AN X-RAY PULSAR IN THE OXYGEN-RICH SUPERNOVA REMNANT G292.0+1.8

JOHN P. HUGHES1, PATRICK O. SLANE2, SANGWOOK PARK3, PETER W. A. ROMING3, AND DAVID N. BURROWS3

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ABSTRACT

We report the discovery of pulsed X-ray emission from the compact object CXOU J112439.1−591620 within the supernova remnant (SNR) G292.0+1.8 using the High Resolution Camera on the Chandra X-ray Observatory. The X-ray period (P = 0.13530915 s) is consistent with extrapolation of the radio pulse period of PSR J1124−5916 for a spindown rate of ˙P = 7.6 × 10−13 s/s. The X-ray pulse is single peaked and broad with a FWHM width of 0.23P (83°). The pulse-averaged X-ray spectral properties of the pulsar are well described by a featureless power law model with an absorbing column density N_H = 3.1 × 1021 cm−2, photon index Γ = 1.6, and unabsorbed 0.3–10 keV band luminosity L_X = 7.2 × 1032 erg s−1. We plausibly identify the location of the pulsar’s termination shock. Pressure balance between the pulsar wind and the larger synchrotron nebula, as well as lifetime issues for the X-ray-emitting electrons, argues for a particle-dominated PWN that is far from the minimum energy condition. Upper limits on the surface temperature of the neutron star are at, or slightly below, values expected from “standard” cooling curves. There is no optical counterpart to the new pulsar; its optical luminosity is at least a factor of 5 below that of the Crab pulsar.

Subject headings: ISM: individual (SNR G292.0+1.8, MSH 11−54) – pulsars: individual (PSR J1124−5916) – stars: neutron – supernova remnants – X-rays: individual (CXOU J112439.1−591620)

1. INTRODUCTION

The composition of the ejecta seen in a supernova remnant (SNR) can be used to constrain the nature of the supernova (e.g., core collapse or thermonuclear), and, in the case of a core collapse SN, estimate a range for the mass of the progenitor star (e.g., Hughes & Singh 1994). Recent studies of the SNR Cas A with Chandra and XMM-Newton (e.g., Hughes et al. 2000; Bleeker et al. 2001; Willingale et al. 2002) highlight the great potential of the new observatories for such studies. Unfortunately, most SNRs that harbor young pulsars are virtually useless for such investigations: they do not show much evidence for shocked ejecta (e.g., the Crab and 3C 58), are too distant for detailed study (e.g., SNR E0554−69.3 and N157B), or are so evolved that the ejecta cannot be easily distinguished from shocked interstellar gas (e.g., Vela and W44). G292.0+1.8 differs from nearly all other pulsar/SNR associations by virtue of showing spectacular evidence for newly synthesized oxygen-, neon-, and magnesium-rich ejecta (optical: Murdin & Clark 1979; X-ray: Park et al. 2002); having a dynamically determined age (~2000 yrs; Murdin & Clark 1979); and being relatively nearby (~6 kpc; Gaensler & Wallace 2003). With G292.0+1.8 we have the opportunity to tie information on the progenitor star derived from nucleosynthesis (Park et al. 2003, in prep.) to the origin and evolution of pulsars and their wind nebulae (PWNe).

Recently Chandra revealed an X-ray point source (CXOU J112439.1−591620) centered on a diffuse synchrotron nebula in G292.0+1.8 (Hughes et al. 2001). In a follow-up study Camilo et al. (2002) discovered a 135-ms young pulsar within or near G292.0+1.8 using the Parkes radio telescope that is almost surely the counterpart to the Chandra point source. However the large beam of the Parkes telescope (~14′ FWHM) means that the case is not ironclad. Here we report on high temporal and spatial resolution X-ray observations in which we detect the pulsed signal from CXOU J112439.1−591620, clearly identifying it as the compact remnant of the SN that formed G292.0+1.8.

2. X-RAY PULSAR

We observed SNR G292.0+1.8 beginning on 14 July 2001 using the Chandra High Resolution Camera (HRC) in timing mode with the pulsar candidate at the aimpoint (ObsID 1953). Timing mode observations utilize the central portion of the HRC-S focal plane array which provides a field of view roughly 6′ by 30′. Individual photons are time tagged to an accuracy of about 16 µs; we corrected photon arrival times to the solar-system barycenter using the position of the pulsar candidate. Our observation was nearly continuous; the only interruptions were 8 gaps of ~2 s duration each, distributed throughout the exposure. The livetime corrected exposure was 49578 s.

Figure 1 (left panel) shows a roughly 6′′ × 6′′ portion of the HRC image containing the pulsar candidate at position R.A. = 11:24:39.1, decl. = −59:16:20 (J2000). There is an unresolved source centered on a small, diffuse, elliptically-shaped nebula. Within a radius of 2″ (15 HRC pixels) of the point source we detected 1324 X-ray photons. First we carried out a blind search for pulsations on these events. Light curves were constructed for the entire duration of the observation using four different binsizes of 0.0237563 s, 0.0118781 s, 0.00593907 s, and 0.00296954 s corresponding...
to $2^{21}$, $2^{22}$, $2^{23}$, and $2^{24}$ temporal bins. A coherent FFT of the entire light curve showed no statistically significant pulsed signal for any of these cases. The distribution of Fourier powers was consistent with noise and the individual peak Fourier powers obtained were 30.4, 31.9, 32.9, and 34.2 for the four cases, respectively, none of which are statistically significant. As a verification of our methods and IDL software we applied the same programs to the HRC data of PSR B0540–69.3, observed on 22 June 2000 (ObsID 1745) using the same configuration as our data. The pulsar was easily detected at a frequency of 19.7941 Hz with a peak Fourier power of 50.3 (99.998% significance).

A much more sensitive search for X-ray pulsations is possible by narrowing the range of trial frequencies to be consistent with the radio pulse and a reasonable range of $P$ values. We employed the $Z_2^2$ test (Buccheri et al. 1983) which applies a harmonic analysis to the phases of photon arrival times for a given trial pulsation frequency. One advantage of the method, compared to epoch-folding for example, is that it requires no binning. Another is that, even for as few as 100 detected photons, the statistic is distributed like $\chi^2$ with $2n$ degrees of freedom. In our searches we use $n = 2$.

We searched eleven trial frequencies spaced by $\Delta f = 1 \times 10^{-5}$ Hz (roughly the frequency resolution of our data) and centered on the expected value based on extrapolating the radio ephemeris to the midpoint of the HRC observation (MJD = 52105.18). The peak $Z_2^2$ value was 22.6 corresponding to the 99.8% significance level. The search was refined by reducing $\Delta f$ to $2 \times 10^{-6}$ Hz and again searching eleven trial frequencies, this time centered on the most likely previous pulsation frequency. This iteration yielded a peak $Z_2^2$ value of 27.9 (99.97% significant or approximately $3.6 \sigma$) at a period of 0.13530915 s. The period error ($4 \times 10^{-9}$ s, 1 $\sigma$) was determined using a bootstrap algorithm. In Table 1 we quote observed properties of the X-ray pulsar. By comparing our pulse period to the value obtained by Camilo et al. (2002) roughly two months later we derive a period derivative of $\dot{P} = 7.62 \pm 0.06 \times 10^{-13}$ s/s that differs by $\sim 2.5 \sigma$ from the value quoted in the radio discovery paper. At present we do not know the relative X-ray and radio pulse phases and, due to apparent rotational instabilities in the neutron star, it is not possible to extrapolate the radio ephemeris from September 2001 back to July 2001 accurately enough to measure relative phases.

As an additional check on the detection of pulsed X-ray emission, we applied the last search iteration to the first and second halves of the data set (split in time) independently. The pulse was detected in each half at the appropriate $Z_2^2$ value and pulsation frequency and with similar light curve shapes.

The pulse in the X-ray band is single peaked and symmetric (see Fig. 2), similar to the radio pulse, although the X-ray pulse width (FWHM $\sim 0.23P$ $\sim 83^\circ$) is somewhat broader than the radio one. The smooth curve in figure 2 is a Fourier series estimate (de Jager, Swanepoel, & Raubenheimer 1986) of the light curve (solid curve) and its 1 $\sigma$ uncertainty (dashed curves).

![Fig. 1.](image1.png)  
**Fig. 1.** — A portion of the *Chandra* high resolution camera image centered on CXOU J112439.1−591620. In the left and middle panels the grayscale is linear from 0 to 15 HRC counts per pixel (0.1318" square). In the right panel the linear grayscale extends from -1.4 to 1.8 counts per pixel. This last image was smoothed with a 1 pixel $\sigma$ gaussian kernel. Coordinates are given in epoch J2000.

![Fig. 2.](image2.png)  
**Fig. 2.** — Pulse phase light curve for PSR J1124−5916 folded modulo the best-fit period of 0.13530915 s. Two complete periods are shown. Note the suppressed zero on the y-axis. Also plotted are the Fourier series estimator (de Jager, Swanepoel, & Raubenheimer 1986) of the light curve (solid curve) and its 1 $\sigma$ uncertainty (dashed curves).
to balance the ram pressure of the wind, \( P_w = \frac{E}{4\pi c r_w^2} \), assuming spherical symmetry. The mean radius of the compact nebula is 0.036 \( d_6 \) pc and the spin down energy loss of the pulsar is \( E = 1.2 \times 10^{38} \) erg s\(^{-1}\) (Camilo et al. 2002), so the pressure is \( P_w = 2.6 \times 10^{-9}\ d_6^{-2} \) erg cm\(^{-3}\).

We estimate the pressure in the PWN from the properties of the radio emission, which we take from Gaensler & Wallace (2003), and the theory of synchrotron emission (Longair 1994). Under the minimum energy condition we find that \( P_{\text{PWN, min}} \sim 1.3 \times 10^{-10}\ d_6^{-4/7} \) erg cm\(^{-3}\) assuming equal energy densities in the protons and electrons and a volume filling factor of unity. The average nebular magnetic field under these conditions is \( B_{\min} \sim 48\ d_6^{-2/7} \) \( \mu \)G, which implies a very short synchrotron lifetime, \( t \sim 140\ d_6^{3/7} \) \(( h\nu / 2 \text{keV})^{-1/2}\) yr, for the electrons giving rise to the X-ray emission. Such a short lifetime is inconsistent with the observation that the X-ray synchrotron nebula covers as large an extent as the radio nebula does.

A possible solution to these discrepancies lies in relaxing the minimum energy condition. If we move in the direction of a smaller mean nebular magnetic field we resolve the lifetime issue. A magnetic field strength of \( \lesssim 8\mu \)G would ensure that the X-ray synchrotron cooling time is \( \gtrsim 2000\) yr. In order that the pressure in the synchrotron nebula be sufficiently strong to balance the ram pressure of the pulsar’s wind requires a value of \( B \sim 3 \) \( \mu \)G. The total energy in the nebula would then be \( \sim 4 \times 10^{49}\) ergs, contained nearly entirely in particles. Since this energy has come from the spin-down of the pulsar, it sets a constraint on the initial spin period: \( P_0 \sim 22\) ms for a canonical NS momentum of inertia of \( I \equiv 10^{45}\) g cm\(^2\). This \( P_0\) value is considerably less than the value of \( \sim 90\) ms estimated by Camilo et al. (2002). The simplest way to accommodate our low value for the initial spin period would be to increase the true age of the pulsar to \( \sim 2800\) yr or more.

It is important to note that neither the magnetic field nor the pressure is expected to be uniform in PWNe, as we assumed in the calculations above. In the Kennel & Coroniti (1984) model for the Crab Nebula the total pressure is greatest at the termination shock and then falls by factors of 3–10 at larger radii. In addition, equipartition between particles and fields is attained only at a significant distance from the pulsar; near the termination shock the magnetic field is low and the pressure is particle-dominated. Because of the higher central pressure, we expect the volume-averaged magnetic field under this model to be somewhat larger than that estimated above, which would have the effect of relaxing the energetics constraint on the pulsar’s initial spin period. Our apparent need for a particle-dominated PWN in G292.0+1.8 is suggestive of a low value for the magnetization parameter in the context of this model. We note, however, that interaction between the reverse shock and the PWN (which has not yet been conclusively established) may offer an alternate explanation for why the nebula is far from the minimum energy condition. Further study of these issues, although beyond the scope of our work here, is clearly warranted.

### 4. Neutron Star Cooling
The NS in G292.0+1.8 is quite young with a most likely age range of \(\sim2000\) yrs to \(\sim2900\) yrs, corresponding to the free expansion age of the O-rich knots and the pulsar characteristic age, respectively. According to NS cooling models (e.g., Tsuruta 1998; Page 1998), the surface temperature at this age should be high enough to produce detectable X-ray emission. As shown by Hughes et al. (2001), the ACIS-S spectrum of the pulsar is fully consistent with a single absorbed power-law. Here we determine the upper limit to the intensity of an additional blackbody spectral component as a function of its temperature, \(T_{BB}\). We utilized two independent spectra extracted from the CTI-corrected data (Park et al. 2002): one from a 3\(\times\)3 pixel (1.5\arcsec\times1.5\arcsec) region centered on the pulsar, and another, comprising the diffuse nebula, from an ellipse of size 7\times11 pixels (3.4\arcsec\times5.4\arcsec) excluding the central pulsar region. The pulsar spectrum was fit to the sum of a blackbody and a power-law model including absorption, while the nebular spectrum was fit to an absorbed power-law model alone. This latter spectrum served as an independent constraint on the column density, which was constrained to be the same between the two spectra. For reference, table 1 lists pure power-law spectral parameters for the pulsar.

For a given fixed value of \(T_{BB}\), the ACIS-S data set an upper limit on the allowed normalization (or flux) of the blackbody component. One can express the normalization upper limit on the allowed normalization (or flux) of the blackbody component as a function of its temperature, \(T_{BB}\). We determined the upper limit to the intensity of an additional blackbody spectral component as a function of its temperature, \(T_{BB}\). We used two independent spectra extracted from the CTI-corrected data (Park et al. 2002): one from a 3\(\times\)3 pixel (1.5\arcsec\times1.5\arcsec) region centered on the pulsar, and another, comprising the diffuse nebula, from an ellipse of size 7\times11 pixels (3.4\arcsec\times5.4\arcsec) excluding the central pulsar region. The pulsar spectrum was fit to the sum of a blackbody and a power-law model including absorption, while the nebular spectrum was fit to an absorbed power-law model alone.

Fig. 3.— Constraint on the normalization of a blackbody spectral component vs. its temperature from fits to the time-averaged ACIS-S spectrum of PSR J1124−5916 (thick solid curve). The thin solid curve indicates the constraint based on the unpulsed HRC count rate of the X-ray pulsar. The allowed region lies to the left and below the curves shown. The dashed lines show the temperature constraint for the nominal value of distance to G292.0+1.8 (6 kpc) and a 12 km radius NS. The vertical dotted line shows the temperature expected for a standard NS cooling curve.

Since the ACIS-S spectrum is consistent with an entirely nonthermal origin, the pulsed emission seen in the HRC, which comprises \(\geq65\%\) of the total HRC rate from the pulsar, therefore must be dominated by nonthermal, i.e., magnetospheric emission as well. The unpulsed HRC emission, however, can be used to set another constraint on the mean surface temperature of the NS. We convert the 3 \(\sigma\) upper limit on the unpulsed HRC count rate (\(2.8\times10^{-3}\) s\(^{-1}\)) assuming the 3 \(\sigma\) upper limit on the column density to the pulsar (\(N_H = 4.75\times10^{21}\) atom cm\(^{-2}\)), derived from the nebular spectrum) to a constraint on the blackbody normalization as a function of \(T_{BB}\). This constraint, which is fully consistent with the one from the ACIS-S spectral analysis, is shown as the thin curve in figure 3.

Recent work (Gaensler & Wallace 2003) suggests that the distance to G292.0+1.8 is \(\sim6\) kpc. Using this value and assuming a 12 km radius for the NS, we obtain a constraint of \(\sim1.18\times10^6\) K on the surface temperature of the NS. The expected temperature, assuming standard NS cooling models, is \(1.28\times10^6\) K (Page 1998). Although this is suggestive of the presence of exotic cooling processes, systematic uncertainties make this result less secure than the recent result on the apparent need for exotic cooling processes for the NS in 3C 58 (Slane, Helfand, & Murray 2002). The NS in G292.0+1.8 would be consistent with standard cooling if it were as distant as 7 kpc, or if the compact star’s radius were as small as 10 km. On the other hand pure blackbody spectral models tend to overpredict (by factors of 1.5 or more) the effective temperature of NS surfaces when light element atmospheres are included (Lloyd, Hernquist, & Heyl 2002).

5. LIMITS ON AN OPTICAL COUNTERPART

Optical emission from isolated pulsars within supernova remnants has currently been detected from only four objects: PSR B0531+21 (Crab), PSR B0540−69.3 (in the LMC), PSR B1509−58 (G320.4−1.2), and PSR B0833−45 (Vela) (see, for example, Nasuti et al. 1997 and references therein). The first three are very young pulsars (1000–2000 years old), while the pulsar in Vela is considerably older (\(\sim10,000\) yrs), although it is still rather young compared to the average radio pulsar. Across the optical band these pulsars show flat power-law spectra (\(\alpha \sim 0\) for \(F_\nu \propto \nu^{-\alpha}\)), although their intrinsic luminosity densities (i.e., \(L_\nu = 4\pi D^2 F_\nu\)) span 5 orders of magnitude from 0.5–2 \(\times 10^{19}\) erg s\(^{-1}\) Hz\(^{-1}\) (PSR B0531+21, PSR B0540−69.3, and PSR B1509−58) to 3–6 \(\times 10^{14}\) erg s\(^{-1}\) Hz\(^{-1}\) (PSR B0833−45). In terms of age and remnant optical properties (i.e., the presence of high velocity, oxygen-rich optical emission), G292.0+1.8 most closely resembles SNR 0540−69.3. However in terms of spin-down energy loss \(\sim10^{37}\) erg s\(^{-1}\)), the pulsar in G292.0+1.8 is more similar to PSR B0833−45 and PSR B1509−58.

With Chandra we have localized the G292.0+1.8 pulsar to an absolute position accuracy of \(\sim1''\). Within double this error circle there is no optical counterpart visible in the Digitized Sky Survey. We have obtained an upper limit on optical emission from the pulsar, \(B \geq 22\), based on a narrow-band blue continuum image of G292.0+1.8 taken by P.F. Winkler and K.S. Long from the CTIO 4-m in 1991. This corresponds to an intrinsic luminosity density of \(L_\nu < 3 \times 10^{18}\) erg s\(^{-1}\) Hz\(^{-1}\) (assuming a distance of 6 kpc and extinction of \(A_B \sim 2.3\)). This is about an order of magnitude less than the optical emission of the Crab and SNR 0540−69.3 pulsars, but is only about a factor of two less than the optical emission from PSR B1509−58 (Caraveo, Mereghetti, & Bignami 1994). A considerably fainter upper limit, based on data acquired at CTIO in April 2002, will be the subject of a forthcoming article.

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