VELA PULSAR AND ITS SYNCHROTRON NEBULA

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ABSTRACT

We present high-resolution Chandra X-ray observations of PSR B0833−45, the 89 ms pulsar associated with the Vela supernova remnant. We have acquired two observations separated by 1 month to search for changes in the pulsar and its environment following an extreme glitch in its rotation frequency. We find a well-resolved nebula with a toroidal morphology remarkably similar to that observed in the Crab Nebula, along with an axial Crab-like jet. Between the two observations, taken \( \sim 3 \times 10^5 \) s and \( \sim 3 \times 10^6 \) s after the glitch, the flux from the pulsar is found to be steady to within 0.75%; the 3 \( \sigma \) limit on the fractional increase in the pulsar’s X-ray flux is \( \lesssim 10^{-5} \) of the inferred glitch energy. We use this limit to constrain parameters of glitch models and neutron star structure. We do find a significant increase in the flux of the nebula’s outer arc; if associated with the glitch, the inferred propagation velocity is \( \gtrsim 0.7c \), similar to that seen in the brightening of the Crab Nebula wisps. We propose an explanation for the X-ray structure of the Vela synchrotron nebula based on a model originally developed for the Crab Nebula. In this model, the bright X-ray arcs are the shocked termination of a relativistic equatorial pulsar wind that is contained within the surrounding kidney-bean shaped synchrotron nebula comprising the postshock, but still relativistic, flow. In a departure from the Crab model, the magnetization parameter \( \sigma \) of the Vela pulsar wind is allowed to be of order unity; this is consistent with the simplest MHD transport of magnetic field from the pulsar to the nebula, where \( B \leq 4 \times 10^{-4} \) G. The inclination angle of the axis of the equatorial torus with respect to the line of sight is identical to that of the rotation axis of the pulsar as previously measured from the polarization of the radio pulse. The projection of the rotation axis on the sky may also be close to the direction of proper motion of the pulsar if previous radio measurements were confused by orthogonal-mode polarized components. We review effects that may enhance the probability of alignment between the spin axis and space velocity of a pulsar, and speculate that short-period, slowly moving pulsars are just the ones best-suited to producing synchrotron nebulae with such aligned structures. Previous interpretations of the compact Vela nebula as a bow-shock in a very weakly magnetized wind suffered from data of inadequate spatial resolution and less plausible physical assumptions.

Subject headings: pulsars: general — pulsars: individual (PSR B0833−45) — stars: neutron — supernova remnants — X-rays: general

1. INTRODUCTION

Within two years of the discovery of radio pulses from CP 1919+21, magnetized, rotating neutron stars were firmly established as the origin of these remarkable signals. Furthermore, the steady increase in pulse period recorded for all sources provided an explanation for the pulsar power source: rotational kinetic energy. The detection of a decelerating 33 ms pulsar in the Crab Nebula solved the long-standing mystery of what powered this unique nebula: the spin-down rate of the Crab pulsar implied an energy loss rate, \( \dot{E} \sim 5 \times 10^{38} \) ergs s\(^{-1}\), more than enough to cover the radiation losses observed from radio to gamma ray frequencies. By 1974 the basic model of the electrodynamics of pulsar magnetospheres and their coupling to the surrounding synchrotron-emitting plasma was in place (Rees & Gunn 1974), although a detailed understanding of the processes involved continues to elude us (e.g., Arons 1998).

After a decade of timing observations, it became clear that most pulsars were not defect-free clocks, which simply slowed smoothly as rotational energy was transformed into an electromagnetic outflow. Two distinct types of non-monotonic behavior were established: “timing noise” characterized by a stochastic wandering in pulse phase and/or frequency, which appeared to afflict most pulsars (Helfand, Taylor, & Backus 1980; Cordes & Helfand 1980; Cordes & Downs 1985; D’Amico et al. 1998), and “glitches,” an apparently instantaneous increase in the pulse frequency (a spin-up) accompanied by a simultaneous change in the spin-down rate; these rare events were found to be most prevalent in young objects (Reichly & Downs 1971; Lyne 1996 and references therein). Thirty years after the first glitch in the Vela pulsar was recorded, a total of 65 events have been seen in 27 different pulsars (Lyne 1996; Wang et al. 2000).

Glitches are a sudden fractional increases in the pulsar spin frequency with \( \delta v/v \approx 10^{-9} \) to \( 6 \times 10^{-6} \). No pulsar with a characteristic age of more \( 10^6 \) yr has been observed to glitch more than once, but some young objects experience these events roughly annually. The best studied and most prolific in terms of large glitches is the first object in which a glitch was seen — the Vela pulsar. A dozen events have been recorded over the past three decades and daily monitoring continues. The largest event yet observed occurred in 2000 January (\( \delta v/v = 3.14 \times 10^{-5} \)) and provided the stimulus for the observations reported here.

In this paper, we report new results on PSR B0833−45 based on observations acquired with the Chandra High-Resolution Camera. The data enable us for the first time to distinguish morphological details of the synchrotron nebula surrounding PSR B0833−45 and reveal a striking picture of bilateral symmetry reminiscent of the loops and jets recently resolved in the Crab Nebula (Weisskopf et al.
In response to an IAU Circular announcing a large Vela pulsar glitch on 2000 January 16.319 (Dodson, McCulloch, & Costa 2000), we submitted a target of opportunity request to the Chandra Observatory (Weisskopf, O’Dell, & van Speybroeck 1996) to observe the pulsar as soon as practical, followed by a second observation roughly 1 month later in order to search for changes in the pulsar’s flux, pulse profile, and/or surrounding nebula. The observations were carried out on 20 January 2000 and 21 February 2000, ~3.5 and ~35 days after the glitch using the Chandra imaging High-Resolution Camera (HRC-I; Murray et al. 1997). Integration times of ~50 ks were achieved in both observations.

The HRC-I detector on-board Chandra is sensitive to X-rays over the 0.08–10.0 keV range, although essentially no energy information on the detected photons is available. Photons are time-tagged with a nominal precision of 15.6 μs; in this work, their arrival times were corrected to the solar system barycenter using a beta version of AXBARY. The data were collected during a portion of the orbit that avoided regions of high background contamination from the bright Earth and radiation belt passages; the second observation was, however, found to be partially contaminated by particle activity, most likely of solar wind origin (see below). The pulsar was centered at the on-axis position of the HRC where the point-spread function (PSF) has a minimum half-power diameter (the radius enclosing 50% of total source counts) of ~0.7, which increases with energy. Images were extracted centered on the pulsar and binned using the native HRC 0.13175 × 0.13175 pixel size into 1024 × 1024 pixel images (2.5 on a side).

We began our analysis using event data calibrated by the initial processing and made available through the Chandra public archive. The first observation revealed several problems in the standard data sets, and further problems were subsequently found during the analysis of the second observation. These problems affected both the spatial and timing analyses and had significant implications for the proper interpretation of the data. We alerted the HRC hardware and software teams to the instrument and data processing anomalies and received considerable support in working through the problems. We document here the various artifacts discovered and the steps taken to correct for, or eliminate, them in our final data sets; our goals in doing so are (1) to allow for the replication of our results, and (2) to alert other early HRC users to problems they may encounter. In fact, we found it necessary to reprocess the data from level 0.5 using custom scripts that incorporated improved filtering and processing tools, making use of several beta versions of software provided by the HRC team.

In the first observation we found evidence for a significant “ghost image,” which appeared as a spectacular jetlike feature emanating from the pulsar along the detector v-axis. Examination by the instrument team found that the standard processing had failed to screen out all events flagged as instrumental. After filtering with a beta version of SCREEN_HRC with the mask parameter set to 32,771, a much truncated jetlike feature was still apparent. In order to isolate any detector-centric artifacts, we obtained our second observation with a roll angle offset by 36° from the first. As discussed below, we were able to confirm the reality of the residual jet-like feature in the cleaned images.

Independent of any filtering, the initial images showed the pulsar to be broader than the nominal PSF. To separate the pulsar from any proximate nebular emission, we followed the same phase-resolved imaging analysis described in Gotthelf & Wang (2000) for their HRC observation of PSR 0540−69, the 50 ms pulsar in the LMC. This separation, however, failed completely. By plotting the arrival times of the pulsar centroid, we observed that the sky coordinates of the pulsar wandered in a sinusoidal fashion with an amplitude of 0.3° and the periodicity of the programmed telescope dither. This accounted for the pulsar’s non-pointlike appearance in the time-integrated image. Discussions with the Chandra attitude aspect team, however, showed a high-quality aspect reconstruction for the Vela observations.

Further analysis by the HRC team revealed a systematic problem with one of the three anode preamplifiers that causes the coarse position algorithm to misplace photon locations depending on the photon input position relative to the HRC tap gaps. This explains the apparent wandering of the pulsar centroid at the dither frequency: a fraction of the detected photons are displaced along the detector coordinates by a fixed amount. Indeed, we were able to ascertain that the apparent diffuse flux was produced by faint echoes of the pulsar itself along the two orthogonal detector axes.

To eliminate the echoes, we initially used the bright pulsar as a fiducial point to reaspect the photons and thus take out the detector-induced wobble in a statistical sense. Subsequently, the instrument team made available a beta version of a code to identify and correct the misplaced photons—HRC_EVT0_CORRECT—along with updated degap parameters (\(cfu1 = 1.068; cfv1 = 0.0; cfu2 = 1.045; cfv2 = 0.0\)) for use in HRC_PROCESS_EVENTS. This software, together with the new parameters, effectively eliminated the echo problem. The images produced by the

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1 This problem does not affect early HRC-I observations obtained prior to an increase in the instrument gain by a factor of 2, such as those of the 50 ms pulsar PSR 0540−69 (see Gotthelf & Wang 2000).
two methods are indistinguishable, and the pulsar now matches the PSF to within its estimated uncertainty.

In the second observation, we noted additional artifacts in the sky image resembling a rabbit-ear antenna extending 20″ from the pulsar in orthogonal directions along the detector axes with point-like sources at the ends. Temporal analysis of the region showed that the rabbit-ear counts occurred during a number of specific time intervals lasting tens of seconds. Examination of the mission time-line parameters showed that the occurrence of these events always followed the “AOFF__GAP” times by a few hundred seconds. Furthermore, data drop-outs were found for tens of seconds at the “AOFF__GAP” times and during the following intervals when the spurious counts were recorded. We wrote an algorithm to generate a new good-time-intervals file that eliminates these intervals based on the “AOFF__GAP” times.

Two additional detector issues needed consideration when extracting accurate timing information: telemetry saturation and a hardware time-stamp misassignment. Although data obtained during the first observation displayed nominal background levels, the second observation was plagued by intervals of telemetry saturation induced by high background levels; such occurrences can seriously affect timing studies by introducing spurious periods in the power spectrum aliased with the full buffer rate of ~4 ms. We filtered out telemetry-saturated time intervals with the dead-time fraction criteria of DFT > 0.9. A further complication for precision timing was recently discovered by the HRC hardware team: the time stamps for each event are misassigned to the following event. Based on the VALID_EVT_COUNT count rate of ~500 cps, the average error in the assigned photon arrival time is 2 ms or a 2% phase error for the Vela pulsar; assuming roughly Poisson fluctuations in the HRC count rate over the observation interval, the maximum error for any photon will be ≤3 ms. Thus, with 25 phase bins across the 88 ms pulsar period, few, if any, photons have been misassigned and we have taken no mitigating action to correct this error.

To compare directly the two observations, we reprocessed both data sets starting from the level 0.5 event files using identical methods and filter/screening/processing criteria, compensating for incorrect keyword values, producing correct GTI extensions, etc. This resulted in a total of 50.3 and 45.3 ks integration times for the first and second observation, respectively. Despite all the initial discrepancies and artifacts in the two observations, this reprocessing produced effectively identical images, light curves, and count rates. We are thus confident that we have eliminated all currently recognized instrumental artifacts in the final data sets upon which we base the analysis herein.

3. AN IMAGE OF THE VELA PULSAR

A global view of the Vela pulsar and its environment as seen by the Chandra HRC is presented in Figure 1. The pulsar is embedded in a complex region of previously resolved thermal X-ray emission from the Vela supernova remnant that is present throughout this image and extends far beyond its boundaries. The X-ray jet noted by Markwardt & Ogelman (1995) is essentially overresolved in this image and extends far to the south of the image boundary; it is evident as a faint enhancement in the diffuse emission extending to the southeast and south of the bright pulsar nebula.

The superb spatial resolution of the Chandra HRC provides the first look at the structure of the synchrotron nebula in the immediate vicinity of PSR B0833−45; Figure 2 shows an image constructed from the two observations that have been centered on the pulsar and summed. The bright point source representing the pulsar has an extent roughly consistent with the local PSF. Apparently emanating from the pulsar, toward the southeast, is a linear, jet-like feature 10″ in length. There is also evidence for a counter jet in the opposite direction. These jets have a position angle of 130° (measured east of north), and are aligned to within 8° ± 5° with the pulsar’s proper motion vector (Bailes et al. 1990; De Luca, Mignani, & Caraveo 2000).

Concentric with the pulsar is a diffuse outer arc of emission perpendicular to the jet. This feature is roughly elliptical in shape and subtends an angle of ~150° as seen from the pulsar. Interior to this arc is an elliptical ring of emission with a curvature very similar to the outer arc. The pulsar, jet, and arcs are embedded in an extended nebula of faint diffuse emission that has been described as “kidney-bean” shaped (Markwardt & Ogelman 1998). The configuration of the jet feature relative to the nebula is reminiscent of the Chandra image of the Crab Nebula (Fig. 3; see Weisskopf et al. 2000). We determined the count rates by extracting counts from the various regions discussed above (see Fig. 4). For each source region we carefully estimated the background. For the diffuse emission, we determined the HRC detector background derived from an annulus 13.2″ wide exterior to the kidney bean emission (r > 52.7″). We extracted counts from the pulsar using a circular aperture 2′64″ in radius and estimated background from the surrounding annulus, 2′64 < r < 3′43. Table 1 summarizes the properties of the individual components, including their estimated sizes and intensities.
Vela X, the \(~100\)' diameter, flat-spectrum radio component near the center of the Vela remnant (Milne 1968; Bock, Turtle, 
& Green 1998) is generally regarded as the pulsar's radio synchrotron nebula. While soft X-rays from this region are detected, 
they are primarily thermal in nature, and represent emission from the hot plasma that fills the entire remnant (Kahn et al. 1985; 
Lu & Aschenbach 2000). Even the bright radio filament detected by Bietenholz, Frail, 
& Hankins (1991) shows no corresponding enhancement in our X-ray image, although more constraining limits will be derivable from ACIS observations.

The compact X-ray source near the pulsar was first recognized by Kellogg et al. (1973) as having a harder spectrum. Subsequent observations with increasing angular resolution (Harnden et al. 1985 and references therein; \Ögelman, Finley, 
& Zimmermann 1993; Markwardt & \Ögelman 1998) localized the compact nebula to a region \(~2\)' in extent roughly centered on the pulsar. \Ögelman et al. (1993) used the nominal point-spread function of the \textit{ROSAT} PSPC and an ad hoc model for the surface brightness of the diffuse emission to attempt a deconvolution of the pulsar and its nebula and to obtain spectral fits to the two components. They found that a blackbody effective temperature of 0.15 keV adequately characterized the point source, while the extended emission exhibited a power-law spectrum with a photon index of \(~2.0\); a column density of \(N_H = 1 \times 10^{20} \text{ cm}^{-2}\) is marginally consistent with both components. Markwardt 
& \Ögelman (1998) subsequently revised the division of the flux between the point source and nebula based on \textit{ROSAT} HRI observations. Seward et al. (2000) attempted to isolate the pulsar emission temporally and found somewhat lower blackbody temperatures. The \textit{RXTE} observations of Gurkan et al. (2000) found a similar power-law index for the nebula, but a much higher normalization; while this could indicate diffuse synchrotron X-ray emission from a larger area (given their 1° field of view), it

The best current measurements for the Vela pulsar and remnant place it at a distance of only \(250 \pm 30\) pc (Cha, Sembach, 
& Danks 1999 and references therein); in all that follows we scale by \(d = 250d_{250}\) pc.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Close-up view of the region surrounding the Vela pulsar PSR B0833−45. The image includes the summed data from two epochs separated by a month and is centered on the pulsar and scaled to highlight the surrounding nebula emission. The data in this and the two subsequent figures have been smoothed with a Gaussian with \(\sigma = 0.66\). A toroidal structure and perpendicular jet similar to that seen in the Crab Nebula is apparent. Also evident is a faint halo of emission likely associated with the postshock pulsar wind (see text).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{Comparison of the relativistic wind nebulae surrounding two young pulsars observed by the \textit{Chandra Observatory}: the 1000 yr Crab pulsar (right) and the 10 kyr Vela pulsar (left). The images are displayed with the same plate scale, although the Vela nebula is 16 times smaller physically assuming distances of 2 kpc (Crab) and 250 pc (Vela); the circles in the two images represent the same physical size at the respective pulsars.}
\end{figure}
The integrated luminosity of the whole nebula \( r < 52 \)" minus the pulsar) in the 0.1–10 keV band is \( 3.5 \times 10^{32} d_{250}^2 \) ergs s\(^{-1}\), corresponding to \( 4.9 \times 10^{-5} \) of the pulsar's spin-down luminosity. This ratio of \( L_{\text{neb}} / E \) is significantly lower than that for any other pulsar, and is a major constraint on models for coupling the pulsar wind to the nebula (see §6).

4. THE X-RAY PULSE PROFILE

After many unsuccessful searches, Ögelman et al. (1993) were the first to detect X-ray pulsations from the Vela pulsar using the ROSAT PSPC. Their observations revealed a complex profile, not obviously related to the pulse profiles previously recorded at radio, optical, and gamma-ray wavelengths. The observed pulsed fraction of 4.4\% \pm 1.1\% was diluted by the inability of the PSPC to resolve the pulsar from the surrounding nebula; using the approximate model described above, the authors estimated a soft X-ray pulsed fraction of 11\%. Seward et al. (2000) constructed a higher signal-to-noise profile by combining six ROSAT HRC observations; they estimated a pulsed fraction of 12\% divided between a broad component (8\%) and two narrow peaks (4\%). Strickman, Harding, & de Jager (1999) and Gurkan et al. (2000) have recently derived 2–30 keV profiles based on RXTE observations of Vela. Strickman et al. illustrate a trend in which the component separation of the main pulse increases with energy.

We have determined the X-ray pulse period for our two observations and compared them to the radio ephemeris (D. Backer 2000, personal communication). We began by constructing a periodogram around a narrow range of periods centered on the expected period \( \pm 0.1 \) ms, sampled in increments of \( 0.05 \times P^2 / T \), where \( T \) is the observation duration, and \( P \) is the test period. For each trial period, we folded photons extracted from a \( r = 2.64 \) aperture centered on the pulsar position using 52 phase bins and computed the \( x' \) of the resultant profile. We find a highly significant signal \((> 8 \sigma)\) at \( P = 89.32842(5) \) ms at epoch 51563.314043 MJD (TBD) and \( P = 89.32876(6) \) ms at epoch 51595.370251 MJD (TBD), completely consistent with the observed radio periods. The uncertainty was estimated according to the method of Leahy (1987). For each fold, we adopted the period derivative determined from the radio ephemeris. Our measurements of the period are consistent (within the errors) with the radio prediction.

In order to compare the pulse profiles for the two observations we used the phase-connected radio ephemeris to fold and align them. We present the sum and difference profiles in Figure 5. This phase alignment is completely consistent with one we computed empirically by cross-correlating the two profiles; this suggests that the Chandra clock is stable to a few milliseconds over a month. We can

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TABLE 1

| COMPONENT | Shape and Size | Counts s\(^{-1}\) |
|-----------|---------------|------------------|
| Pulsar    | Pointlike     | 2.012 ± 0.006    |
|           | Observation 1 |                  |
|           | Observation 2 | 1.997 ± 0.007    |
| Nebula    | 2\textdegree 6 × 52\textminute 7 circle | 2.720 ± 0.007 |
|           | Observation 1 |                  |
|           | Observation 2 | 2.762 ± 0.008    |
| Arc       | 20\textdegree × 10\textdegree NE-SW | 0.675 ± 0.004 |
|           | Observation 1 |                  |
|           | Observation 2 | 0.700 ± 0.004    |
| Jet       | 10\textdegree long SE-NW | 0.037 ± 0.001 |
|           | Observation 1 |                  |
|           | Observation 2 | 0.036 ± 0.001    |

* See §3.

b Count rates are background subtracted.
also derive the absolute radio to X-ray phase offset if we assume that the absolute Chandra time assignment is accurate (the calibration of this quantity has not yet been finalized). The phase of the radio peak relative to the X-ray profile is indicated in Figure 5.

The ~200,000 counts, uncontaminated by nebular emission, provide us with the highest signal-to-noise X-ray pulse profile for Vela yet reported (Fig. 5). Greater than 99% of the counts from the blackbody component detected by the HRC fall in the 0.1–2.4 keV ROSAT band. We compute a pulsed fraction by integrating the counts in the light curve above the lowest point and dividing by the total counts within a radius of \( r = 2.64 \) and subtracting the small amount of nebular background in this extraction radius (see Table 1). Our value for the pulsed fraction is 7.1% ± 1.1%; the quoted error is dominated by the Poisson uncertainty in the number of counts recorded in the bin representing the light-curve minimum. This value is somewhat lower than those cited above but has the advantage of utilizing a direct measure of the total point-source contribution with subarcsecond resolution. We measure a separation between the two peaks of the main component of \( \delta \phi \sim 0.325 \), consistent with a linear extrapolation of the energy-dependence of this quantity reported by Strickman et al. (1999).

The background-corrected pulsar count rates were found to be \( 2.012 \pm 0.006 \) and \( 1.997 \pm 0.007 \) counts s\(^{-1}\), respectively, for the first and second epochs; the overall count rate is constant to within 0.75% (the second observation is 1.5 \( \sigma \) fainter than the first). Thus, the 3 \( \sigma \) limit on any increase in the pulsar luminosity in response to energy input from the glitch is less than \( 1.2 \times 10^{30} \) ergs s\(^{-1}\) or \( \Delta T \sim 0.2\% \), 35 days (\( 3 \times 10^6 \) s) after the event. The lower half of Figure 5 shows the difference between the two observations as a function of pulse phase, where the second data set has simply been scaled by the ratio of the total integration times; no single bin has a discrepancy exceeding 1.5 \( \sigma \). This constancy in both the pulsed luminosity and pulse profile sets interesting constraints on the glitch mechanism (see § 6.4).

5. CHANGES IN THE NEBULA

While the primary energy release from a glitch must be within (or on the surface of) the neutron star, the response of the star’s magnetosphere could result in the release of energy to the synchrotron nebula, triggering changes in its morphology and/or brightness. Even without the stimulus of a glitch, the optical wisps of the Crab Nebula near the pulsar have been shown to change on timescales of weeks, presumably in response to instabilities in the relativistic wind from the pulsar (Hester et al. 1995). Greiveldinger & Aschenbach (1999) have also reported changes in the X-ray surface brightness of the Crab Nebula on larger scales and somewhat longer timescales. Thus, we have examined our two images of the Vela nebula carefully in a search for surface brightness fluctuations.

We examined the count rate in the kidney-bean region bracketed by the outer-arc and an inner circle with \( r = 1.32 \) centered on the pulsar. No significant change was observed between the two observations. Similarly, no measurable change in the count rate associated with the jet-like feature was found. Comparisons of other regions defined in Table 1 also showed no change, with the notable exception of the outer arc itself, which appeared to increase in brightness by \( \sim 5\% \) in the second observation.

To investigate this further, we examined regions congruent with the morphology of the nebula by constructing radial bins which are elliptical in shape; the ratio of the semimajor to semiminor axes of the ellipse is 1.76, and the elliptical annuli are oriented at a position angle of 50° (east of north). As Figure 6 shows, the sector of the radial profile encompassing the bright northwestern arc exhibits a 7.8 \( \sigma \) excess between semiminor axis radii of 13.5 and 18.0 in the sense that the source is brighter in the second observation. No other sectors or radii show any significant changes. In Figure 7 we display the azimuthal profile of the whole nebula in the elliptical ring 4.5 wide centered on these radii.
lie along circular rings highlighting shocks in which the energy of an outflowing equatorial wind is dissipated to become the source of synchrotron emission for the compact nebula extending to the boundary of the “bean”. One reason that the arcs are not complete rings might be that the emission is from outflowing particles which Doppler boost their emission in the forward direction.

This is essentially the picture for the similar arcs surrounding the Crab pulsar first suggested by Aschenbach & Brinkmann (1975) and later elaborated by other authors (Arons 1998 and references therein). The main difference is that the dark cavity that contains the unshocked pulsar wind in the Kennel & Coroniti (1984a) model of the Crab is small compared with the volume of the Crab Nebula, while the radius of the Vela nebula (the bean), is barely twice as large as its pulsar wind cavity (see Fig. 4). We assume that the two rings straddle the equator symmetrically and suppose that the deficit of emission exactly in the equatorial plane is related to the fact that this is where the direction of a toroidally wrapped magnetic field changes sign; i.e., the field may vanish there. The semimajor axis of the ring $a = 25\,\alpha_7$, and the ratio $a/b = 1.67$ specifies the angle that the axis of the torus (i.e., the rotation axis of the pulsar) makes with the line of sight, $\xi = \cos^{-1}(b/a) = 53\,\alpha_7$. The angle $\Psi_0 = 130^\circ$ is the position angle of the axis of the torus on the plane of the sky, defined according to convention as the angle measured to the east from north. The direction of rotation (the sign of $\Omega$) is arbitrary.

The projected separation of the two rings is measured as $s = 17\,\alpha_7$. The half opening angle of the wind $\theta$ is then given by $\tan \theta = s/(2a \sin \xi) = 0.43(\theta = 23.3^\circ)$, and the radius of the shock is $r_s = ad \cos \theta$, where $d$ is the distance to the pulsar. For $d = 250$ pc we find $r_s = 1.05 \times 10^{17}$ cm.

The rotating vector model of pulsar polarization (Radhakrishnan & Cooke 1969) is commonly used to derive information about the geometry of the pulsar magnetic inclination and viewing angles. The angles $\xi$ and $\Psi_0$ can in principle be evaluated independently using information derived from polarization measurements of the radio pulse.
In particular, the swing in position angle $\Psi(t)$ of linear polarization across the pulse is very sensitive to $\zeta$, the angle between the line of sight and the rotation axis. The angle $\alpha$ between the magnetic axis and the rotation axis is much more difficult to measure unless $\alpha \approx \zeta$ — i.e., unless the line of sight passes near the center of the polar cap. Accordingly, $\alpha$ is often assumed while $\zeta$ is fitted. For example, Krishnamohan & Downs (1983) assume $\alpha = 60^\circ$ in their model for Vela; this is consistent with the value $\alpha = 65^\circ$ derived by Romani & Yadigaroglu (1995) from a fit of their geometric gamma-ray emission models to Vela's pulse profile. When an interpulse is observed, $\alpha$ is often inferred to be $90^\circ$ (that is, both polar caps are visible in this case). With these definitions (see Fig. 8) or Figure (13) of Krishnamohan & Downs (1983) for the geometry,

$$\tan (\Psi(t) - \Psi_0) = \frac{\sin \phi(t)}{\cot \alpha \sin \zeta - \cos \zeta \cos \phi(t)}. \quad (1)$$

Here $\phi(t)$ is the longitude of the emitting region, which increases linearly with time, and $\Psi_0$ is the position angle of the rotation axis of the pulsar projected on the sky as in Figure (8).

In the context of the rotating vector model, $\Psi_0$ is identical to the position angle of polarization $\Psi$ at the peak of the pulse where the magnetic dipole axis crosses the rotation axis ($\phi(t) = 0$ in eq. [1]). Because the emission mechanism is thought to be curvature radiation from particles moving along magnetic field lines, the electric vector is tangent to those field lines, rather than perpendicular to them as is the case with synchrotron radiation. While this measurement is in principle straightforward, in practice it is not routinely accomplished. Observations at two or more frequencies are needed to determine (and to correct for) the interstellar rotation measure and to demonstrate that the intrinsic polarization is in fact frequency-independent. Another complication is that a pulse is often composed of several identifiable components, some of which can be polarized in the orthogonal mode (a result of propagation effects in the magnetosphere) obscuring the "true" polarization. Furthermore, the pulse itself might not even contain an identifiable core component, being composed instead of emission from random patches within a cone (e.g., Lyne & Manchester 1988; Manchester 1995; Deshpande & Rankin 1999). Accordingly, measurements of $\Psi_0$ are rarely attempted, measurements of $\alpha$ are rarely trusted, and measurements of $\zeta$ are rarely questioned.

In fact, there are several determinations of $\Psi_0$ for the Vela pulsar that are not in particularly good agreement with each other; we review a representative subset here. The original value of Radhakrishnan & Cooke (1969) is $\Psi_0 = 47^\circ$ with an uncertainty of $\approx 5^\circ$. Hamilton et al. (1977) made measurements over several years, all of which are consistent with $\Psi_0 = 64^\circ \pm 1^\circ$. A detailed decomposition into four separate pulse components was performed by Krishnamohan & Downs (1983), in which they concluded that one of the components was polarized in the mode orthogonal to the other three. However, they did not attempt an absolute measurement of the angle $\Psi_0$. Bietenholz et al. (1991) measured $\Psi_0 = 35^\circ$ using the VLA (although this measurement may not be directly comparable, in that it represents a mean value weighted by the degree of linear polarization rather than the value at the center of symmetry of the position angle curve). Thus, while the published values of $\Psi_0$ differ by as much as $30^\circ$, it appears that none is even close to being aligned with the axis of the nebula, and that all are roughly perpendicular to it.

Interestingly, the model of Krishnamohan & Downs (1983) produces a precise (albeit model-dependent) value of the angle between the rotation axis and the line of sight, $\zeta = 55.57 \pm 0.15$: This value agrees well with the inclination angle of our postulated equatorial wind torus to the line of sight derived by fitting an ellipse to the shape of the X-ray features: $\zeta = \cos^{-1} (b/a) = 53.2^\circ$. This striking coincidence gives us courage to pursue the basic physics of the equatorial wind model using the geometry of Figure 8, and even to be so bold as to suggest that all of the radio determinations of $\Psi_0$ for Vela are incorrect by $90^\circ$ because of incorrect mode identification (i.e., perhaps three out of four of the pulse components are actually polarized in the orthogonal mode). In this case, $\Psi_0 = 130^\circ$ (as inferred from the orientation of the X-ray torus), and can be identified with the projected direction of the pulsar rotation axis. Speculations about the true orientation of $\Psi_0$ in pulsars go back to Tademaru (1977), who first discussed the possible alignment between spin axis and proper motion in the context of the radiation rocket hypothesis (Harrison & Tademaru 1975).

6.2. Implications of the Proper Motion

For both the Crab and Vela pulsars, the direction of proper motion (transverse velocity $v_t$) is strikingly close to the projected X-ray symmetry axis of the inferred equatorial wind and polar jetlike structures. The proper motion of the Vela pulsar has been measured with comparable accuracy using both radio interferometry (Bailes et al. 1990) and images from HST (De Luca et al. 2000). The resulting mean value $0.056 \pm 0.004$ yr$^{-1}$ at a position angle of $332^\circ \pm 4^\circ$ is within $8^\circ$ of the axis of the nebula ($\Psi_0 + 180^\circ = 310^\circ$). The transverse velocity $v_t = 65$ km s$^{-1}$ at $d = 250$ pc. The proper motion of the Crab pulsar is $0.018 \pm 0.003$ yr$^{-1}$ at a position angle of $292^\circ \pm 10^\circ$ (Caraveo & Mignani 1999), which corresponds to $v_t = 123$ km s$^{-1}$ at $d = 2000$ pc. The axis of the Crab's toroidal optical and X-ray structure is $299^\circ$ (Hester et al. 1995), only $7^\circ$ from the direction of proper motion. The probability that two such close alignments will occur by chance when drawn from a pair of uncorrelated distributions is 0.7%. We also note that both Vela and the Crab are rather slow moving compared to typical young pulsars; Lyne & Lorimer (1994) found a mean velocity for young pulsars of between 400 and 500 km s$^{-1}$.

If these relationships are not a coincidence, then they may be understandable in terms of the scenario proposed by Spruit & Phinney (1998), who suggested that the rotation axes and space velocities of pulsars could be connected through the nature of the "kicks" given to neutron stars at birth. Spruit & Phinney argue that the rotation rate of the progenitor stellar core is too slow in the few years before the formation of the neutron star for pulsar spin periods to be explained by simple conservation of angular momentum during core collapse. Instead, it is likely that the same asymmetric kicks (whatever the cause) that are responsible for the space velocities of pulsars, are also the dominant contributors to their initial spin rates. If neutron stars acquire their velocities from a single momentum impulse, then their rotation axes should be perpendicular to their space velocities. If, however, they receive many random, independently located impulses over time, as might result from convection
which leads to anisotropic neutrino transport or anisotropic fallback, then their velocities and spins should be uncorrelated in direction. However, if those multiple thrusts are not short in duration relative to the resulting rotation period, it is possible that kicks applied perpendicular to the rotation axis will average out, while those that are along the rotation axis will accumulate. In the latter case, particularly germane for short rotation periods, the space velocity will be preferentially aligned with the rotation axis. This is actually the scenario preferred by Spruit & Phinney, for which they appeal to long duration (several-thousand) thrusts that could result from the effect of parity violation in neutrino scattering in a magnetic field.

Thus, in the context of the above models, we speculate that the Crab and Vela pulsars have relatively low space velocities because the components of their kicks perpendicular to their rotation axes were averaged out and, as a result, their final space velocities were aligned closely with their spin axes (cf. Lai, Chernoff, & Cordes 2001). We also note that alignment of the spin axis and proper motion is a natural consequence of the Harrison & Tademaru (1975) photon rocket acceleration mechanism. With the recent revision of Lai et al. (2001), an initial spin period as long as 6 ms suffices to account for the measured transverse component of the velocity in the maximum acceleration case. Since pulsars that rotate most rapidly at birth are also the ones most capable of powering synchrotron nebulae, either scenario might argue for a stronger than average correlation of the axes of such nebulae with the proper motion directions of their parent pulsars.

Before the toroidal arcs in the Vela nebula were resolved by Chandra, Markwardt & Ogleman (1998) interpreted the overall shape of the nebula as seen by the ROSAT HRI as being determined by the space velocity of the pulsar. In particular, they noted that the outline of the nebula, which is dominated by the bean shape, resembles a bow shock whose symmetry axis at position angle 295° is identical to the direction of the radio proper motion (297°). However, the rather uniform and gently curved outline of this structure could be reconciled with the sharper, asymmetric curve expected of a bow shock only if the space velocity were nearly along the line of sight. This requirement, coupled with the large absolute velocity needed for the pulsar to exceed the speed of sound in the surrounding supernova remnant forced Markwardt & Ogleman to conclude that the velocity vector is less than 22° from the line of sight. This notion of the compact Vela nebula as a bow shock also led Chevalier (2000) to a considerably different model of its physics. As we shall argue below, the Chandra observations do not support such a bow-shock interpretation, but instead favor a physical model in which the entire structure is a synchrotron nebula similar in physics to the Crab, but with an interesting difference in one of its parameters.

6.3. A Physical Model of the Nebula

In the basic Kennel & Coroniti (1984a, 1984b) model of the Crab Nebula, a relativistic pulsar wind terminates in an MHD shock, which produces the nonthermal distribution of particles and postshock magnetic field that comprise the synchrotron nebula. Although the pulsar wind is assumed to carry the entire spin-down luminosity of the pulsar, specific wind parameters such as the particle velocity and the fraction of the power carried in magnetic fields are not known a priori. Rather, they are inferred by using the results of the shock jump conditions to model the spectrum of the Crab Nebula and also to match the observed radii of the MHD shock and the outer boundary of the Nebula. It is necessary to adopt outer boundary conditions; a natural one is to require the final velocity of the flow to match the observed expansion velocity of the Nebula, although it is not clear how this outer boundary condition is communicated to the inner MHD shock which is a factor of 20 smaller in radius.

A peculiar result of the Kennel & Coroniti model is that the wind magnetization parameter \( \sigma \) is required to be \( \approx 0.003 \) in the Crab. That is, the fraction of power carried in \( B \) field is much less than 1%. Such a small fraction is required in order that sufficient compression occurs in the shock to convert the bulk flow energy into random energy of the particles so that they can radiate the observed synchrotron luminosity. Highly magnetized shocks produce less radiation because there is little energy dissipation and, for the Crab, would supply an insufficient number of X-ray emitting particles. Furthermore, highly magnetized shocks are weak because all of the energy dissipation allowed by the jump conditions is used in making the small increase in \( B \) field needed to conserve magnetic flux. The postshock flow velocity is still relativistic.

The reason that such a small magnetization is difficult to understand is that the pulsar magnetic field energy carried out to the radius of the shock in the simplest MHD wind should be of the same order of magnitude as the spin-down power, as the following argument shows. The total wind energy flux at the shock is

\[
\frac{\dot{I} \dot{\Omega}}{4\pi R_s^4} = \left( \frac{B_s^2 R_s^6 \Omega_s^4}{6c^3} \right) \frac{1}{4\pi R_s^4} = \frac{B_s^2 R_s^4 \Omega_s^4}{24\pi c^3 R_s^4},
\]

where the transported pulsed magnetic field \( B_s \) at the location of the shock is

\[
B_s \approx \frac{B_s}{2} \left( \frac{R_s}{r_{ic}} \right)^3 \frac{r_{ic}}{r_s} = \frac{B_s}{2} \frac{R_s^3 \Omega_s^2}{c^2 r_s},
\]

where \( r_{ic} \) is the radius of the light cylinder defined as \( r_{ic} = c/\Omega \) and \( R \) is the neutron star radius at which the magnetic field strength is \( B_r \). Therefore, the magnetic energy flux at \( r_s \) is

\[
c^\frac{2}{8\pi} \frac{B_s^2 R_s^4 \Omega_s^4}{32\pi c^3 r_s^2},
\]

comparable to the value in equation (2). While various solutions to this paradox for the Crab have been proposed, we argue here that the dimensions and spectrum of the Vela synchrotron nebula are in much better accord with \( \sigma \approx 1 \).

A basic application of the pulsar wind model to the Vela synchrotron nebula was made by de Jager, Harding, & Strickman (1996) in conjunction with their detection of Vela with the Oriented Scintillation Spectrometer Experiment (OSSE) on the Compton Gamma-Ray Observatory. We summarize their conclusions here. De Jager et al. noted that the unpulsed part of the hard X-ray spectrum extends with power-law photon index \( \Gamma = 1.73 \) up to 0.4 MeV, which implies that the synchrotron nebula radiates \( \sim 2 \times 10^{34} \left( E_{max}/0.4 \text{ MeV} \right)^{0.27} \text{ ergs s}^{-1} \), or only \( \sim 3 \times 10^{-3} \) of the pulsar spin-down power. The absence of an observed spectral break limits the residence time \( \tau_e \) of the electrons in the nebula that radiate in this energy range to less than their
such a large pulsar velocity is hardly likely, since the sound speed in the hot con\-fining medium. In the first place, the velocity of the pulsar which necessarily exceeds the speed of light, the wind may remain relativistic across the distance from the pulsar. Indeed, equation (3) predicts a preshock field of $\sim 1.5 \times 10^{-4} \, G$, consistent with the limit derived above; thus, the wind may remain relativistic across the nebula, which extends a factor of 2 in radius beyond the shock.

Such a synchrotron nebula is in approximate pressure balance with the surrounding supernova remnant. Markwardt & Og\-leman (1997) found by fitting a two-temperature thermal model to the ASCA spectrum of the inner remnant that the thermal pressure is $\approx 8.5 \times 10^{-10} \, \text{ergs cm}^{-3}$. This compares well with the pulsar wind pressure at $r, P_{\text{w}}/(4\pi r^2 c) = 5.2 \times 10^{-10} \, \text{ergs cm}^{-3}$. The entire compact X-ray nebula, then, is consistent with being powered by a strongly magnetized pulsar wind shock whose still relativistic downstream flow is confined by the Vela SNR. The modest production of synchrotron electrons in such a shock naturally explains the very low value of $L_{\text{syn}}/L_{\text{x}}$ observed.

In summary, the match between the nebular field upper limit derived from the OSSE data and the value found from equation 3 using our measured value of $v_{\rho}$, and the fact that the pressure corresponding to this field strength matches the confining thermal pressure of the X-ray gas, leads us to conclude that our high-magnetization model of the Vela nebula is both self-consistent and plausible. Thus, in a sense, Vela may be a more natural realization of the Kennel & Coroniti model than is the Crab, for which the model was created. While this appears to be a quite satisfactory model, certain details are subject to additional constraints. First, since the radiation from the nebula is so inefficient, energetic electrons must be able to escape to much larger distance scales before losing all of their energy to synchrotron radiation. Indeed, the radio luminosity of the 100 $'$ Vela X region, $\sim 8 \times 10^{32} \, \text{ergs s}^{-1}$, could be one manifestation of the escaping electrons. Second, there is a natural upper energy to the synchrotron spectrum when the electron gyroradius $r_{\rho}$ exceeds the radius of the nebula. Since

$$r_{\rho} = 1.6 \times 10^{17} \left( \frac{B}{10^{-4} \, G} \right)^{-3/2} \left( \frac{E}{100 \, \text{MeV}} \right)^{1/2} \text{cm}, \quad (5)$$

this is not a restrictive limit. Thus, we find the de Jager et al (1996) description of the Vela synchrotron nebula basically in accord with the Chandra observations.

An alternative picture was proposed by Chevalier (2000) based on the bow-shock interpretation of Markwardt & Og\-leman (1998) and a simplified version of the Kennel & Coroniti model. If the Vela synchrotron nebula is energized by a shock between a relativistic pulsar wind and the surrounding supernova remnant, then the bow shock travels at the velocity of the pulsar $v_{\rho}$, which necessarily exceeds the sound speed in the hot confining medium. In the first place, such a large pulsar velocity is hardly likely, since the thermal sound speed $(dP/d\rho)^{1/2} \approx 875 \, \text{km s}^{-1}$ in the Vela SNR according to the ASCA spectral analysis of Markwardt & Og\-leman (1997). Markwardt & Og\-leman (1998) assumed that $v_{\rho} \geq 260 \, \text{km s}^{-1}$ is sufficient.

An additional consequence of this scenario, however, is that the residence time of the emitting particles in the nebula is much longer than in the de Jager et al. model, $\tau_{\rho} \sim r/v_{\rho}$ instead of $\tau_{\rho} \sim \sqrt{2\tau}/c$. Consequently, Chevalier (2000) was forced to assume $v_{\rho} \sim 10^9 \, \text{yr}$, requiring an extremely small magnetization parameter, $\sigma < 10^{-4}$, in order that the model's radiated luminosity not exceed the observed X-ray luminosity. We consider that the physical difficulties of the bow-shock interpretation, in conjunction with the new Chandra evidence that the X-ray morphology is dominated by a pair of arcs resembling similar toroidal structures in the Crab Nebula, strongly disfavor such a model. Chevalier's revised estimate of $\sigma$ is 0.06 after adopting our assumption of relativistic postshock flow. Determining whether $\sigma$ is actually of order unity or not will require more detailed modeling.

While our model provides a plausible explanation for the toroidal arcs and outer nebula, it says nothing about the other striking feature of the image, the jet and counterjet. The jet is 10 $'$ long, giving it a deprojected length of $4.1 \times 10^{16} \, \text{cm}$. At $v = 65 \, \text{km s}^{-1}$, it has taken the pulsar ~200 $\text{yr}$ to travel this distance. The synchrotron lifetime of electrons producing $1 \, \text{keV}$ emission ranges from 5 to 40 $\text{yr}$ for the fields of $(1-4) \times 10^{-4} \, \text{G}$ discussed above. Thus, the jet is not simply a wake, but must be supplied with particles from the pulsar (as the existence of the counterjet also suggests). The luminosity required is modest: $L_{\text{x}} \sim 5 \times 10^{30} \, \text{ergs s}^{-1}$, roughly 1% of the nebular luminosity and less than $10^{-6}E$. While we have no scenario to propose, the existence of such features in both Vela and the Crab suggests understanding their origin may prove useful in modeling particle flow from young pulsars.

6.4. Thermal Emission Constraints on the Neutron Star Interior

Several models have been advanced to explain the sudden apparent change in the moment of inertia of a glitching neutron star. Originally, starquakes, resulting from the release of strain in the stellar crust induced by the change in the equilibrium ellipticity of the star as it slows, were invoked (Ruderman 1969). But the magnitude and frequency of the Vela glitches could not be explained by this model, and a picture involving the sudden unpinning from the inner crust of superfluid vortices in the core of the star became the dominant paradigm (Anderson & Itoh 1975). Observations of the relaxation of the star back toward its original spin-down rate suggest that ~1% of the star's mass is involved in the event (Alpar et al. 1988; Ruderman, Zhu, & Chen 1998), implying a total energy release of $\sim 10^{42} \, \text{ergs}$.

The fate of this energy is unclear and predictions concerning the observable consequences vary widely. The timescale for energy deposited at the base of the crust to diffuse outward, the fraction of the surface area whose temperature will be affected, and the secondary effects, such as the rearrangement of the surface magnetic field which could dump energy into the surrounding synchrotron nebula, are all uncertain by one or more orders of magnitude.

Our stringent upper limit on a change in the X-ray flux from the neutron star within the 35 days following the glitch
allows us to begin setting meaningful constraints on the parameters of the neutron star and the glitch. Seward et al. (2000) provide a concise introduction to the published models for the thermal response of the stellar surface to a glitch generated by the sudden unpinning of superfluid vortex lines deep in the star (van Riper, Epstein, & Miller 1991; Chong & Cheng 1994; Hirano et al. 1997; Cheng, Li, & Suen 1998), and we need not repeat it here. We follow their approach in deriving parameter limits from the models.

The allowable change in the pulsar’s flux derived in § 4 corresponds to a fractional change in the surface temperature of < 0.2%. For timescales of ~30 days, we are primarily sensitive to stars with small radii (R < 14 km) which correspond to soft or moderate equations of state. Using Figure 2 of van Riper et al. (1991), we can set a limit of $E_{\text{glitch}} < 10^{42}$ ergs independent of the depth of occurrence within the inner crust. For depths corresponding to local densities $\rho < 10^{13}$ gm cm$^{-3}$, $E_{\text{glitch}} < 3 \times 10^{44}$ ergs, and for shallow events ($\rho \sim 10^{12}$ gm cm$^{-3}$), the glitch energy must be less than $10^{41}$ ergs. For the softest equation of state used by Hirano et al. (1997) corresponding to a 1.4 $M_\odot$ star with a radius of 11 km, glitch depths shallower than $10^{13}$ gm cm$^{-3}$ require an energy deposition of less than $10^{41}$ ergs. With observations of similar sensitivity ~300 and ~3000 days after the event, we could rule out $E_{\text{glitch}} \sim 10^{43}$ ergs for all equations-of-state and glitch-depth combinations, and require $E_{\text{glitch}} < 10^{41}$ ergs for soft and moderate equations of state for depths $\rho < 10^{13.5}$ gm cm$^{-3}$. Note that on the longest timescales (appropriate for deep glitches in stars with very stiff equations of state), Vela may be an inappropriate target for constraining glitch parameters, since another glitch may well have occurred before the thermal pulse has peaked; indeed, if even 10% of the glitch energy appears as surface thermal emission, the total X-ray luminosity can be powered by events with $\langle E_{\text{glitch}} \rangle \sim 2 \times 10^{41}$ ergs.

7. SUMMARY AND CONCLUSIONS

We have presented a high-resolution X-ray image of the Vela pulsar revealing a highly structured surrounding nebula. We interpret the nebula’s morphology in the context of the shocked MHD wind model developed by Kennel & Coroniti (1984a, 1984b) for the Crab Nebula and find that the Vela nebula allows a large magnetization parameter, possibly of order unity. This picture also provides a natural explanation for the low $L_x/E$ of the Vela nebula. We speculate that the alignments of the symmetry axes of the Crab and Vela nebulae with the proper motion vectors of their respective pulsars should be expected preferentially in rapidly spinning young pulsars with surrounding X-ray synchrotron nebulae if the causal connection between spin and proper motion suggested by Spruit & Phinney (1998) is correct.

Our two observations, centered 3.5 and 35 days after the largest glitch yet recorded from the pulsar, allow us to set significant limits on changes in the pulse profile and stellar luminosity that can be used to constrain glitch model parameters. We find that, for soft and moderate equations of state, the glitch energy must be less than $10^{42}$ ergs; an additional observation a year following the event will substantially tighten this constraint. An apparent change in the nebula surface brightness between the two observations may or may not be a consequence of the glitch; the implied velocity of the disturbance, assuming that it originates near the pulsar, is $\sim 0.7c$, similar to the velocity inferred from changes in the Crab Nebula wisps.

Future observations with Chandra and XMM can be used to gain further insight into the structure of the neutron star and its surrounding nebula. An observation $\sim 1.5$ yr after the glitch, now scheduled, will further constrain models for the glitch and the parameters of the neutron star. Additional HRC observations will also be required to decide whether the nebula changes reported here are a consequence of the glitch or whether they occur routinely in response to instabilities in the pulsar’s relativistic wind, as appears to be the case in the Crab Nebula. Data from the EPIC PN camera on XMM will yield spectral clues helpful in understanding the complex pulse profile, while either EPIC or Chandra’s ACIS could be used to search for spectral changes caused by synchrotron energy losses and/or internal shocks in the nebula.

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