combined emission from the pulsar and its PWN is faint, with a best-fit power-law photon index of Γ = 1.7+0.4 −0.2 and unabsorbed luminosity of ~1032 ergs s−1 in the 0.5–10.0 keV range (assuming a distance of 2.7 kpc). A spatially resolved imaging analysis suggests the presence of softer emission from the pulsar. No pulsations are detected from PSR B1046–58: assuming a worst-case sinusoidal pulse profile, we derive a 3σ upper limit for the pulsed fraction in the 0.5–10.0 keV range of 53%. Extended PWN emission is seen within 2″ of the pulsar: the additional structures are highly asymmetric and extend predominantly to the south-east. We discuss the emission from the PWN as resulting from material downstream of the wind termination shock, as outflow from the pulsar or as structures confined by a high space velocity. The first two interpretations imply equipartition fields in the observed structures of ≥ 40–100 μG, while the latter case implies a velocity for the pulsar of ≥ 190 km s−1 (where n0 is the ambient number density in units of cm−3). No emission from an associated supernova remnant is detected.

Subject headings: pulsars: general — pulsars: individual (PSR B1046–58) — X-rays: general

1. INTRODUCTION

X-ray observations of rotation-powered pulsars represent a powerful tool for studying the energetics and emission mechanisms of these objects. A large fraction of the available rotational energy is thought to be carried away in a relativistic wind of particles. When this wind is confined by the surrounding medium it accelerates and a synchrotron nebula forms, called a pulsar wind nebula (PWN). The overall PWN characteristics provide insights into the content and energy spectrum of the pulsar wind, the large-scale magnetic fields, and the surrounding medium. The small-scale structures of the nebula provide details of the acceleration sites, instabilities in the magnetic field, and the interaction between the wind and its surroundings. In young, energetic pulsars, nonthermal emission from particles accelerated in the magnetosphere and thermal emission from the surface of the star are also expected to be present.

The radio pulsar (PSR) B1046–58 was discovered during a Parkes survey of the Galactic plane (Johnston et al. 1992). It has a period of P = 124 ms and period derivative D = 9.6×10−14 s s−1. These values imply a characteristic age of τc = P/2D = 20.4 kyr, spin-down luminosity of L = 4π2IP/P 3 = 2.0×1036 ergs s−1 (with a moment of inertia of the neutron star I = 1045 g cm−2) and surface dipole magnetic field strength of B = 3.2×1019√PP G = 3.5×1012 G. These properties are similar to those of other young neutron stars typified by the Vela pulsar. The dispersion measure of 129 pc cm−3 towards the pulsar implies a distance of 2.7 kpc (Cordes & Lazio 2002).

Deep radio observations did not detect extended emission associated with PSR B1046–58 (Stappers et al. 1999). X-ray observations with ASCA and ROSAT detected emission near the pulsar and suggested the presence of large-scale structures surrounded by faint emission (Pivovaroff et al. 2000a). However, the poor angular resolution of these observations prevented conclusive interpretation of the data. PSR B1046–58 is also one of a few pulsars with a possible EGRET γ-ray counterpart. The EGRET source 2EG J1049−5827 is coincident with the radio coordinates of PSR B1046–58 and likely γ-ray pulsations at the radio period have been found (Kaspi et al. 2000).

Here we report on observations of PSR B1046–58 carried out with the Chandra and XMM–Newton satellites. Our study reveals a faint, arcsecond-scale PWN surrounding the pulsar. A detailed imaging and spectral analysis of the system suggests the presence of soft emission from the pulsar. We also examine the characteristics of the nebula in light of current models for the production of PWNe.

2. OBSERVATION AND DATA ANALYSIS

PSR B1046–58 was observed with XMM–Newton on 2002 August 10. The European Photon Imaging Camera (EPIC) MOS and PN instruments (Str"oter et al. 2001) were operated in full- and small-frame modes, respectively. These settings provide a temporal resolution of 2.6 s for EPIC-MOS and 6 ms for EPIC-PN. The medium filters were used for MOS, the thin filter for PN. The CCD data were reduced with the XMM–Newton Science Analysis System (SAS v6.2.0). The standard screening criteria results in an exposure time for the MOS cameras of 20 ks. For the PN camera, only ~70% of the exposure time was used in the small-
window position (4′ field of view), resulting in an effective exposure time of 15 ks.

The Chandra observation of PSR B1046−58 was carried out on 2003 August 8–9. The aimpoint of the back-illuminated ACIS-S3 chip (Garmire et al. 2003) was positioned at the radio coordinates of the pulsar. The observation was taken in timed exposure, very faint mode, providing a temporal resolution of 3.2 s. The data were reduced using the CIAO 3.2.0 software and standard routines. The resulting effective exposure time was 15 ks. The EPIC-PN instrument offers a higher sensitivity than ACIS-S, but its lower exposure time and reduced field of view limited its use to spectral and temporal analyses of the pulsar emission. In turn, the Chandra data were used to perform spectral and high-resolution imaging analyses of PSR B1046−58 and its surroundings, while the EPIC-MOS observations were mainly used as a consistency check due to their lower sensitivity and lower spatial resolution.

3. IMAGING ANALYSIS

Figure 1 shows the area surrounding the radio position of PSR B1046−58 obtained with Chandra. The image has been smoothed with a Gaussian with σ=0.5′. It reveals for the first time the detailed extended structures surrounding PSR B1046−58, which we designate as its pulsar wind nebula (PWN) based on its overall characteristics discussed in the next sections. The nebula is elongated and ∼6′×11″ in size, with its major axis oriented in a SE-NW direction. The line in Figure 1 marks the radio coordinates of the pulsar at α2000=10h48m12.6s (4.7′) and δ2000=−58°32′37.5″ (0.0′′), 2σ errors (Stappers et al. 1999). While there is emission immediately surrounding the pulsar position (PWN “head”), there is also clumped emission to the SE (PWN “body”) and a bright clump to the NW (“north clump”).

The head region of the nebula is consistent with a point source surrounded by extended structures. Figure 2 shows the intensity profile of the observed emission along a 10″×35″ region in a SE-NW direction aligned with the implied axis of symmetry of the nebula. The shaded region represents the 2σ background level obtained from a nearby, source-free region. The dashed line represents Chandra’s PSF at an energy of 1.5 keV obtained using CALDBv3.0.3 and the mkpsf tool. As the head region is also consistent with the radio coordinates of the pulsar, we consider the source embedded in the region to be the X-ray counterpart of the pulsar. Comparing the X-ray position of other sources in the field with their optical counterparts we derive an X-ray position for the pulsar of α2000=10h48m12.6s and δ2000=−58°32′37.5″, with an overall rms error of 0′′.55. This is coincident within 1σ of the radio position, especially in the more constraining declination direction (see Figure 1). We then define the “pulsar” emission as that arising in a circle of 1″ in radius centered on the above X-ray coordinates.

Fig. 1.— Combined Chandra image of PSR B1046−58 and its PWN using individual images in the 0.5−2.0 keV (red) and 2.0−10.0 keV (blue) ranges. Each image was smoothed with a Gaussian with σ=0.5′. The circle (0′′.55-radius) and line (4′′.7 length) mark the X-ray and radio positions of the pulsar, respectively (see §3). The main components discussed in the text are labeled.

Fig. 2.— Chandra axial profile of PSR B1046−58 and its PWN in the 0.5−10.0 keV range in a SE-NW direction (solid line) aligned with the implied axis of symmetry (see Fig. 1). The origin represents the X-ray position of the pulsar. The extended emission at offsets of ∼−3″ to −8″ arises from the “body” of the PWN (in the SE direction) while the emission at offsets of ∼3″−5″ arises from the “north clump”. We also show the 2σ level of the background (shaded region) along with the PSF of the telescope at 1.5 keV (dashed line).

7 The slight asymmetry in the PSF profile is due to the binning and extraction region used in order to match the profile settings for the pulsar. A small, intrinsic asymmetry in the PSF has been suggested and could also contribute (see http://cxc.harvard.edu/cal/docs/cal present_status.html#psf).
The soft point source in Chandra scope significantly affected the above arc-second structures. We then conclude that the detected components can be attributed to the PWN beyond the nebula. ges et al. 2001). No additional extended emission was (e.g., USNO B1.0; 2MASS, Cutri et al. 2003; RASS, V o-dra and XMM observations confirm the presence of these X-ray point sources in the field, in addition to many others resolved by Chandra (see Figure 3). The soft point source in Chandra coincident with “Src 2” from Pivovaroff et al. (2000a) has an optical counterpart in the USNO B1.0 catalog (Monet et al. 2002), while we find no counterparts for the hard sources coincident with “Src 3” and “Src 4” in present catalogues (e.g., USNO B1.0; 2MASS, Cutri et al. 2003; RASS, Voges et al. 2001). No additional extended emission was detected that can be attributed to the PWN beyond the above arc-second structures. We then conclude that the low angular resolution and broad PSF wings of the telescope significantly affected the ASCA observations due to the large number of point sources in the field. We also note that the ASCA positions appear to be systematically north of the Chandra coordinates, the latter being in agreement with source positions at other wavelengths.

4. SPECTRAL ANALYSIS

The data obtained from both Chandra and XMM–Newton were used to perform a spectral analysis of the emission from PSR B1046–58 and its PWN. For the Chandra data, an elliptical region of 12″×18″ in size was used with a surrounding annulus as background. A total of 184±14 background-subtracted counts were detected in the 0.5–10.0 keV range. The XMM–Newton data were extracted from circular regions of 25″ radii in each detector, encompassing ~77% of the photons from a point source, with a nearby region used as background. The data from MOS1 and MOS2 were not included in the analysis due to the low number of counts detected in them (106±17 and 47±17, respectively). The PN detector collected 260±47 background-subtracted counts in the same range. The extracted spectra from Chandra’s S3 chip and XMM–Newton’s PN detector were fit simultaneously in the 0.5–10.0 keV range using XSPEC (v.11.3.0) and a minimum of 20 counts per bin in each spectrum.

Thermal models for the integrated emission from the PWN and PSR B1046–58 are statistically acceptable (χ2/1.1). However, they result in temperatures far too high to represent shock-heated thermal plasma (T >8×107 K, Raymond-Smith model, Raymond & Smith 1977) or emission from the surface of the neutron star (T >1×107 K, blackbody model). Instead, a non-thermal absorbed power-law model produces an equally acceptable fit (see Table 2) with a photon index of Γ=1.7±0.4, similar to what is observed for other pulsars and their PWNes (e.g., Gaensler & Slane 2006). The Chandra spectrum with the best-fit power-law model is shown in Figure 4. The observed emission is thus consistent with having a predominantly non-thermal origin.

It has been found that the MOS1 count rate can be artificially boosted by statistical fluctuations by up to ~70%, especially for sources with <50 true counts. See §2.1 and §4 in [http://xmm.vilspa.esa.es/docs/documents/CAL-TN-0023-2-1.ps]
We then searched for differences in the spectral characteristics of the different components of the system, as is hinted from our imaging analysis. The high spatial resolution available with Chandra was essential. The 116±14 counts detected from the PWN alone were fit with a power-law model. Holding the interstellar absorption fixed to the best-fit value from Table 2, the resulting photon index was $\Gamma_{\text{PWNe}} \approx 1.2$. Holding this contribution from the nebula fixed while fitting the overall spectrum, the residual (presumably pulsar-dominated) emission was well described by a power-law model with a photon index of $\Gamma \approx 2.4$. If a blackbody model is fitted to this emission the resulting temperature is $\sim 6.1 \times 10^6$ K, too high to represent purely thermal emission from the neutron star but lower than thermal fits to the overall spectrum. Although the small number of counts did not allow us to constrain the above parameters, emission from the pulsar softer than that of the nebula seems to be present.

5. Timing Analysis

The data from the XMM-Newton EPIC-PN camera were used to search for pulsations from PSR B1046–58. No evidence for an instrumental 1-s jump in the data was found (see, e.g., Woods et al. 2001). The dataset was converted to the solar system barycenter and a circular region of 25" radius centered at the above Chandra coordinates was used to extract the pulsar events. We also examined the dataset in different energy ranges using 0.5–10.0 keV, 0.5–2.0 keV and 2.0–10.0 keV. Radio observations of the pulsar obtained with the Parkes telescope predict a period for the middle of our observation (MJD 52496.5) of $f = 8.08512306$ Hz ($P = 123.683955$ ms).

The $Z^n$ test (Buccheri et al. 1983) was used to search for a periodic signal by folding the extracted photons over a range of 10 trial frequencies centered on the radio prediction. The number of harmonics used was varied to be $n = 1, 2, 4, 8$. The most significant signal was found in the 0.5–2.0 keV range at $f=8.08517(4)$ Hz ($1\sigma$ error) with $Z^2 = 8.9$. Although this signal is consistent with the radio period of PSR B1046–58, it has a probability of chance occurrence of 6.3% for a single trial and is not significant given the number of searches performed. Following Vaughan et al. (1994) and, e.g., Ransom et al. (2002), we can derive an upper limit on the pulsed fraction. Assuming a worse-case sinusoidal modulation, the maximum Fourier power observed for a small range of frequencies centered on the radio prediction can be used to calculate an upper limit for the pulsed fraction at a specific level of confidence. In this way, we derive an upper limit for the pulsed fraction at the 99% confidence level of 53%, 65% and 61% in the 0.5–10 keV, 0.5–2.0 keV and 2.0–10.0 keV ranges, respectively.

6. Discussion

6.1. PSR B1046–58

X-ray emission from young radio pulsars is expected to include contributions from any of the following processes: thermal emission from the entire surface due to initial cooling, non-thermal emission from magnetospheric processes, and possibly thermal emission from localized hot spots reheated by back-flowing magnetospheric currents (see, e.g., Kaspi et al. 2004).

The combined emission from the pulsar and its PWN is best described by a non-thermal power-law model. However, our imaging and spectral analysis suggests that an additional, soft component may be present in the pulsar’s emission. The soft emission can be well described by a steep power law with $\Gamma \sim 2.4$, although such an interpretation would contradict the generally observed trend of young pulsars having spectral indices harder than those of their PWNe (e.g., Gotthelf 2003). The additional soft emission cannot be entirely thermal, as the derived temperature is too high. It could, however, represent a combined spectrum of (hard) non-thermal plus (soft) thermal emission. The number of counts detected does not allow us to fit two-component models to this emission alone.

5.2. The PWN

The high spatial resolution available with Chandra allowed us to discover the arc-second scale PWN structures surrounding the pulsar. The “head” of the nebula is coincident with the radio position of the pulsar, while diffuse emission is seen predominantly to the SE. The emission from the pulsar and PWN is very faint, with a combined unabsorbed luminosity of only $\sim 1 \times 10^{32}$ ergs s$^{-1}$ in the 0.5–10.0 keV range. The efficiency with which the pulsar converts its rotational kinetic energy into X-rays is then $\eta_X \equiv L_X / E \sim 5 \times 10^{-5}$, comparable to the values found for other Vela-like systems (e.g., Pavlov et al. 2001a; Camilo et al. 2004). It has been recently suggested that an empirical relationship exists between the X-ray spectral power-law indices of young pulsars ($\Gamma_{\text{psr}}$) and their PWN ($\Gamma_{\text{pwn}}$) with the pulsar’s spin-down energy loss $E$ (Gotthelf 2003). According to this relationship, lower $E$ pulsars exhibit harder spectral indexes. For PSR B1046–58, the predicted values are $\Gamma_{\text{psr}} \sim 0.1$ and $\Gamma_{\text{pwn}} \sim 0.9$. The PWN emission appears to exhibit a spectrum similar to that predicted by this relationship ($\Gamma_{\text{pwn}} \sim 1.2$). However, the small number of counts and the possible detection of thermal emission limit our ability to constrain the spectral characteristics of the pulsar and its PWN. Observations of other Vela-like pulsars do not seem to support this relationship (e.g., PSR B1823–13, Gaensler et
Radio observations did not detect emission from the PWN and constraints on the radio properties depend directly on the underlying assumption for the radio efficiency ($\eta_R = L_R/E$; [Stappers et al. 1999]). Detected nebulae show efficiencies in the range $\eta_R \sim 10^{-4} - 10^{-3}$, while upper limits for unseen nebulae imply values of $\eta_R < 10^{-5}$ [Frail & Scharringhausen 1997; Gaensler et al. 2000]. In the case of an undetected, extended radio nebula surrounding PSR B1046–58 and using a value of $\eta_R = 2 \times 10^{-4}$, the upper limit on the radio flux and required surface brightness imply a large radius of 8 pc for a circular nebula ([Stappers et al. 1999]). At a distance of 2.7 kpc this represents a radius of $\sim 10^{15}$. While the X-ray size of PWNe is often found to be up to a few times smaller than the radio size due to smaller synchrotron lifetimes in the X-rays (e.g., [Hester et al. 2002]), we find no evidence for extended PWN structures on arcminute scales. For radio sizes $\lesssim 30''$, based on the small angular size of the X-ray nebula, the required efficiencies are very low at $\eta_R \lesssim 5 \times 10^{-7}$.

The origin of PWNe is commonly attributed to the interaction of a highly relativistic pulsar wind with its surroundings. At a radius $r_s$ from the pulsar, representing the point of pressure balance at which the wind is confined and decelerated, we expect $P = \dot{E}/4\pi\Omega^2 c$. Here, $P$ is the surrounding pressure and $\Omega \lesssim 1$ is the filling factor of the wind. As the head region of the nebula is resolved as an extended structure with Chandra, we suggest that its outer radius can represent an upper limit on the location of the wind termination shock, while the body represents the expected emission downstream. The shock radius in this case is $r_s < 2'' = 0.026 d_{2.7} {\text{pc}}$, very similar to that found for the Vela pulsar [Helfand et al. 2001] and an order of magnitude smaller than those of much more energetic pulsars such as the Crab and PSR B1509–58 (e.g., [Weisskopf et al. 2001; Gaensler et al. 2002]). The required pressure in this case is $P \gtrsim 8.2 \times 10^{-10} d_{2.7}^2$ ergs cm$^{-3}$ ($d_{2.7}$ is the distance to the pulsar in units of 2.7 kpc). In the region downstream of the shock we expect equipartition between the particles and magnetic field to be reached, so that $B^2/4\pi = P$, where $B$ is the mean magnetic field in the nebula. We then estimate a value of $B \gtrsim 100 d_{2.7}^{-1} \mu G$. The corresponding synchrotron lifetime of particles emitting at an energy $\epsilon_{\text{keV}}$ (in units of keV) is very small, at $t_{\text{synch}} \lesssim 40 d_{2.7}^{3/2} \epsilon_{\text{keV}}^{-1/2}$ yr. The velocity that is needed for these particles to reach the edge of the nebula within their synchrotron lifetimes is $v \gtrsim 2.6 \times 10^8 d_{2.7}^{-1/2} \epsilon_{\text{keV}}^{1/2}$ km s$^{-1} \gtrsim 0.01 d_{2.7}^{-1/2} \epsilon_{\text{keV}}^{1/2}$ c.

One problem with the above interpretation is that we expect the emission downstream of the shock to be symmetric about the pulsar. A possible explanation for the lack of emission to the NW involves Doppler boosting of the approaching (in this case SE) component. The observed flux ratios on either side of the pulsar require an intrinsic expansion velocity of $v \sin \theta \gtrsim 0.22 c$, where $\theta$ is the inclination of the nebula to the line of sight.

9 Gotthelf (2004) has later suggested that this relationship only holds for pulsars with $E > 4 \times 10^{36}$ ergs s$^{-1}$ and without a bow-shock morphology.
tions at higher X-ray energies (e.g., deep exposures us-

A consistent bow-shock interpretation in both radio and X-rays is possible if the unde-


tal and energetic properties of the pulsar. This argues for the unpulsed γ-ray emission associated with 2EG J1049–5827 to also arise, at least in part, from the nebula, as proposed for the Vela and Crab pulsars (Nolan et al. 1993; Kanbach et al. 1994; Fierro et al. 1998).

6.4. Non-detection of a Supernova Remnant

As we do not detect emission from a supernova remnant (SNR) in the field containing PSR B1046–58, following Gaensler et al. 2003, we can estimate the flux from a possible unseen remnant by scaling the emission observed from the Vela SNR. The emission from this remnant can be described by a two-component Raymond-Smith plasma with temperatures $kT_1 \sim 0.15$ keV and $kT_2 \sim 1$ keV (Lu & Aschenbach 2000). The total unabsorbed luminosity in the 0.1–2.4 keV range is $2.2 \times 10^{35}$ ergs s$^{-1}$ and the cooler component has a volume-integrated emission measure $\sim 10$ times higher than the hot component. Scaling to a distance of 2.7 kpc, the unabsorbed flux densities for each component would be $f_1 = 2.3 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$ and $f_2 = 2.2 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$, respectively.

The expected ACIS-S$^{10}$ count rate predicted by the WebPIMMS tool$^{11}$ is $<2.6$ counts s$^{-1}$ (on-axis) for absorbing columns $>5 \times 10^{21}$ cm$^{-2}$. Scaling the size of the Vela SNR ($\sim 8^\circ$ at 300 pc, Lu & Aschenbach 2000), we would expect a shell with a radius of $\sim 26'$ at 2.7 kpc. This size is larger than the ACIS-S (and EPIC-MOS) field of view. However, parts of the remnant might be visible in the present data given the uncertainties in the spatial distribution of the remnant and direction of motion of the pulsar. Assuming emission areas for the remnant proportional to having a shell thickness $\lesssim 20\%$ of its radius, the expected surface brightness density is $\lesssim 0.8 \times 10^{-6}$ counts s$^{-1}$ arcsec$^{-2}$. This is lower than the ACIS-S background level during the observation, estimated to be $\sim 2.6 \times 10^{-6}$ counts s$^{-1}$ arcsec$^{-2}$ (account-

$^{10}$ The EPIC-MOS data provide less constraining limits for this emission due to their lower sensitivity and higher background levels. The EPIC-PN data had a much smaller exposure time and limited field of view.

$^{11}$ http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html
ing for vignetting at large off-axis angles). It is then possible that a remnant with similar properties to that of the Vela remnant might be present and it is undetected by these observations. The lack of radio or X-ray emission from the SNR has also been attributed to an initial fast expansion into a low-density cavity (e.g., [Braun et al. 1989]). This expansion is followed by a collision with a dense surrounding shell of stellar wind material from the progenitor where the emission fades rapidly and energy is dissipated through radiative shocks.

7. CONCLUSIONS
We have detected an asymmetric, arc-second scale PWN surrounding the young, energetic PSR B1046−58. The overall emission from the pulsar and PWN is best described by a non-thermal power-law model with $\Gamma=1.7^{+0.4}_{-0.2}$ and a low X-ray luminosity of $\sim 10^{32}$ ergs s$^{-1}$ in the 0.5−10.0 keV range. The brightest emission region in the PWN is coincident with the radio coordinates of the pulsar. It is resolved as an extended structure with Chandra and we suggest that it can represent an upper limit to the location of the wind termination shock. The additional, asymmetric structures can represent nebular emission downstream of the shock or collimated outflow from the pulsar. The implied equipartition magnetic fields are $\gtrsim 40−100$ $\mu$G. The overall size and energetics of the system in this case are very similar to those of the Vela pulsar. Instead, if the observed asymmetry in the nebula were to arise due to a large space velocity for the pulsar we estimate a value of $\gtrsim 190$ $u_{\\infty}^{-1/2}$ km s$^{-1}$. In this case, we would favor the presence of arcsecond-scale nebulae with low efficiencies in both X-ray and radio.

Our spatially resolved analysis also hints at the presence of softer emission from the pulsar than from the rest of the nebula. In the case that thermal emission from the whole surface of the star is present, we derive an upper limit for the temperature of $<1.4 \times 10^6$ K, which is not constraining on cooling models of neutron stars. In the case of a small hot spot on the surface, the implied temperature is $>2.5 \times 10^6$ K and would be consistent with those seen for other pulsars.

The results shown here demonstrate the need for high-resolution, high-sensitivity observations in order study the wide range of structures associated with rotation-powered pulsars. While the origin of these structures cannot be unambiguously determined in the case of PSR B1046−58, they can be broadly understood using current theories for the production PWNe. Additional data and theoretical work are needed to reach a consistent picture of this interesting phenomenon in neutron star physics.

This work was supported in part by an NSERC Discovery Grant and Steacie Supplement, FQRNT, NSERC Graduate Scholarship and a Canadian Institute for Advanced Research Fellowship, the Canada Research Chair Program, SAO grant GO3−4068X awarded by the CXC and by NASA grant NAG5−11376 awarded by NASA’s XMM Guest Observatory Facility. B.M.G. acknowledges the support of NASA through LTSA grant NAG5−13032, and of an Alfred P. Sloan Research Fellowship. We thank R. N. Manchester for kindly providing the Parkes radio ephemeris for PSR B1046−58.

REFERENCES

Cutri, R. M., et al. 2003, VizieR Online Data Catalog II/246
Gaensler, B. M., & Slane, P. O. 2006, ARAA, 44, 17
Gotthelf, E. V. 2004, in IAU Symposium, ed. F. Camilo & B. M. Gaensler, 225

Pacholczyk, A. G. 1970, Radio Astrophysics (San Francisco: Freeman)
Voges, W., et al. 2000, VizieR Online Data Catalog IX/29
### TABLE 1
Spatial analysis of PSR B1046−58 and its PWN with Chandra

<table>
<thead>
<tr>
<th>Region</th>
<th>0.5−2.0 keV counts (S)</th>
<th>2.0−10.0 keV counts (H)</th>
<th>HR = (S−H)/(S+H)</th>
<th>S/N (0.5−10.0 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar (1′′ radius)</td>
<td>43 ± 8</td>
<td>24 ± 6</td>
<td>0.27 ± 0.10</td>
<td>8.5σ</td>
</tr>
<tr>
<td>PWN, all (- Pulsar)</td>
<td>36 ± 9</td>
<td>70 ± 11</td>
<td>−0.21 ± 0.06</td>
<td>9.1σ</td>
</tr>
<tr>
<td>PWN, “head” (- Pulsar)</td>
<td>12 ± 5</td>
<td>31 ± 7</td>
<td>−0.44 ± 0.21</td>
<td>6.1σ</td>
</tr>
<tr>
<td>PWN, “body”</td>
<td>22 ± 6</td>
<td>34 ± 7</td>
<td>−0.22 ± 0.10</td>
<td>9.1σ</td>
</tr>
<tr>
<td>“North clump”</td>
<td>5 ± 2</td>
<td>5 ± 2</td>
<td>0.00 ± 0.02</td>
<td>2.9σ</td>
</tr>
<tr>
<td>Pulsar + PWN</td>
<td>89 ± 11</td>
<td>95 ± 12</td>
<td>−0.03 ± 0.01</td>
<td>12.1σ</td>
</tr>
</tbody>
</table>

*See §3 for detailed discussion.*

### TABLE 2
Power-law fit to combined emission from PSR B1046−58 and its PWN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (±1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_H$ (10^{22} cm$^{-2}$)</td>
<td>0.9$^{+0.4}_{-0.2}$</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>1.7$^{+0.4}_{-0.2}$</td>
</tr>
<tr>
<td>$\chi^2$ (dof)</td>
<td>79(68)</td>
</tr>
<tr>
<td>$f_{\text{abs}}$ (ergs s$^{-1}$ cm$^{-2}$)</td>
<td>0.7$^{+0.1}_{-0.1}$ × 10$^{-13}$</td>
</tr>
<tr>
<td>$f_{\text{unabs}}$ (ergs s$^{-1}$ cm$^{-2}$)</td>
<td>1.0$^{+0.7}_{-0.2}$ × 10$^{-13}$</td>
</tr>
<tr>
<td>$L_X$ (ergs s$^{-1}$)</td>
<td>0.9$^{+0.6}_{-0.2}$ × 10^{32}</td>
</tr>
</tbody>
</table>

*aSimultaneous fit to both Chandra and XMM–Newton spectra.

bAbsorbed and unabsorbed X-ray fluxes, $f_{\text{abs}}$ and $f_{\text{unabs}}$, in the 0.5−10.0 keV range.

cUnabsorbed X-ray luminosity in the 0.5−10.0 keV range for a distance of 2.7 kpc.