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CHANDRA X-RAY OBSERVATIONS OF G11.2−0.3: IMPLICATIONS FOR PULSAR AGES

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ABSTRACT

We present *Chandra X-Ray Observatory* imaging observations of the young Galactic supernova remnant G11.2−0.3. The image shows that the previously known young 65 ms X-ray pulsar is at position (J2000) R.A. $18^{\rm h}11^{\rm m}29\overset{\rm s}{.}22$, decl. $-19°25'27\overset{''}{.}6$, with 1 σ error radius of $0\overset{''}{.}6$. This is within 8″ of the geometric center of the shell. This provides strong confirming evidence that the system is younger, by a factor of ~ 12, than the characteristic age of the pulsar. The age discrepancy suggests that pulsar characteristic ages can be poor age estimators for young pulsars. Assuming conventional spin-down with constant magnetic field and braking index, the most likely explanation for the age discrepancy in G11.2−0.3 is that the pulsar was born with a spin period of ~ 62 ms. The *Chandra* image also reveals, for the first time, the morphology of the pulsar wind nebula. The elongated hard X-ray structure can be interpreted as either a jet or a Crab-like torus seen edge-on. This adds to the growing list of highly aspherical pulsar wind nebulae and argues that such structures are common around young pulsars.

Subject headings: pulsars: general — pulsars: individual (AX J1811.5−1926, PSR J1811−1925) — supernovae: individual (G11.2−0.3) — X-rays: general

1. INTRODUCTION

Determining the ages of neutron stars is important for several reasons. First, ages are crucial for establishing the number and birthrate of neutron stars in the Galaxy. This is useful for comparison with the Galactic supernova rate in order to ultimately establish the fraction and types of supernovae that lead to the formation of a neutron star. Second, one of the few experimental constraints on the nature of matter at very high densities comes from models of neutron star cooling. In order to test such models, a reliable neutron star age is key. The latter can help constrain the age of associated objects, such as supernova remnants, which is important for understanding remnant evolution and morphology. Also, ages can constrain young pulsar velocities and proper motions, given an association with a supernova remnant.

The standard age estimator for radio pulsars assumes the frequency evolution is of the form

$$\dot{\omega} = k\omega^n , \quad (1)$$

where n is the "braking index" and k is a constant that depends on the magnetic moment of the neutron star. The braking index can be determined from a measurement of the second time derivative of the frequency. Assuming k and n to be constant, the age is given by (Manchester & Taylor 1977)

$$\tau = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right] , \quad (2)$$

where P is the rotation period, $\dot{P}$ is its time derivative, and P_0 is the spin period of the pulsar at the time it became a dipole rotator, which is generally presumed to coincide with the supernova event. The braking index is equal to 3 in a simple vacuum dipole spin-down model. For $P_0 \ll P$ and $n = 3$, equation (1) reduces to $\tau_c = P/2\dot{P}$, the often-used pulsar characteristic age.

For the five pulsars for which a constant value of n has been measured (Lyne, Pritchard, & Smith 1988; Lyne et al. 1996; Kaspi et al. 1994; Deeter, Nagase, & Boynton 1999; Camilo et al. 2000), the observed values are in the range 1.4–2.91. Thus, pulsars do not rotate like simple vacuum dipoles (e.g., Melatos 1997). Nevertheless, the range of behaviors is limited and is observationally well constrained.

The situation is less clear for the initial spin period, P_0. This can be determined from equation (1) if the age is known and the braking index measured. This is the case only for the Crab pulsar, whose estimated $P_0 \sim 19$ ms has led to the generally made assumption that the initial period is much smaller than the current spin period for all but the very fastest pulsars. Further support for such short birth spin periods comes from the existence of a young 16 ms pulsar PSR J0537−6910 (Marshall et al. 1998). However, the initial spin period distribution of neutron stars is not well predicted by theory since the rotation rates of the cores of the massive progenitors are largely unknown; differential rotation could make them deviate significantly from those of surface layers (Endal & Sofia 1978). Furthermore, circumstances at the time of, or shortly after, core collapse could significantly affect the neutron star spin independent of the angular momentum properties of the progenitor (e.g., Spruit & Phinney 1998).

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The supernova remnant G11.2−0.3 has received considerable observational attention because of the possibility that it is associated with a "guest star" witnessed by Chinese astronomers in the year A.D. 386 (Clark & Stephenson 1977). The remnant's highly circular morphology and high surface brightness are clear indicators of youth. Downes (1984) postulated that G11.2−0.3 is the remnant of a Type II supernova and suggested that it is a more evolved version of Cas A, the well-known and much younger oxygen-rich remnant. Morsi & Reich (1987) reported evidence for a central, flat-spectrum radio component, suggesting the presence of a neutron star, which supports the Type II interpretation. Green et al. (1988) presented a high-resolution radio map that revealed clumps in the shell, further suggesting that G11.2−0.3 is an evolved Cas A. In spite of these points, Reynolds et al. (1994) argued on the basis of *ROSAT* spectral observations that G11.2−0.3 is the remnant of a Type Ia supernova.

The hard X-ray capabilities of the *ASCA* satellite were the key to establishing the true nature of G11.2−0.3. Vasisht et al. (1996), using *ASCA*, reported a hard nonthermal X-ray source near the center of the remnant, as would be expected if it harbored an energetic neutron star, thus confirming the suggestion made by Morsi & Reich (1987). However, Vasisht et al. could neither resolve the nebula nor determine its precise location within the shell because of the $\sim 3'$ spatial resolution of the *ASCA* mirrors. They did, however, perform nonequilibrium ionization modeling of the spectrum of the shell. This put an upper bound on the age of $\lesssim 2000$ yr, in agreement with the A.D. 386 association (Aoki 1995).

Also using *ASCA* data, Torii et al. (1997) discovered a 65 ms pulsar (AX J1811.5−1926) in the direction of G11.2−0.3, in agreement with the hypothesis that the remnant contains an energetic neutron star. However, surprisingly, Torii et al. (1999) found that it had a characteristic age of 24,000 yr, in contradiction with the apparent youth of the remnant as well as with the tentative A.D. 386 association.

One way to verify the association and constrain the age independently is by using high spatial resolution X-ray observations. Since pulsars are a high-velocity population, a pulsar located very close to the geometric center of the remnant implies both a highly probable association and that the entire system is very young, as insufficient time must have elapsed for the pulsar to travel far from its birthplace.

High spatial resolution X-ray imaging of young pulsars and supernova remnants is important for another reason. Recent *Chandra X-Ray Observatory* images of the Crab and Vela pulsars and PSR B1509−58 (Weisskopf et al. 2000; Helfand, Gotthelf, & Halpern 2001; Kaspi et al. 2000) have revealed a wealth of detail regarding the structures surrounding them and have argued strongly that pulsar wind nebulae, also known as "plerions," in general do not have simple, spherically symmetric structures as has often been assumed in models (see Gotthelf 2002 for a review).

Here we present *Chandra X-Ray Observatory* images of G11.2−0.3 that reveal, for the first time, the precise projected location of the pulsar within the shell and the morphology of the pulsar wind nebula. We restrict our present discussion to the image of the remnant; detailed results from spectroscopy will be reported separately (M. E. Roberts et al. 2001, in preparation).

2. OBSERVATIONS AND RESULTS

NASA's *Chandra X-Ray Observatory* observed G11.2−0.3 at two epochs, the first (sequence 50076) on 2000 August 6 and the second (sequence 50077) on 2000 October 15. The exposure for the first epoch was 20 ks. The second epoch consisted of two exposures, one of 10 ks and the other of 5 ks. In all observations, the remnant was positioned on the back-illuminated CCD chip S3 of the Advanced CCD Imaging Spectrometer (ACIS) in standard exposure mode. In this mode, the time resolution (3.2 s) is too coarse to resolve the pulsations from the pulsar.

The data were analyzed using the CIAO 2.02 and MIRIAD software packages. Following the energy binning scheme of Hughes et al. (2000), we added together the individual count maps from the three different observing epochs in the 0.6–1.65, 1.65–2.25, and 2.25–7.5 keV energy bands. Spectrally weighted exposure maps were created for each observation and energy band and were summed over the three observations, creating a total count map and exposure map for each energy band. The count maps were divided by the exposure maps, and the result was convolved with a $5''$ FWHM Gaussian to enhance the nebular structure given the low count rate. The three individual maps were then combined into a three-color image, with red, green, and blue assigned to the low, medium, and high energy bands, respectively.

In Figure 1 we present the *Chandra* image of G11.2−0.3. The image clearly shows the symmetric ringlike structure of the shell. The overall shell X-ray morphology is remarkably like the radio morphology, with a similar enhancement in the southeast quadrant and similar clumps along the edge (Green et al. 1988). At the geometric center of the shell is a bright point source, the pulsar. Note that because of the smoothing, the point source has been broadened in this image beyond the $\lesssim 1''$ width of the ACIS point-spread function. From the unsmoothed image, the position of the pulsar is (J2000) R.A. $18^h11^m29^s.22$, decl. $-19°25'27''.6$. As the pulsar is a bright point source, the uncertainty in the position is completely dominated by the uncertainty in the *Chandra* aspect solution. The nominal 1 σ radius uncertainty of the latter is $0''.6$.[10] We verified this by optically identifying two sources in the field of view and comparing their positions as reported by *Chandra* with their cataloged positions. One source (at *Chandra* reported [J2000] R.A. $18^h11^m39^s.77$, decl. $-19°22'5''.1$) was identified in the 2 Micron All-Sky Survey (2MASS), Digitized Sky Survey, US Naval Oservatory (USNO) Catalog, and Guide Star Catalog, which had positions that agreed with each other and with the *Chandra* position to within $0''.5$. The other source (at *Chandra* reported [J2000] R.A. $18^h11^m41^s.88$, decl. $-19°28'16''.0$) was identified in the 2MASS and USNO catalogs, again with positional consistency of $0''.6$. Thus, the *Chandra* position appears to be reliable to within the nominally quoted uncertainty of $0''.6$. Given its newly determined position and because it is a rotation-powered pulsar, we rename the source PSR J1811−1925 and refer to it as such hereafter.

The pulsar wind nebula (PWN) morphology is revealed for the first time in this image. There are two distinct emission regions within the shell. The hard emission (blue in the image) is collimated, with axis at $\sim 60°$ east of north. To

[10] Chandra Proposers' Observatory Guide, Rev. 3.0, 60.

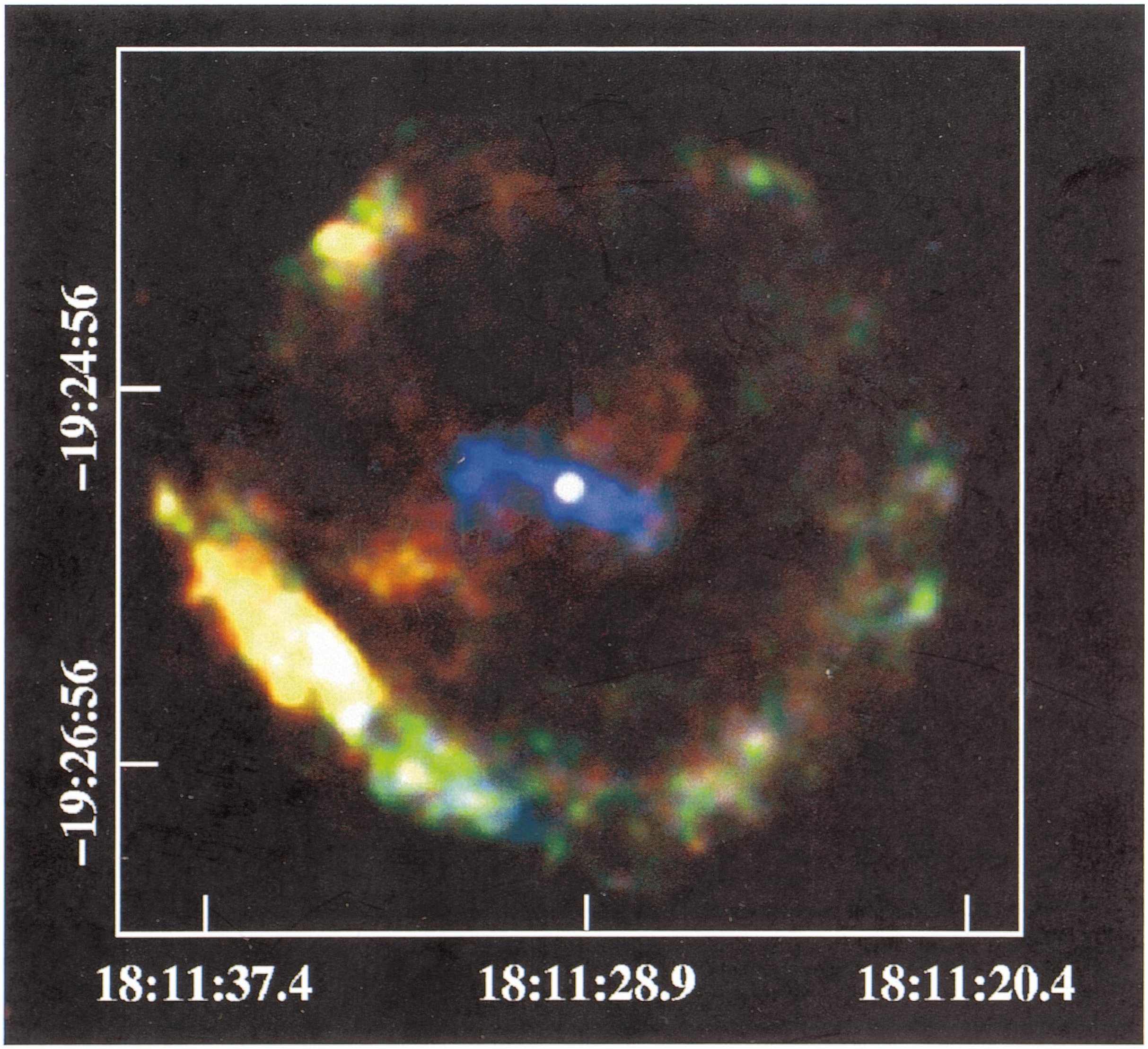

FIG. 1.—*Chandra* image of G11.2−0.3, smoothed by a 5″ Gaussian and color-coded as follows: red represents photons of energies 0.6–1.65 keV; green, 1.65–2.25 keV; and blue, 2.25–7.5 keV.

examine this component better, we made a 4–9 keV image, which is dominated by nonthermal emission, and smoothed it with a 2″ Gaussian to highlight the fine structure (see Fig. 2). The PWN extends for a total of ∼40″ to the northeast and southwest of the pulsar. To the southwest, a significantly brighter plume starts ∼5″ from the pulsar, peaks at ∼10″, extends to ∼20″, then becomes much fainter. To the northeast, the emission remains narrowly confined for ∼20″ before "bending" by ∼90° and fading. There is a second emission region also roughly centered on the pulsar with a much softer spectrum (red in Fig. 1). Its long axis lies at an angle of ∼60° relative to the hard emission. It extends roughly 2′ and is much broader in width than the hard emission.

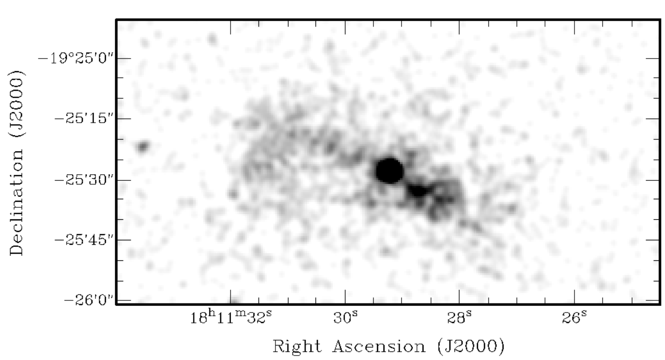

FIG. 2.—Central PWN in hard (4–9 keV) X-rays, smoothed by a 2″ Gaussian.

3. DISCUSSION

The *Chandra* image clearly reveals that the pulsar is very close to the geometric center of the shell. Fitting circles by eye to the outer through inner portions of the shell suggests the center is within a few arcseconds of the pulsar. In order to verify this less subjectively, we made a smoothed image of the remnant in which all pixels had a value of zero below a threshold ∼10 σ above the average background pixel, or unity otherwise, i.e., if they were clearly part of the remnant. We then calculated average radial profiles centered at various points near the center on a 2″.5 grid. If the shell were a perfect annulus, the most central position should correspond to the radial profile that drops to zero at the smallest radius. Since the shell has structure, we chose 0.01 as our average pixel value cutoff for the shell edge. The nominal best-fit center from this process is to the southeast of the pulsar ([J2000] R.A. $18^h11^m29^s.3$, decl. $-19°25'31''.1$), although only profiles from points greater than $\sim 8''$ from the pulsar were unambiguously broader than the one centered on the pulsar. We varied both the image threshold and the edge cutoff values and obtained similar results. We therefore consider $8''$ to be a firm upper limit on the displacement of the pulsar from the shell center. This number is dominated by the difficulty in determining the center of the shell, not the location of the pulsar. We also examined the radio image of the remnant, and visual fitting of circles came up with a best-fit center within a few arcseconds of the pulsar. The broadening of the radio emission in the southwest quadrant of the remnant causes on/off threshold images to differ significantly from a circle, making a radial profile analysis similar to that used for the X-ray data of questionable use.

This result strongly supports the association of the pulsar with the shell. Furthermore, the fact that the pulsar is so close to the center of the remnant provides strong independent evidence for the youth of the entire system, i.e., that the pulsar characteristic age is an overestimate of the true age. This is because, as we now show, if the system really were 24,000 years old, the pulsar would probably have moved significantly away from its birthplace.

First, we discuss distance estimates to the supernova remnant. These have been made using neutral hydrogen absorption spectra. Radhakrishnan et al. (1972) found $d > 5$ kpc. Becker, Markert, & Donahue (1985), upon redoing this observation at the Very Large Array, found weak evidence for absorption at negative velocities, which they interpreted as suggestive of a distance of 26 kpc on the outskirts of the Galaxy and implying a diameter of some 30 pc. This latter estimate is not supported by any other observation, particularly not the other indicators of youth, namely, the high radio surface brightness and symmetric structure. Indeed, as argued by Green et al. (1988), the lack of any absorption between $+45$ km s^{-1} and the tangent point at $+120$ km s^{-1} argues against a distance outside the solar circle. Rather, it implies a distance of ~ 5 kpc, the near distance corresponding to $+45$ km s^{-1}. The weak absorption at negative velocities in the spectrum of Becker et al. (1985) is probably due to unusual motions in local gas. A distance of 5 kpc implies a diameter of ~ 6 pc, in agreement with the apparent youth inferred from its morphology and surface brightness, and has been adopted in subsequent studies of the remnant. The equivalent neutral hydrogen absorption toward the system, 2×10^{22} cm^{-2} as inferred from X-ray observations (M. E. Roberts et al. 2001, in preparation), is not inconsistent with a distance as small as 5 kpc. No radio pulsations have been detected from the pulsar (Crawford et al. 1998), so a dispersion-measure–based distance estimate is not available.

The angular displacement of the pulsar from its birthplace would be

$$\theta = 24''\left(\frac{v_t}{345 \text{ km s}^{-1}}\right)\left(\frac{\tau}{1614 \text{ yr}}\right)\left(\frac{d}{5 \text{ kpc}}\right)^{-1}, \qquad (3)$$

where v_t is the pulsar transverse velocity, τ is the true age, and d is the distance. Thus, even in the unlikely event that the system is as far away as 15 kpc, the pulsar would have to have $v_t < 23$ km s^{-1} if $\tau = 24{,}000$ yr, given that $\theta < 8''$. For $d = 5$ kpc at this age and given the constraint on θ, $v_t < 8$ km s^{-1}.

Lyne & Lorimer (1994) showed that the mean pulsar transverse velocity is 345 km s^{-1} and inferred a mean three-dimensional velocity of 450 km s^{-1}. Although other analyses have attempted to refine this result (Lorimer, Bailes, & Harrison 1997; Hansen & Phinney 1997; Cordes & Chernoff 1998), it is clear that pulsars are a high-velocity population, with mean three-dimensional velocity in the range 250–450 km s^{-1}. Cordes & Chernoff (1998) suggest that the velocity distribution may have two components, one with a three-dimensional mean of ~ 700 km s^{-1} and one with a three-dimensional mean of ~ 175 km s^{-1}, representing 14% and 86% of the population, respectively. They speculate regarding a third component with a mean of less than 50 km s^{-1} but conclude that it could represent at most 5% of pulsars.

We can estimate the probability for occurrence of the low velocity required by our constraint on θ (eq. [3]) by assuming a reasonable model for the pulsar transverse-velocity distribution. For a Maxwellian distribution of velocities having mean transverse speed $\overline{v_t} = 345$ km s^{-1} (Lyne & Lorimer 1994), the probability of a pulsar having $v_t < 8$ km s^{-1} is less than 0.1%. By contrast, for $d = 5$ kpc and $\tau = 1600$ yr, $v_t < 108$ km s^{-1}, still small compared to the average but with a more reasonable 7% probability of occurring. Although these probabilities depend on the true pulsar population velocity distribution (e.g., for $\overline{v_t} = 100$ km s^{-1}, the above probabilities are 0.4% and 60%, respectively), the overall conclusion appears firm: the location of the pulsar is at odds with its characteristic age for any reasonable distance, unless it has an improbably low transverse velocity or it happens to be representative of a very small ($<5\%$) subset of the pulsar population that has very low (<50 km s^{-1}) space velocity (Cordes & Chernoff 1998). Although we cannot unambiguously rule out these latter possibilities, given the independent evidence for the youth of the remnant, we conclude that the pulsar characteristic age is in all likelihood an overestimate of the true age of the system by a factor of ~ 12.

Figure 3 is a plot of true age versus unknown initial spin period for four different braking indices representing the observed range, using equation (2) (see also Torii et al. 1999). The true age of the system, ~ 2000 yr, is indicated by a straight horizontal line near the bottom of the plot. To have $P_0 \lesssim 20$ ms requires $n \gtrsim 24$, which is unlikely given the range of observed values of n. Although there have been claims of values of n outside this narrow range (e.g., Gullahorn & Rankin 1978; Johnston & Galloway 1999), in no case is the measured value known to be constant. Specifically, for no case in which a measurement of $n > 3$ has been claimed have repeated measurements yielded the same value. Such "variable" braking indexes are probably due to either random timing noise or long-term glitch recovery (Cordes & Helfand 1980; Shemar & Lyne 1996). Thus, Figure 3 clearly indicates that for any constant braking index that is consistent with those of the five pulsars for which it has been measured (§ 1), the initial spin period of the G11.2−0.3 pulsar must be near ~ 62 ms. This is significantly longer than those of the Crab and N157B pulsars. So large a difference may be hinting that the true distribution of initial spin periods of neutron stars is larger yet.

There are, in principle, alternative explanations for the fact that the pulsar's characteristic age is much larger than

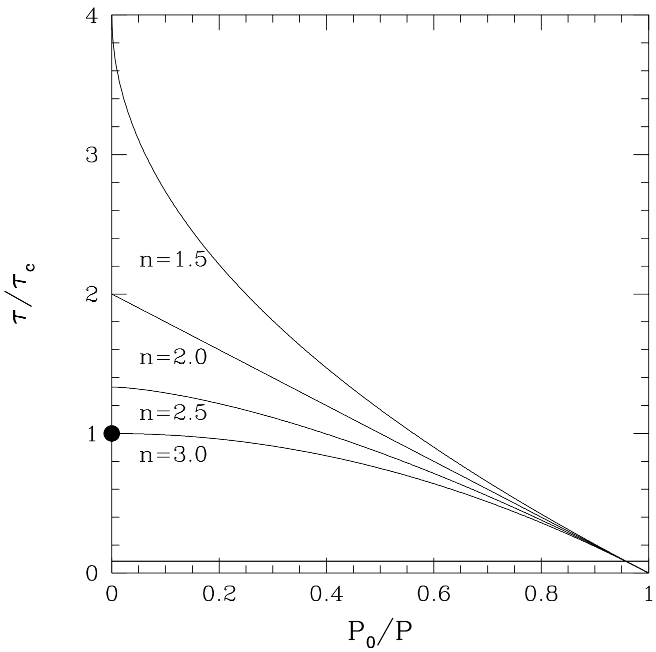

FIG. 3.—True age τ in units of the characteristic age $\tau_c \equiv P/2\dot{P}$, vs. initial spin period P_0 in units of the current spin period P, for four different braking indexes n. For G11.2−0.3, τ_c = 24,000 yr and P = 65 ms. The dot corresponds to the conventional assumptions of $n = 3$ and $P_0 \ll P$. The horizontal line indicates the true age of the system as estimated from the remnant properties as well as the observations reported here. It demonstrates that for any braking index within the observed range, the initial spin period of the pulsar had to be ∼62 ms.

the true age. The simple spin-down equation (2) might not hold. This could be true if, for example, the magnetic moment were not constant, that is, $k = k(t)$ in equation (1). However, if so, it is not hard to show (Blandford & Romani 1988) that the magnetic moment would have to decay on a timescale of $\lesssim$2 kyr. This is at odds with the existence of many older pulsars having comparable or larger magnetic fields, as well as with models of magnetic field decay in neutron stars (e.g., Goldreich & Reisenegger 1992).

Alternatively, it might be noted that very significant deviations from simple spin-down have been observed for soft gamma repeaters (SGRs; e.g., Woods et al. 1999) and anomalous X-ray pulsars (AXPs; e.g., Oosterbroek et al. 1998; Kaspi et al. 2001), both of which have been suggested to be young, isolated neutron stars. However the same spin-down processes operating in those sources are unlikely to be relevant to PSR J1811−1925 as the latter has spin period, X-ray spectrum, and spin-down power characteristic of rotation-powered pulsars. The absence of radio pulsations from the source (Crawford et al. 1998) is not evidence against this, given the broad range of pulsar radio luminosities (Taylor, Manchester, & Lyne 1993). The SGRs and AXPs, by contrast, cannot be powered by rotation and have been suggested to be powered by their enormous inferred magnetic fields—the "magnetar" model (Thompson & Duncan 1996). In this model, spin-down anomalies are a direct result of the large magnetic field, inapplicable to PSR J1811−1925.

An alternative model, in which SGRs and AXPs are accreting from a disk of material that fell back onto the neutron star shortly after the supernova explosion, has recently been invoked for rotation-powered pulsars (Marsden, Lingfelter, & Rothschild 2001; Menou, Perna, & Hernquist 2001). In this model a fallback disk exerts a significant torque on the neutron star via the propeller mechanism and results in braking indexes very different from the vacuum dipole value (though typically less than 3) and hence characteristic ages very different from true ages. However, even if such a disk could survive the pulsar wind (an issue not addressed by existing studies), it would be very difficult for the propeller mechanism to spin the pulsar down from a Crab-like initial spin period on a timescale of ∼2 kyr (M. Lyutikov 2001, personal communication).

Finally, we note that possible contamination of the pulsar's $\dot{P}$ by Doppler shift due to binary motion is unlikely to explain the age discrepancy because it would have to exactly cancel out a much larger intrinsic $\dot{P}$. On the other hand, if the source were accreting near its equilibrium spin period, the observed $\dot{P}$ would be due to accretion torque. However, there is no evidence for accretion from the observed X-ray emission, nor is there any evidence for a binary companion. In particular, from the 2MASS survey we find an upper limit $m_J > 16.5$, which, assuming extinction $A_J = 3.0$ (Zombeck 1990), rules out all stars of spectral type B5 and earlier and all O and B giant stars. Thus, a high-mass X-ray binary is all but ruled out, while a low-mass X-ray binary is unlikely given the association with the young supernova remnant.

Thus, the most conservative conclusion is that the initial spin period of PSR J1811−1925 is close to its present period.

Of all known pulsars having characteristic ages under 100 kyr, one-quarter have periods under 90 ms. Discarding the Crab, N157B, and PSR B0540−69 pulsars (all of which have very short current spin periods), if the remainder were born spinning at ∼60 ms, all would have true ages substantially less than their characteristic ages (see Fig. 3).

Even if an alternative spin-down mechanism is at work and the initial spin period of the pulsar is not long, the large characteristic age for PSR J1811−1925 casts doubt on the characteristic ages of other young pulsars. This has a variety of implications for young pulsar astronomy. Smaller true ages drive up required transverse velocities when attempting to associate a remnant with a pulsar that is not at its center. Population synthesis studies have generally assumed that all pulsars have much shorter Crab-like initial spin periods (e.g., Lorimer et al. 1993; Narayan & Ostriker 1990; Cheng & Zhang 1998; Chatterjee & Hernquist 2000; McLaughlin & Cordes 2000). This could be problematic for some of these studies. For example, longer initial spin periods imply lower initial spin-down luminosities, which could affect the observability of the pulsar population at gamma-ray energies. In addition, as tests of neutron star cooling models require good age constraints (see reviews by Tsuruta 1986; Ögelman 1995), use of the characteristic age in these applications may be problematic as well. A factor of 10 age error in the age range 10^3–10^4 yr could cause confusion in discriminating among nonstandard cooling models (Umeda, Tsuruta, & Nomoto 1994).

We note, however, that larger initial spin periods do not affect the age estimates for the bulk of the pulsar population unless the initial spin period distribution is much broader. The possibility of the existence of a population of pulsars "injected" into the population spinning at a few hundred milliseconds has been considered in the literature (e.g., Emmering & Chevalier 1989; Narayan & Ostriker 1990), although more recent studies suggest that this does not occur (Lorimer et al. 1993). Indeed, for long period pulsars, τ_c is more likely to be a significant underestimate of the true age since the effects of a braking index less than 3 becomes important (Lyne et al. 1996; Gaensler & Frail 2000).

3.1. *The Pulsar Wind Nebula*

The hard emission centered on the pulsar is undoubtedly some form of PWN. Given its elongated morphology, we speculate that it is either a torus or disk being viewed edge-on, or else it is collimated jetlike emission.

A hard X-ray torus has been seen around the Crab pulsar and is likely the result of an equatorial outflow interacting with the supernova ejecta. Helfand et al. (2001) have suggested that such a torus also exists around the Vela pulsar, although only a portion of it is observed. For G11.2−0.3, if the hard emission is a torus like that in the Crab Nebula, it is being viewed very close to edge-on and would have to have significant asymmetry about the pulsar. The brightest feature in the emission is in the southwest "arm" some 10″ from the pulsar. This corresponds to a size of $0.24 \times [d/(5\ \mathrm{kpc})]$ pc, nearly double the size of the "inner ring" around the Crab (Weisskopf et al. 2000) but comparable to that of the inner region of the main torus. Indeed the entire extent of the hard emission matches in scale with the overall size of the Crab X-ray torus. If this interpretation is correct, it would suggest that the pulsar spin axis lies in the plane of the sky, perpendicular to the hard-spectrum elongation. However, given that the spin-down luminosity of PSR J1811−1925 is over 60 times smaller than that of the Crab pulsar, if hot gas in the supernova remnant interior is containing the PWN, the pressure in G11.2−0.3 must be ~ 8 times lower than in the Crab Nebula. Also, if this interpretation is correct, there is no evidence for collimated jets as seen in the Crab pulsar. As the jets in the Crab are aligned with the pulsar's space velocity, the lower inferred velocity of PSR J1811−1925 could be related to the absence of visible jets.

On the other hand, the elongated hard-spectrum emission may itself be the analogy of the jets in the Crab pulsar and may directly delineate the pulsar spin axis. The asymmetry about the pulsar could be due to differences in the densities of the stellar ejecta along the jet axes or to Doppler boosting, or to some combination of both. If this emission does originate from a jet, it is hard to understand the apparent $\sim 90°$ bend in the emission on the south side, unless there is a significant density enhancement in that direction. In this interpretation, there is no clear evidence for a hard X-ray torus, although the fainter emission out to $\sim 40''$ from the pulsar and the few arcsecond enhancement around the pulsar perpendicular to the "jets" (Fig. 2) are both possibilities.

The other emission component within the shell clearly has a significantly softer spectrum and could be an enhancement in the shell seen in projection. However, its apparent symmetry around the pulsar suggests a possible association. It could represent material heated by the forward shock from the pulsar wind, analogous to the heating of material by the spherical supernova blast wave. If so, the direction of elongation is likely to delineate either the equatorial plane of the pulsar or the polar axis. A detailed spectral analysis of this and the other components will be presented elsewhere (M. E. Roberts et al. 2001, in preparation).

4. CONCLUSIONS

Thanks to the superb spatial resolution of *Chandra*, we have determined that the 65 ms pulsar in G11.2−0.3, which we designate PSR J1811−1925, is at the precise geometric center of the remnant, formally to within 8″. This provides strong support for the pulsar's association with the shell, consistent with the A.D. 386 guest star and in agreement with the shell properties. However, the inferred age, ~ 2000 yr (or 1615 yr if the A.D. 386 association holds), is at odds with the much larger characteristic age of the pulsar. For the reasonable spin-down assumptions, this suggests that this pulsar had a birth spin period very close to its present spin period. This result is insensitive to the pulsar's braking index, assuming the latter is not very different from those measured for other pulsars. This result calls into question the reliability of characteristic ages as true age estimators for a significant fraction of young pulsars (see also Lyne et al. 1996; Gaensler & Frail 2000).

In addition, these *Chandra* observations have, for the first time, revealed the morphology of the PWN at the center of the supernova remnant. Its elongated morphology at hard X-ray energies, like those seen in high-resolution X-ray observations of the Crab and Vela pulsars, adds to the growing evidence that such structures are ubiquitous around young pulsars and demand explanation.

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