THE PULSAR WIND NEBULA IN G11.2–0.3

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ABSTRACT

We present an X-ray and radio study of the wind nebula surrounding the central pulsar PSR J1811–1925 in the supernova remnant G11.2–0.3. Using high-resolution data obtained with the Chandra X-Ray Observatory and with the VLA radio telescope, we show the X-ray and radio emission is asymmetric around the pulsar, despite the latter’s central position in the very circular shell. The new X-ray data allow us to separate the synchrotron emission of the pulsar wind nebula from the surrounding thermal emission and that from the pulsar itself. On the basis of X-ray data from two epochs, we observe temporal variation of the location of X-ray hot spots near the pulsar, indicating relativistic motion. We compare thermal emission observed within the shell, which may be associated with the forward shock of the pulsar wind nebula, to thermal emission from a nearby portion of the remnant shell, the temperature of which implies an expansion velocity consistent with the identification of the remnant with the historical event of 386 A.D. The measured X-ray and radio spectral indices of the nebula synchrotron emission are found to be consistent with a single synchrotron cooling break. The magnetic field implied by the break frequency is anomalously large, given the apparent size and age of the nebula, if a spherical morphology is assumed but is consistent with a bipolar morphology.

Subject headings: pulsars: general — pulsars: individual (AX J1811.5–1926) — stars: neutron — supernovae: individual (G11.2–0.3) — X-rays: general

1. INTRODUCTION

The overall structure and evolution of the X-ray emission produced by a spherically symmetric relativistic particle wind coming from a young pulsar in a supernova remnant has been modeled extensively (Reynolds & Chevalier 1984; Kennel & Coroniti 1984; van der Swaluw et al. 2001; Blondin, Chevalier, & Frierson 2001). In addition, some progress has been made on the fine structure and time dependence of the sites of shock acceleration in the inner regions (Gallant & Arons 1994). The observational tests of these models have been dominated by discussions of the Crab Nebula. The advantages of studying the Crab, with its high luminosity, known age, and well-observed pulsar, are many. However, the Crab is less than an ideal test case for understanding pulsar wind nebulae (PWNe) in supernova remnants (SNRs) as a class due to its anomalously high luminosity and lack of an observable SNR shell. There are a number of observed radio composite SNRs that consist of a shell and a spectrally distinct inner nebula, presumably PWNe. Only in a few cases, however, has the central pulsar been detected (e.g., W44; see Kaspi & Helfand 2002 for a review; Gotthelf 2001), leaving the spin-down energy driving the emission to be inferred from the PWN itself.

G11.2–0.3 is a remarkably spherical young SNR plausibly associated with the historical event of 386 A.D. recorded by Chinese astrologers (Clark & Stephenson 1977). A 65 ms pulsar with spin-down energy $E = 6.4 \times 10^{36}$ ergs s$^{-1}$ was discovered in X-rays by ASCA (Torii et al. 1997, 1999). The characteristic spin-down age is much greater than the apparent age of the SNR and that inferred from its remarkably central position within the remnant given any reasonable transverse velocity (Kaspi et al. 2001, hereafter Paper I). The simplest explanation for this apparent age discrepancy is that the initial spin period of the pulsar is very near the current spin period, which in turn suggests that $E$ has remained nearly constant since the supernova explosion. The distance to G11.2–0.3 has been reasonably well determined to be $d \sim 5$ kpc from $H_\alpha$ measurements (Becker, Markert, & Donahue 1985; Green et al. 1988). We therefore have a system where the assumptions of spherical symmetry, at least in regards to the shell around the pulsar, and constant known energy input are observationally supported, and reasonable estimates of the physical size of various components can be made.

The bright spherical radio shell, reminiscent of the remnants of Tycho’s and Kepler’s supernovae (Downes 1984)
and the lack of an obvious hard central component in the ROSAT PSPC image, initially led some authors to conclude that G11.2−0.3 was the remnant of a Type Ia supernova (Reynolds et al. 1994). The first hints of a central plerionic component came from high-frequency, single-dish radio measurements that suggested a central flattening of the radio spectrum (Mori & Reich 1987). ASCA observations first clearly demonstrated that there was a central, nonthermal X-ray source (Vasisht et al. 1996). This component was resolved by Chandra, the image of which has been presented in Paper I. Further single-dish radio observations have clearly demonstrated the existence of a flat central radio component (Kothes & Reich 2001). Archival VLA observations separate the central plerion from the shell and measure the spectral index to be $\alpha_r \sim 0.25$ [defined as $S = S_0 (\nu/\nu_0)^{-\alpha_r}$, where $S_0$ is the energy flux density at frequency $\nu_0$, a fairly typical value (Tam, Roberts, & Kaspi 2002, hereafter Paper II). In this paper, we combine the radio data with the Chandra data to make spectral measurements of the pulsar itself, the hard pulsar wind nebula, and soft thermal emission possibly related to the PWN, which we compare to a portion of the shell. We also present evidence for apparent temporal variation in the positions of emission features in the central portion of the X-ray PWN and make a detailed comparison of the X-ray morphology with a new 3.5 cm VLA image. We then compare these observations to models of PWN evolution and explore the possibility that within the SNR shell, a wind termination shock produces the variable hard emission, and the forward shock of the PWN expanding into the stellar ejecta produces the interior thermal structures.

2. OBSERVATIONS AND ANALYSIS

2.1. X-Ray and Radio Observations

NASA’s Chandra X-Ray Observatory observed G11.2−0.3 at two epochs, the first (50076) on 2000 August 6 and the second (50077) on 2000 October 15, for 20 and 15 ks, respectively. The remnant was positioned on the back-illuminated CCD chip S3 of the ACIS instrument in standard-exposure mode with a time resolution of 3.2 s, too coarse to detect pulsations from the pulsar. The data were reduced and analyzed with CIAO 2.2.1 using Caldb 2.12, XSPEC V.11.1.0, and the MIRIAD software packages. Details of the image analysis and a three-color X-ray image of the SNR can be found in Paper I. Here, we focus on the emission interior to the shell.

Analysis of archival 20 and 6 cm VLA data presented in Paper II revealed the extent of the radio PWN by showing that most of the central enhancement has a significantly flatter spectrum than the surrounding shell. In order to further enhance the relative brightness of the PWN over the shell, we have obtained new 20, 6, and 3.5 cm data with the VLA in the DnC, C, and CnB configurations (2001 June–September) as part of a campaign to better constrain the broadband radio spectrum and measure the shell expansion. Details of the radio observations will be presented elsewhere (C. Tam et al. 2003, in preparation).

2.2. Spatial Analysis

The multiwavelength image of G11.2−0.3 is presented in Figure 1. The 3.5 cm radio image is shown in green, the soft (0.6−1.65 keV) X-ray image, dominated by thermal emission, is in red, and the hard (4−9 keV) X-ray image is in blue, all smoothed with a 5″ FWHM Gaussian. This image shows the relationship between the interior thermal X-ray emission, the radio PWN, and the bright, hard X-ray emission of the PWN. It also shows how the relative brightness of the soft X-ray emission and the radio emission changes around the shell. The point source at the center is the pulsar, which is seen only in the X-ray images. Paper I noted that the hard X-ray PWN consists of a bright region southwest of the pulsar, a narrow, almost linear component to the northeast, and a larger, faint, diffuse component with reasonable bilateral symmetry around the pulsar (see Fig. 2 in Paper I).

In Figure 2, we show the exposure corrected, 4−9 keV summed image of the two observing epochs, smoothed with a 5″ Gaussian, with 6 cm radio (which better shows a combination of flatter and steeper features) contours (4.78′ × 4.8′ beam) overlaid. The SNR shell predominantly emits soft, thermal X-ray emission that is mostly invisible above 4 keV, and so the features in this image show regions of nonthermal emission. The central PWN is quite hard, and the grayscale levels in this image have been chosen to highlight the difference between the bright and faint parts of the PWN, where the surface brightness of the bright portions is a factor of 2−5 greater than the larger, faint portion. The extent and shape of the radio PWN correlate well with the faint, hard PWN X-ray component. To the northeast of the pulsar, the narrow, bright, hard X-ray feature goes through a region of low radio luminosity and then terminates at a bright arc in the radio emission. To the southwest, the bright hard X-rays coincide with the radio emission, with a radio enhancement coincident with the X-ray peak (the spot region referred to below). The shell is seen clearly in hard X-rays, although they are concentrated toward the inner edge of the shell, especially in the bright southwestern section. These hard X-rays are largely interior to the peak emission of the radio shell in this region.

In Figure 3, we show the soft (0.6−1.65 keV) X-ray emission with the same radio contours as in Figure 2. There is a large, soft X-ray structure that we refer to as the soft PWN, which is centered on the pulsar, reaching to the northwest and southeast. The ratio of medium-to-soft X-ray flux suggests this structure does not have any large spectral variations (see Paper I). This soft X-ray emission seems to outline much of the radio PWN and largely coincides with radio features that were shown in Paper II to have steeper spectra consistent with the radio shell emission rather than the PWN emission. The soft X-ray and radio shells are quite similar, except the radio emission is slightly more extended than are the X-rays around most of the shell. However, the bright enhancement in the southeastern portion of the shell seems to be relatively broader in thermal X-rays compared to the radio than elsewhere in the shell, as can be seen in Figure 1 by the red outlining the shell.

To study the details of the PWN, we produced separate hard X-ray images for the two observation epochs whose coordinates we aligned by using the bright emission of the pulsar to correct for slight differences in the aspect solution. These were then exposure corrected and smoothed with a 3″ Gaussian (Fig. 4). For comparison, we also present the same region from the 3.5 cm radio observation that best shows the PWN due to its flatter spectra relative to the shell. The brightest features in both X-ray images other than the pulsar are two spots to the southwest of the pulsar, which are ~10 and ~7 σ above the surrounding PWN level. To better
see the relative amplitudes, we also show line intensity profiles of all three images of the slice indicated in the images (Fig. 5). The positions of the two spots were determined for each epoch both by centroiding and by fitting a two-dimensional Gaussian on top of a constant background, the two methods giving consistent results. The latter method gives uncertainty estimates with which we add in quadrature a relative aspecting uncertainty of \(0.31\) using the pulsar as our reference. (See aspecting calibration memos by M. Markovitch.)\(^6\) During the first observation, the physical distances of the spot centers from the pulsar were \((0.20 \pm 0.01) d_5\) and \((0.34 \pm 0.01) d_5\) pc, where \(d_5 = d/(5 \text{ kpc})\). By the second observation, the apparent centers had moved significantly, \(~3''49 \pm 0'31\) and \(~1''90 \pm 0'44\) away from the pulsar, implying apparent transverse velocities of \(~1.4d_5 c\) and \(~0.8d_5 c\).

2.3. Spectral Analysis

2.3.1. Methodology

Chandra’s high-resolution imaging capabilities allow the measurement of point-source spectra to be made with remarkably low background levels. Initially, we used a 7

\(^6\) Go to http://asc.harvard.edu/cal/Hrma/hrma/optaxis/platescale/geom_public.html.
pixel radius circular region to extract a pulse height spectrum from the pulsar with an annular background region from 7 to 10 pixels. The spectrum showed an enhancement at high energies, a clear signature of pileup. From the observed count rate of \( \sim 8 \times 10^{-2} \) counts s\(^{-1} \), we estimate a pileup fraction \( \sim 5\% \), which is enough to significantly affect the measurement of the spectral index. Around half of the counts are contained within 1 pixel at the center of the point-spread function (PSF), which is where most of the pileup occurs. By excluding the central pixel, we can minimize the effects of pileup but must then worry about the variations in the PSF as a function of energy that will affect the spectrum when a restricted extraction region is used. Since the current version of CIAO is not able to calculate the effective area when only a fractional part of the PSF is enclosed, we examined the PSF enclosed energy curves and chose annular extraction regions for the on-source and background spectra whose difference would provide a relatively constant enclosed energy fraction over most of the Chandra wave band. We used an annular source extraction region with inner and outer radii of 0\(\cdot\!3\)–1\(\cdot\!0\) and a background annular region of 1\(\cdot\!0\)–1\(\cdot\!38\). We then used the MKPSF tool in CIAO and extracted model PSFs for energies between 1 and 9 keV in steps of 1 keV. By integrating the flux in our model PSFs over our on-source and background regions and taking the difference, we calculated enclosed energy fractions varying between 0.48 at 1 keV and 0.42 at 9 keV. We fit a linear function to these derived fractions and used this to modify the ancillary response function (arf) calculated for the center of the point source. In this way, we correct for the variations of the PSF to within \( \sim 1\% \). We fit the resulting spectrum to an absorbed power-law model, the results of which are listed in Table 1.

For extended sources, both the cosmic X-ray and particle background are nonnegligible and vary with position on the detector. At the moment, there is no consensus on the best way of approaching this problem. We have therefore used the following procedure, based on one developed by Roberts, Romani, & Kawai (2001) for analysis of ASCA GIS data. We assume that the background consists of three components: a particle component that is not necessarily spatially correlated with the telescope effective area, an extragalactic component that suffers from absorption by the Milky Way, and a Galactic component. We further assume that the particle background is relatively time independent once the data are screened for background flaring events and that the two cosmic contaminating components uniformly illuminate the telescope over the S3 chip field of view. The Chandra science support center has made available blank-sky observations of high Galactic latitude fields that we assume accurately represent the particle and unabsorbed extragalactic components of the background.

Using the above assumptions, we account for the different background contributions in the following way. We extract spectra from the region of interest and a source-free region of the chip. From each of these, we subtract spectra...
extracted from blank-sky data sets from the same chip regions in order to remove the particle background contribution. Since the effective exposure varies as a function of chip position, we scale the local background spectra by the ratio of average exposures of the source and background regions using the exposure maps that were used in producing the exposure-corrected images of Paper I. Although this corrects for the gross differences in effective area between the source and background extraction regions, it should be noted that the variation in effective area with position is energy dependent, which is not taken into account with the current procedure. However, this assumption allows us to account for the background in a model-independent way. In practice, for G11.2−0.3, the spectral results are not strongly sensitive to the background subtraction method used, as the source-to-background ratio is high. To create effective area and response matrix files, we make a binned image of the source region photons from which we subtract an image created from the blank-sky data set and use this as the input weighting map to the CIAO mkwarf and mkrmf tools. The resulting source and background spectra and calibration files are used in XSPEC to fit models to the spectra. Note that given the assumptions described above, all three background components are accounted for by this procedure.

2.3.2. Results of Model Fitting

In Figure 6, we show the extraction regions used for spectral analysis. The gray scale again shows the hard X-ray emission, while the contours show the soft X-ray emission. The interior of the shell has enhanced emission over the general background, so for features within the shell, we choose...
a background region interior to the shell. In the case of the
shell itself (region 1), a region exterior to the shell is chosen
as background.

We analyzed the bright region of the shell (region 1) near
that of a portion of the interior soft feature (region 4). In
order to compare the two regions, we initially used the con-
stant temperature, plane-parallel shock plasma model
PSHOCK in XSPEC for both. However, there is a clear
hard excess in region 1 seen in both the spectrum and the
hard X-ray image (Fig. 6), while there is very little emission
above 4 keV in region 4. This hard X-ray emission is
expected from shock acceleration of particles in SNR shells,
the presumed source of Galactic cosmic rays. To account
for this, we add the synchrotron roll-off SRCUT model
(Reynolds & Keohane 1999), which simulates the roll-off of
the synchrotron emission spectrum of an exponentially cut
off power-law distribution of electrons to the region 1 fit, fix-
ing the radio spectral index $\alpha = 0.56$ as determined in Paper
II and the 1 GHz flux extrapolated from the 1465 MHz
image. We then fit for the roll-off break frequency that will

![Angular distance from pulsar (degrees)]

**Fig. 5.**—Intensity profile of a line through the spots for the two observing epochs and the radio image, showing the displacement between the two epochs. The y-axis is in arbitrary units of flux density.

| Table 1: Spectral Fits |
|------------------------|
| Model                  | Parameter          | Pulsar                  | Shell         | PWN           | Spots         | Soft PWN      |
|                        |                    | (Region 1)              | (Region 2)     | (Region 3)    | (Region 4)    |               |
| (V)PHABS$^a$           | $n_H$ (10$^{22}$ cm$^{-2}$) | 2.22(1.65–3.00)$^b$    | 1.71(1.70–2.36) | 2.14(2.04–2.25) | 2.28(1.86–2.77) | 2.15(2.03–2.27) |
| POWER$^c$              | $\Gamma$           | 0.97(0.65–1.36)         | ...           | 1.73(1.54–1.90) | 1.73(1.55–1.95) | ...           |
| (V)PSHOCK$^d$          | $kT$ (keV)         | ...                     | 0.58(0.533–0.595) | 0.583(frozen)   | 0.583(frozen)   | 0.583(0.517–0.691) |
| SRCUT$^e$              | $\tau_e$ (10$^{11}$ s cm$^{-3}$) | ...                     | 6.7(5.7–8.1)  | 4.2(frozen)    | 4.2(frozen)    | 4.2(2.3–14.9) |
|                        | $\alpha$           | ...                     | 0.56          | ...           | ...           | ...           |
|                        | $v_b$ (10$^7$ GHz) | ...                     | 1.80(1.68–1.90) | ...           | ...           | ...           |
|                        | $S_{1400}$ (Jy)    | ...                     | ...           | ...           | ...           | ...           |
|                        | $F_X$ (10$^{-12}$ ergs cm$^{-2}$ s$^{-1}$) | 2.82 ± 0.12 | 3.70 ± 0.03 | 4.44 ± 0.12$^f$ | 0.87 ± 0.04$^f$ | 0.37 ± 0.01   |

$^a$ Photoelectric absorption model, allowing the elemental abundances to vary for the shell (region 1) only.
$^b$ Values in parentheses are 90% multiparameter confidence regions.
$^c$ Simple photon power law.
$^d$ Plane-parallel shock model of Borkowski, Lyerly, & Reynolds 2001, allowing the elemental abundances to vary for the shell (region 1) only.
$^e$ Synchrotron roll-off model of Reynolds & Keohane 1999.
$^f$ Unabsorbed flux of power-law component only.
reproduce the observed hard excess. In both regions, the spectral features seemed to be shifted by \( \sim 1.5 \) channels. Since we used a 10 eV per channel binning scheme when generating the response matrices, this is similar to the +16 eV zero-point gain shift reported on 2002 January 31 to the Chandra users committee.\(^7\) We corrected for this by applying a 1.6 channel bin shift to the response matrices for all the extended regions. A significant improvement to the region 4 fit could be made by adding a weak narrow line at 1.18 keV, and there was weaker evidence for this feature in the other spectra. The strength of this line varied with the size of the extraction region and not the total flux, and its energy does not correspond to any common astrophysical X-ray feature. We therefore suspect that this is some background component not adequately removed by the procedure described in the above section.

For region 4 (and, subsequently, regions 2 and 3), we were able to obtain a reasonable fit using the simple absorption and shock models but found the much greater signal-to-noise ratio region 1 spectrum, with \( \sim 25,000 \) counts, showed significant residuals around all of the spectral line features. Using the VPSHOCK model, which allows the individual element abundances to vary, greatly improved the fit, but there still seemed to be systematic offsets in the location of the spectral features. Allowing a redshift improved the fit statistically, but the implied velocities were too large to be plausible. We then tried allowing variable abundances in the absorption using the VPHABS model, which significantly improved the overall fit resulting in a reduced \( \chi^2 \sim 1 \). However, there is significant correlation between the individual element abundances as well as between the abundances in the shock model and their corresponding absorption abundances. It is also true that calibration uncertainties in the response, which are known to lead to overestimates of line widths, will have had an unknown effect on the abundance values. We therefore do not report the individual abundance values quantitatively and instead make only general comments. It should be noted that the various model changes only slightly alter the fit temperature and overall absorption column of the region 1 spectrum.

\(^7\) Go to http://asc.harvard.edu/udocs/ucom.jan02.html.

![Figure 6](figure.png)

Fig. 6.—Hard (4–9 keV) X-ray image with soft (0.6–1.65 keV) X-ray photon contours showing spectral extraction regions.
and allow only the normalization and total values from the interior soft emission (region 4) spectral fits accounted for. We use our best-fit PSHOCK and PHABS emission in the central regions near the pulsar needs to be temperature differences could not be ruled out. (Borkowski, Lyerly, & Reynolds 2001) and moderate temperature of the model on changes in ion temperature is weak and absorptions. The ionization timescale upper limit \( \tau_u \) parameter of the shock model and the SRCUT break frequency were somewhat more sensitive but did not vary by more than a factor of 2. We emphasize that the 90% multi-parameter confidence regions presented in Table 1 are statistical around our best-fit values and may not represent the true uncertainty. However, the systematic uncertainties are not likely to affect the qualitative interpretation of the results presented in the discussion below.

We also tried fitting the shell portion using the VNPSHOCK model that allows for different ion and electron temperatures. There were no significant differences between the two temperatures, indicating that the ions and electrons are in rough equilibrium. However, the dependence of the model on changes in ion temperature is weak (Borkowski, Lyerly, & Reynolds 2001) and moderate temperature differences could not be ruled out.

In order to determine the synchrotron emission properties of the hard PWN (regions 2 and 3), the soft thermal emission in the central regions near the pulsar needs to be accounted for. We use our best-fit PSHOCK and PHABS values from the interior soft emission (region 4) spectral fits and allow only the normalization and total \( n_H \) to vary. To this we add a simple power-law model to fit the hard PWN components. The synchrotron X-rays are clearly seen in the data (Fig. 7). The results of all the fits are listed in Table 1 with 90% multiparameter confidence regions in parentheses. The observed fluxes with 1 \( \sigma \) errors are listed for the energy ranges indicated for the pulsar and regions 1 and 4. For regions 2 and 3, the unabsorbed fluxes of the power-law model component only are given.

3. DISCUSSION

Models of PWN evolution in SNRs suggest there are two major epochs in the life of the system. In the early evolution, the PWN expands into the freely expanding ejecta of the SNR. The highly relativistic pulsar wind is terminated at a shock near the pulsar, which continuously injects electrons and ions having a power-law distribution of energies as well as magnetic field into a surrounding cavity. The particles then gyrate in the nebular magnetic field, causing the synchrotron emission. This cavity itself expands at supersonic speeds relative to the surrounding SNR ejecta. Therefore, there should be a forward shock at the edge of this cavity similar to the SNR forward shock moving into the surrounding ISM.

As the SNR shell expands, sweeping up more of the interstellar medium, a reverse shock is launched that travels toward the SNR center, carrying information about the external medium to the inner portions of the remnant. When the reverse shock encounters the forward shock of the PWN, the PWN is compressed and reverberates several times (van der Swaluw et al. 2001). The compressed PWN finally settles into a smaller size relative to the SNR shell and begins to expand again, this time subsonically. This corresponds to the SNR entering the Sedov expansion phase, where the dynamics are dominated by the swept-up ISM mass.

Hydrodynamical models of spherically symmetric PWNe in SNRs suggest the collision between the reverse shock and the PWN occurs after \( \sim 2000\) yr (van der Swaluw et al. 2001; Blondin, Chevalier, & Frierson 2001). Although the energy input of the pulsar in these models was appropriate for the high energy output of the Crab and not the relatively steady low energy output of PSR J1811–1925, the time of collision is determined largely by the propagation of the reverse shock, which depends only on the dynamics of the supernova ejecta. We therefore expect the timescale in the case of G11.2–0.3 to be roughly similar. If we assume the age of the SNR to be 1615 yr, corresponding to the 386 A.D. historical association, then we would expect the time of collision to be near. If the collision has not yet occurred, the PWN should be near its largest extent relative to the SNR shell, and its morphology should be largely determined by the geometry of the pulsar wind. If the collision has occurred or is currently occurring, then the PWN should be compressed and distorted by the reverse shock.

The separation of the PWN from the surrounding shell in both the X-ray and radio images suggests that the reverse shock has not yet reached the PWN. The hard X-ray emission concentrated at the inner edge of the shell may result

![Figure 7](image-url)
from the recent passage of the reverse shock, suggesting the latter is still near the observed shell. This hypothesis is somewhat supported by the rather large size of the radio PWN (Paper II).

In this case, one might hope to see evidence of the PWN forward shock in the form of thermal X-rays. The thermal emission interior to the shell, which we refer to as the soft PWN, may be a result of this shock. The smaller ionization timescale of this feature compared to the nearby shell emission may support this interpretation. The similar temperatures suggest the shock speeds are nearly identical, which might be unexpected if the radius of the soft PWN is only two-thirds the radius of the shell as it appears in the image. However, the SNR forward shock will have been slowed significantly by the accumulation of ISM material over the lifetime of the remnant, and the relative magnitude of the velocity jumps at the two shock fronts is model dependent (van der Swaluw et al. 2001). It is therefore difficult to say what relative shock velocities and, hence, relative temperature should be expected.

Following the reasoning of Reynolds et al. (1994), the Rankine-Hugoniot shock speed can be inferred from the best-fit temperature of \( kT \sim 0.58 \) keV of the shell region to be \( v_j = (16 kT/3 \mu m_p)^{1/2} \approx 700 \) km s\(^{-1}\), assuming electron-ion equilibrium and that the mean mass per particle \( \mu m_p \) is 0.6 times the proton mass. Since the ions heat the electrons, the observed electron temperature is a lower bound on the ion temperature and, hence, the shock velocity. However, the results of the VNPSHOCK model suggest that the electrons and ions are not far from equilibrium. The velocity thus derived implies a current expansion rate of \( \theta \leq 0.03/\Delta t \) yr\(^{-1}\), giving a free expansion age of \( t_{fe} = R_{mn}/v_s \lesssim 5000 \) d for the SNR radius \( R_{mn} \sim 150'' \). If we adopt the Sedov relation for a blast wave of radius \( R_S = 2.5 v_{r,\gamma} t \), we obtain a Sedov age estimate of \( t_{S} \lesssim 2000 \) d, close to the historical age \( \tau = 1615 \) yr. The ionization timescale parameter from the VNPSHOCK model implies a reasonable electron density of \( n_e \sim 10 \) cm\(^{-3}\) for a 1615 yr old shock, while the synchrotron roll-off break frequency implies a maximum electron energy of \( \sim 20 \) TeV for a typical magnetic field strength \( B \sim 10 \mu G \) (Reynolds & Keohane 1999).

The pulsar has a hard spectrum with no sign of a thermal component, although that is not surprising given the high level of absorption. The photon index \( \Gamma \sim 1 \) is similar to what has been found recently from other \textit{Chandra} observations of young pulsars (Lu et al. 2002; Pavlov et al. 2001; Gaensler et al. 2002). The unabsorbed flux, \( F_{X} \sim 3.5 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\) in the 1–10 keV energy band, is similar to the \( \sim 4 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\) quoted by Torii et al. (1997) for the total pulsed flux, suggesting that the pulsed fraction is nearly 100%.

### 3.1. Spots as Wisps

The spatial variability observed in the bright PWN spots may be the equivalent of the Crab’s wisps, which are seen to form at the radius of the inner ring (\( r \sim 0.14 \) pc) then move outward at a speed \( v_{wp} \sim 0.5c \) (Morii et al. 2002). In the Gallant & Arons (1994) model, the wisp spacing roughly corresponds to the postshock ion Larmor radius. In such a scenario, the spots should form at the characteristic radii and then propagate outward and dissipate. The coincident enhanced radio emission (Fig. 4), with its much longer cooling timescale, suggests that these spots are persistently found in this region. We also note that there appears to be dynamical activity within the narrow feature on other side of the pulsar, but the variations in the flux levels are too near the noise level to unambiguously identify individual knots at both epochs. The bright features may also represent a collimated, jetlike outflow. In this case, we might expect new knots to be ejected near the pulsar and move outward and diffuse. The apparent velocity of \( c \) or even greater and the brightness asymmetry around the pulsar suggest this may be the case.

The asymmetry of the radio emission compared with the X-ray emission is puzzling. On one side of the pulsar, the emission is coincident, while on the other, the radio and X-ray emission are anticoincident. Such correlations have been observed in other PWN, most notably around PSR B1509–58 (Gaensler et al. 2002), whose characteristic age is similar to the age of G11.2–0.3. The central location and corresponding upper limits on the velocity of the pulsar (see Paper I) make interpretations of such features as a trail marking the previous passage of the pulsar through the region untenable and argue against a large asymmetry in the birth explosion as a causal factor.

### 3.2. Magnetic Field

In this section, we present a very simplistic modification to standard PWN magnetic field estimates to account for nonsphericity. We can identify the location of spot 1, \( r_{s1} \), as being downstream from the pulsar wind termination shock \( r_{s1} \gtrsim r_{r} \) and use this to estimate the downstream magnetic field \( B_d \) of the PWN. If we assume a radial relativistic flow and a postshock velocity of \( c/3 \), then (Chevalier 2000)

\[
B_{1} = \left( \frac{6e_{t}E_{t}}{f_{r}r_{c}} \right)^{1/2} \sim 6 \times 10^{-5} \frac{r_{s1}^{1/2}}{f_{r}(r_{s1}/r_{c})} G ,
\]

where \( e_{r} \lesssim 1 \) is the ratio of magnetic energy to total energy in the postshock flow. To allow for a nonspherical outflow, we include a beaming fraction at the termination shock \( f_{r} \lesssim 1 \).

The current best estimate of the radio energy spectral index is \( \alpha_{r} \approx 0.25 \) (defined as \( S_{\nu} \propto \nu^{-\alpha_{r}} \)) with an acceptable range of \( \alpha_{r} = 0.15 \pm 0.3 \). The corresponding range of the X-ray energy index is \( \alpha_{X} = 1 - \theta = 0.4 \pm 0.9 \) with a best-fit value \( \alpha_{X} = 0.73 \). The difference between the X-ray and radio spectral indices \( \delta \alpha_{X} \approx 0.5 \) is consistent with what is expected for a single synchrotron cooling break between the radio and X-ray bands, although the uncertainty may be as large as 0.25. By assuming \( \delta \alpha_{X} = 0.5 \), we can find the break frequency from the measured radio index and radio and X-ray flux densities,

\[
\nu_{b} = \left( \frac{S_X\nu^{\alpha_X-0.5}}{S_r\nu^{\alpha_r}} \right)^2 .
\]

We estimate the flux density of the radio nebula at 1.5 GHz to be \( S_{r}(\text{PWN}) \sim 0.4 \) Jy and of the spot region to be \( S_{s}(\text{spot}) \sim 0.04 \) Jy, although these could be off by a factor of 2 (see Paper II for a discussion of flux uncertainties). For the observed range of values for \( \alpha_{r} \), this results in estimated upper limits on the break frequencies of \( \nu_{b}(\text{PWN}) \lesssim 50 \) and \( \nu_{b}(\text{spot}) \lesssim 200 \) GHz, with values for the nominal spectral index \( \alpha_{r} = 0.25 \) of \( \sim 8 \) and \( \sim 25 \) GHz, respectively.

If we assume a constant energy injection of particles over the lifetime of the PWN, as indicated by the inferred initial
spin being nearly the same as the current spin period (Paper I), we can estimate the average magnetic field from the apparent break frequency (Chevalier 2000) from

$$B_N \sim \frac{4 \times 10^{-3}}{(v_\nu/10 \text{ GHz})^{1/3}(t/1614 \text{ yr})^{2/3}} \text{ G}.$$  (3)

This is very large compared to the postshock estimate above (eq. [1]). Even with the most extreme values of flux and spectral index because of the weak dependence on $v_\nu$, the magnetic field in the nebula and in the spot region $B_N \gtrsim 10^{-3}$ G. If the magnetic field is constant throughout the emitting volume of the PWN, then the maximum magnetic field can be inferred from the energy injected over the lifetime of the pulsar assuming negligible radiative losses (Pacini & Salvati 1973),

$$B_N \leq \left( \frac{6 \epsilon_N E_1}{f_N r_N^2} \right)^{1/2} \approx 2.6 \times 10^{-4} \left( \frac{\epsilon_N}{f_N d_5^2} \right)^{1/2} \text{ G},$$  (4)

where $\epsilon_N$ is the fraction of the spin-down energy that ultimately goes into magnetic field (0.5 for equipartition) and $f_N$ is the ratio of the emitting volume to a sphere of radius $r_N \sim 40''$, the distance from the pulsar to the radio arc. In order to reconcile equations (3) and (4), we need a nebular filling fraction $f_N \lesssim 0.01$. This is feasible if the emission region is bipolar or toroidal rather than spherical and if the emission region is high magnetic field, where most of the emission takes place, is somehow confined to the narrow region of high X-ray emission and the surface of the wind bubble. The observed PWN structure in the 3.5 cm image may support this picture (see Fig. 4). In general, $f_\perp \lesssim f_N$, since we expect that the outflow would not become much further collimated after the termination shock, but rather the solid angle of the flow would tend to increase with radius. This suggests that the pulsar wind is initially confined to narrow, polar outflows with opening angles $\theta \lesssim 10^{\circ}$ in the case of a bipolar nebula or a thin, equatorial sheet in the case of a toroidal nebula.

We introduce the parameters $\beta \equiv (B_N/B_0)^2(\epsilon_\perp/\epsilon_N)$ and $f \equiv f_\perp/f_N \lesssim 1$. It can be shown that the arguments of Rees & Gunn (1974; see also Kennel & Coroniti 1984) for the build-up of the magnetic field to approximate equipartition strength may be applied to both a conical and nozzle type flow, in which case, we expect $\beta \sim 1$. We can then combine equations (1) and (4) to derive the following estimate of the termination shock radius,

$$\frac{r_N}{r_1} \approx \left( \frac{f e c t}{\beta \sigma_N} \right)^{1/2} \sim 20,$$  (5)

suggesting $r_1$ should be a few arcseconds from the pulsar. In that case, monitoring of the emission by Chandra should resolve the region of spot formation.

Bandiera, Pacini, & Salvati (1996) noted that the extrapolated ASCA PWN spectra combined with previous estimates of the radio PWN flux led to an anomalously high magnetic field and suggested a period of rapid spin-down early in the pulsar’s history where the magnetic field was dumped into the surrounding region and confined by the external SNR shell. This was previous to the discovery of pulsations, and their models greatly overestimate the pulsar spin period. It is interesting to note, however, that an initial spin period $P_0 \sim 20$ ms, similar to that of the Crab pulsar’s, would provide the necessary energy for the magnetic field. Nevertheless, the arguments made above for nonsphericity in the nebula obviate the need for an ad hoc invocation of an early, short-term, very rapid spin-down era.

Inferring the magnetic field by extrapolating the total PWN radio and X-ray spectra assuming a single break may be questionable. There may be a change in spectral index over the PWN to which we are not sensitive. There is also a possibility that the reverse shock has begun to encounter the PWN, temporarily enhancing the magnetic field at the edges. However, the spot region shows evidence of current particle injection and likely is not yet affected by the reverse shock. The break frequency of this region is $\sim 5$ times higher here than for the PWN as a whole, which only lowers the magnetic field estimate by a factor of 2, assuming this feature has existed for the entire lifetime of the PWN.

4. CONCLUSIONS

We have measured the X-ray spectrum of various components of the shell and pulsar wind nebula of G11.2–0.3 and compared them with the radio spectrum and morphology. The shell temperature and hard X-ray structure are consistent with a ~2000 yr old remnant nearing the onset of the Sedov phase. The pulsar wind nebula itself shows evidence of relativistic dynamic evolution of bright X-ray enhancements near the pulsar. We argue that the reverse shock has not yet reached the expanding pulsar wind bubble, and therefore, the observed structure is largely determined by the structure of the wind itself. The morphology and magnetic field suggested by the low spectral break energy suggests the outflowing wind is highly nonspherical. The wind may be largely constrained to a narrow, bipolar outflow or possibly a thin, equatorial sheet. Further high-resolution observations at X-ray, radio, and infrared wavelengths could identify the region of spot formation, help determine the true morphology, and further constrain the break energy of the spectrum.

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