THE X-RAY SPECTRUM OF THE VELA PULSAR RESOLVED WITH THE CHANDRA X-RAY OBSERVATORY

G. G. Pavlov, V. E. Zavlin, D. Sanwal, V. Burwitz, and G. P. Garmire
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ABSTRACT

We report the results of the spectral analysis of two observations of the Vela pulsar with the Chandra X-Ray Observatory. The spectrum of the pulsar does not show statistically significant spectral lines in the observed 0.25–8.0 keV band. Similar to middle-aged pulsars with detected thermal emission, the spectrum consists of two distinct components. The softer component can be modeled as a magnetic hydrogen atmosphere spectrum—for the pulsar magnetic field \( B = 3 \times 10^{12} \text{ G} \) and neutron star mass \( M = 1.4 M_{\odot} \), and radius \( R = 13 \text{ km} \), we obtain \( T_{\text{eff}} = 0.68 \pm 0.03 \text{ MK} \), \( L_{\text{bol}} = (2.6 \pm 0.2) \times 10^{32} \text{ erg s}^{-1} \), and \( d = 210 \pm 20 \text{ pc} \) (the effective temperature, bolometric luminosity, and radius are as measured by a distant observer). The effective temperature is lower than that predicted by standard neutron star cooling models. A standard blackbody fit gives \( T_{\text{eff}} = 1.49 \pm 0.04 \text{ MK} \), \( L_{\text{bol}} = (1.5 \pm 0.4) \times 10^{32} \text{ ergs s}^{-1} \) (\( d = 250 \text{ pc} \) is the distance in units of 250 pc); the blackbody temperature corresponds to a radius \( R = (2.1 \pm 0.2) \times 10^{13} \text{ km} \), much smaller than realistic neutron star radii. The harder component can be modeled as a power-law spectrum, with parameters depending on the model adopted for the soft component: \( \gamma = 1.5 \pm 0.3, L_X = (1.5 \pm 0.4) \times 10^{33} \text{ ergs s}^{-1} \) and \( \gamma = 2.7 \pm 0.4, L_X = (4.2 \pm 0.6) \times 10^{33} \text{ ergs s}^{-1} \) for the hydrogen atmosphere and blackbody soft component, respectively (\( \gamma \) is the photon index; \( L_X \) is the luminosity in the 0.2–8 keV band). The extrapolation of the power-law component of the former fit toward lower energies matches the optical flux at \( \gamma = 1.35–1.45 \).

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

1. INTRODUCTION

X-ray observations of rotation-powered pulsars with the Einstein, EXOSAT, and, particularly, ROSAT observatories have established (Ogelman 1995) that at least three middle-aged pulsars, PSR B0656+14, B1055−52, and Geminga, with characteristic ages of \( 10^8−10^9 \) yr, show thermal soft X-ray radiation, with temperatures 0.5–1 MK, interpreted as emitted from the surfaces of cooling neutron stars (NSs). Investigation of this radiation is needed to understand the NS cooling history and to study the properties of the NS surface layers. Further observations with the ASCA observatory have confirmed that, as it had been suggested from the ROSAT data, the spectra of these pulsars at higher energies (\( \geq 1.5–2 \text{ keV} \)) are dominated by nonthermal, power-law components, with photon indices \( \gamma \approx 1.2–2.0 \), presumably generated in the NS magnetospheres (e.g., Wang et al. 1998). Studying the power-law components is important in order to understand the mechanisms of the multiwavelength pulsar radiation.

In addition to these three pulsars (dubbed “The Three Musketeers” by Becker & Trümper 1997), the younger Vela pulsar \( \tau = 11 \text{ kyr}, P = 89.3 \text{ ms}, E = 6.9 \times 10^{36} \text{ ergs s}^{-1} \), \( B \sim 3 \times 10^{12} \text{ G} \) has been mentioned as a possible source of thermal radiation, based on the softness of its spectrum (e.g., Ogelman 1995). Ögelman, Finley, & Zimmermann (1993) obtained acceptable fits of its ROSAT spectrum with a power-law (PL) model with \( \gamma \approx 3.3 \) and a blackbody (BB) model of temperature \( T_{\text{eff}} = 1.7 \text{ MK} \). The PL slope is much steeper than typical nonthermal spectra of young and middle-aged pulsars. The temperature and luminosity inferred from the BB fit correspond to an effective radius of emitting region about 1.3 km at a distance \( d = 250 \text{ pc} \) (Chu, Sembach, & Danks 1999). A two-component fit with a BB + PL model yielded a lower temperature, 1.3 MK, a larger radius, 3 km at 250 pc, and a surprisingly small photon index, \( \gamma \approx 0 \) (Ögelman 1995).

Page, Shibanov, & Zavlin (1996) fitted the same spectrum with the NS hydrogen atmosphere models (Pavlov et al. 1995) and obtained a lower effective temperature and a larger \( R : T_{\text{eff}} \approx 0.8 \text{ MK}, d = 300 \text{ pc} \) for \( R = 250 \text{ km} \) \( \gamma = (1 - 2GM/Rc^2)^{1/2} \) is the gravitational redshift parameter.

The true spectrum of the soft X-ray pulsar radiation (not to mention the presence of two components) has remained elusive because angular resolution of the X-ray telescopes has been too low to separate the pulsar from the bright pulsar-wind nebula (PWN) of about 2° diameter around the pulsar (Harrnen et al. 1985; Markwardt & Ögelman 1998). The subarcsecond resolution of the Chandra X-Ray Observatory (Chandra) provides the first opportunity to resolve the pulsar spectrum. The high-energy resolution of the Chandra grating spectrometers allows one to address another important problem: if the soft component of the pulsar radiation indeed originates from the NS surface layers (an atmosphere), it may show spectral features that can be used to investigate chemical composition, gravity, and magnetic field of the surface layers. In this Letter we present first results on the X-ray spectrum of the Vela pulsar obtained with Chandra.

2. OBSERVATIONS AND SPECTRAL ANALYSIS

To investigate the low-energy part of the pulsar spectrum with high energy resolution, the spectrum dispersed with the Low-Energy Transmission Grating (LETG; Brinkman et al. 2000) was imaged on the Spectroscopic Array of the High Resolution Camera (HRC-S; Murray et al. 1997). The 25.6 ks observation was taken on 2000 January 28. We analyzed the level 2 data files produced by the standard pipeline processing (version 11.1). The dispersed LETG spectrum (dispersion 1.148 Å mm⁻¹) was extracted from a strip of a 3.6° (0.18 mm) width in the cross-dispersion direction, which contains about 90% of source events dispersed at a given wavelength (see Chandra Propos-
ers’ Observatory Guide [POG], version 3.0).3 Since the zero-order and dispersed radiation from the PWN contaminates the dispersed pulsar spectrum at $\lambda < 5–6$ Å and the plate background dominates at $\lambda > 50–60$ Å, we chose the range $\lambda = 6–50$ Å ($E = 0.25–2.0$ keV) for spectral analysis. The background was taken from boxes between 10° and 30° from the center of the source spectrum in the cross-dispersion direction. To search for spectral lines, we binned the extracted source-plus-background and background spectra in 0.02 Å bins (intrinsic resolution of the instrument in the chosen wavelength range is $\approx 0.05$ Å). We used groups of 10–20 sequent bins to estimate the deviation in number of source counts in each bin of a given group from the mean value in the group. The maximum deviation was found to be at a 2.7 σ level. Therefore, we conclude that the LETG spectrum of the Vela pulsar shows no statistically significant spectral lines.

For further analysis, we removed the contribution of the higher orders using a “bootstrap” method (see Chandra POG) and obtained the first-order pulsar spectrum (91% of the total dispersed data), with a source count rate $281 \pm 6$ ks$^{-1}$ (312 $\pm 6$ ks$^{-1}$ after correcting for the extraction efficiency) in the 0.25–2.0 keV range. To examine various continuum models, we grouped the counts in 162 energy bins with at least 30 source counts per bin and fitted the models making use of the first-order effective area.4 We found that a simple PL model requires a large photon index $\gamma = 4.1–4.3$ and an implausibly high hydrogen column density $n_{\text{H}} \geq 10^{20}$ cm$^{-2} = 9.1–9.3$, and the best-fit model spectrum exceeds the observed one at $E \geq 1.2$ keV. The spectrum fits much better with thermal models (blackbody, NS hydrogen atmosphere), but the observed spectrum somewhat exceeds the model spectra at the highest energy channels (1.5–2.0 keV), which indicates the presence of a second component with a harder spectrum.

To search for the harder component, we used the archived 37.0 ks observation5 (pipeline processing version 8.2) taken on 1999 October 11–12 with the Spectroscopic Array of the Advanced CCD Imaging Spectrometer (ACIS-S; G. P. Garmire et al. 2001, in preparation) in continuous clocking (CC) mode, which allows timing at the expense of one dimension of spatial resolution (along the CCD chip columns). This observation was carried out with the High-Energy Transmission Grating, which, in principle, gives a high-resolution source spectrum at higher energies. However, the dispersed spectra, integrated along the chip columns in the CC mode, are severely contaminated by the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV. The pipeline-processed data are not corrected properly for the background, which strongly complicates their analysis. Therefore, we use only the zero-order image (on chip S3), which provides a pulsar spectrum with resolution of about 0.1–0.2 keV.

For the analysis of the pulsar spectrum, we extracted counts from a one-dimensional 2’5 wide aperture. The PWN background was found by interpolating between the adjacent regions on both sides of the pulsar. The estimated source count rate is $288 \pm 4$ ks$^{-1}$, or $320 \pm 5$ ks$^{-1}$ after correcting for the 90% fraction of point-source counts in the one-dimensional aperture. Because of the dither, the pulsar and the PWN were imaged on two nodes of the chip (node 0 and node 1), which use different amplifiers and have different gains and responses. Therefore, we consider the two nodes as separate instruments while fitting the spectra. Since the ACIS response below 0.5 keV is still poorly known, we discarded the corresponding counts. We find that the ACIS spectrum of the pulsar does not fit with one-component models (BB, PL, NS atmosphere), but it fits fairly well with two-component models (e.g., a PL plus a thermal component).

The spectral parameters obtained from fitting the separate LETG and ACIS spectra, as well as from the combined fit, are presented in Table 1. While fitting the LETG spectra, one cannot reliably find the parameters of the harder component, so we fix them at the values found from the ACIS fits. Similarly, the hydrogen column density $n_{\text{H}}$ cannot be determined reliably from the ACIS spectra with low-energy counts discarded, so we fix $n_{\text{H}}$ at the value found from the LETG fit. We see from Table 1 that the spectral parameters obtained from the separate

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3 See http://asc.harvard.edu/udocs/docs/docs.html.
4 Version of 2000 October 31; http://asc.harvard.edu/cal/Links/Letg/User/Hrc_QE/EA.
5 Preliminary results of this observation were presented by Stage et al. (2000).
6 Preliminary results of this observation were presented by Pavlov et al. (2000).
fits and from the combined (LETG plus ACIS) fit (see Fig. 2) are generally consistent with each other; the differences can be attributed to systematic errors caused by inaccuracies of the HRC/LETG and ACIS responses.

3. DISCUSSION

Thanks to the superb angular resolution of the Chandra telescope, we are able to resolve the pulsar from its PWN and investigate its spectrum. Our analysis proves that the pulsar soft X-ray emission, at $E \lesssim 1.8$ keV, is indeed dominated by a soft thermal component, so that the three Musketeers (see § 1) are now joined by d’Artagnan—the Vela pulsar. The parameters of the soft thermal component are drastically different for the BB fit ($T_{bb} = 1.4$–1.5 MK, $R_{bb} = (1.9$–$2.4) d_{250}$ km) and the hydrogen atmosphere fit [$T_{atm} = 0.65$–0.71 MK, $R^* = (14$–$17)d_{250}$ km]. For the BB model, one might assume that the observed radiation is emitted from small hot spots (e.g., polar caps heated by relativistic particles produced in the pulsar magnetosphere), whereas the $R/ld$ ratio obtained in the H atmosphere fit implies radiation emitted from the entire NS surface, with a lower temperature.

Rigorously speaking, the surface (atmosphere) of an NS is not a blackbody, but a BB spectrum could mimic the spectrum of a heavy-element (e.g., iron) atmosphere if it is observed with low spectral resolution (Rajagopal, Romani, & Miller 1997). However, a lack of significant spectral lines in the LETG spectrum hints that there are no heavy elements in the radiating atmosphere layers (although the exposure was too short to take full advantage of the high spectral resolution).

Because of the enormous NS gravity, the outer layers of the NS atmosphere should be comprised of the lightest element present. If, in the absence of H, the NS has an He atmosphere, we still expect spectral features in the observed range if the magnetic field is $\sim 3 \times 10^{12}$ G. In such a field the He atmosphere is not completely ionized even at $T \sim 1$ MK because of the large increase of the ionization potentials (Ruder et al. 1994); $I \approx 0.63$ keV for the He$^+$ ion ($\sim 0.5$ keV if we account for the gravitational redshift). The fact that we see neither a photoionization edge around $E \sim 0.5$ keV nor spectral lines at somewhat lower energies suggests that there is no He in the atmosphere. On the other hand, if even a small amount of H is present in the surface layers, it should be strongly ionized ($I \approx 0.23$ keV at $B = 3 \times 10^{12}$ G), and, if even some neutral fraction is present, it will not show spectral features at $E \gtrsim 0.17$ keV. Thus, the featureless spectrum we observe is consistent with the hypothesis of a hydrogen NS atmosphere. The observed part of the spectrum decreases with $E$ slower than the ideal Wien spectrum because the radiation at higher energies comes from hotter layers (the H opacity strongly decreases with frequency). As a result, BB fits to the H atmosphere spectra give a temperature higher than the true effective temperature and an area smaller than the true emitting area (e.g., Pavlov et al. 1995). If we adopt the H atmosphere hypothesis, the effective temperature of the Vela pulsar is below the predictions of the so-called standard models of the NS cooling (e.g., Tsuruta 1998), even if the pulsar is a factor of 2–3 older than its characteristic age (Lyne et al. 1996).

An important result of our analysis is the detection of the hard spectral component. Because of the small number of high-energy photons detected, both the PL and thermal fits of this component are formally acceptable. However, the thermal fits yield an implausibly small size, $\sim 10$ m, and a very high temperature, $\sim 10$ MK, and extrapolation of the model spectrum to lower and higher energies is inconsistent with optical and hard

| Parameter | HRC-S/LETG | ACIS-S | Combined |
|-----------|------------|--------|----------|
| $T_{bb}$ (MK) | 1.47 ± 0.06 | 1.51 ± 0.03 | 1.49 ± 0.04 |
| $R_{bb}$ (km) | 2.2 ± 0.3 | 2.0 ± 0.2 | 2.1 ± 0.2 |
| $L_{bb}$ ($\times 10^{37}$ ergs s$^{-1}$) | 1.6 ± 0.3 | 1.4 ± 0.3 | 1.5 ± 0.4 |
| $\gamma$ | (2.2) | 2.2 ± 0.4 | 2.7 ± 0.4 |
| $N$ ($\times 10^{24}$ photons (cm$^{-2}$ s$^{-1}$) keV)$^{-1}$ | (6.0) | 6.0 ± 1.3 | 10.7 ± 1.0 |
| $L_{\nu,bb}$ ($\times 10^{37}$ ergs s$^{-1}$) | (1.8) | 2.2 ± 0.3 | 4.2 ± 0.6 |
| $n_{e}$ ($\times 10^{26}$ cm$^{-3}$) | 1.7 ± 0.3 | (1.7) | 2.2 ± 0.3 |
| $\chi^2$ [degrees of freedom] | 1.0 [159] | 1.3 [113] | 1.1 [274] |

H Atmosphere + Power Law

| Parameter | HRC-S/LETG | ACIS-S | Combined |
|-----------|------------|--------|----------|
| $T_{atm}$ (MK) | 0.67 ± 0.03 | 0.69 ± 0.03 | 0.68 ± 0.03 |
| $d$ (pc) | 200 ± 25 | 220 ± 20 | 210 ± 20 |
| $L_{atm}$ ($\times 10^{37}$ ergs s$^{-1}$) | 3.9 ± 0.3 | 3.7 ± 0.3 | 3.8 ± 0.3 |
| $\gamma$ | (1.4) | 1.4 ± 0.3 | 1.5 ± 0.3 |
| $N$ ($\times 10^{24}$ photons (cm$^{-2}$ s$^{-1}$) keV)$^{-1}$ | (2.3) | 2.3 ± 0.7 | 2.5 ± 0.6 |
| $L_{\nu,atm}$ ($\times 10^{37}$ ergs s$^{-1}$) | (0.5) | 1.3 ± 0.4 | 1.5 ± 0.4 |
| $n_{e}$ ($\times 10^{26}$ cm$^{-3}$) | 3.0 ± 3.0 | (3.0) | 3.3 ± 0.3 |
| $\chi^2$ [degrees of freedom] | 0.7 [159] | 1.2 [113] | 1.0 [274] |

Note. — The values in parentheses were fixed during fitting. The radius $R_{bb}$ and the luminosities $L_{bb}$ and $L_{\nu,bb}$ are related to $d = 250$ pc. The nonthermal luminosities $L_{\nu,atm}$ are in the bands 0.2–2, 0.5–8, and 0.2–8 keV for the LETG, ACIS-S, and combined spectra, respectively. The quantities $\gamma$ and $N$ are the photon index and normalization constant of the power-law component; $dN/dE = N E^{-\gamma}$, $E$ in units of keV. The hydrogen atmosphere models were calculated for $B = 3 \times 10^{12}$ G, $M = 1.4 M_{\odot}$, $R = 10$ km ($g_*=0.766$, $R^* = 13.05$ km).

Note: $T_{bb}$ and $R_{bb}$ are the temperature and the radius given by the standard BB fits; we use the superscript “*” by analogy with the case of atmosphere fits, to emphasize that in both cases the quantities are given as measured by a distant observer. It should be noted that $T_{bb}$ and $R/ld$’d very weakly depend on the input parameters of the atmosphere models (Zavlin, Pavlov, & Trümper 1998).
X-ray observations. Therefore, we favor the nonthermal interpretation of the hard component: a PL ($\gamma = 1.2$–1.8 if the H atmosphere model is adopted for the soft component) that dominates at $E \approx 1.8$ keV. With this interpretation, the overall X-ray spectrum of the Vela pulsar is quite similar to those of the Three Musketeers, which show the nonthermal component dominating above 1.5–2.0 keV. It is interesting that the ratio of the nonthermal X-ray luminosity ($L_{\text{X}} = 4\pi d^2 F_\text{X}$) to the spin-down energy loss rate, $L_{\text{X}}/E = (1.7–2.6) \times 10^{-5}$ in the 0.2–8.0 keV range, is much smaller than $L_{\text{X}}/E \sim 10^{-3}$ for the majority of X-ray–detected pulsars (Becker & Trümper 1997). Thus, luckily for us, the magnetosphere of the Vela pulsar is very underluminous in the X-ray range—if its $L_{\text{X}}/E$ were as high as for other pulsars, the thermal radiation would be undetectable in the phase-integrated spectrum.

Since the Vela pulsar has been detected in the optical and gamma-ray ranges, where its radiation is certainly nonthermal, it is illuminating to compare its X-ray nonthermal spectrum with those in the other ranges. Figure 3 shows the energy flux spectrum of the pulsar from optical to gamma rays. We see that extrapolation of the PL spectrum obtained in the atmosphere + PL fit matches fairly well with the optical and hard X-ray (soft gamma-ray) time-averaged fluxes. On the contrary, the slope of the PL component in the BB + PL fit is too steep to be consistent with the optical and gamma-ray data, which is an additional argument in favor of the H atmosphere model. Moreover, if we assume that the spectrum has the same slope in the optical through X-ray range, we can include the optical points in the fit for the PL component, which constrains the photon index very tightly: $\gamma = 1.35–1.45$.

In the present Letter we analyze only the phase-integrated spectra. Energy-integrated light curves, with at least three peaks per period, have been observed with the Chandra HRC-I detector (Pavlov et al. 2000; Helfand, Gotthelf, & Halpern 2001). Phase-resolved spectral analysis could provide much more information about the pulsar. For instance, we should expect that the pulsed fraction and pulse shapes (and, perhaps, even the number of peaks per period) are quite different at energies below and above 1.8 keV because of the different emission mechanisms. However, such an analysis would require a factor of 10 more pulsar photons than the 16,000 photons collected in the described observations.

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