XMM-NEwTON OBSERVATIONS OF THE VELA PULsAR

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ABSTRACT

We present spectral analysis from \textit{XMM-Newton} observations of the Vela pulsar. We analyzed thermal emission from the pulsar dominating below $\sim 1$ keV since extracted spectra are heavily contaminated by nebular emission at higher energy. Featureless high-resolution spectra of the Reflection Grating Spectrometer aboard \textit{XMM-Newton} suggest the presence of a hydrogen atmosphere, as previously indicated by \textit{Chandra} results. Both the temperature and radius are consistent with those values deduced from \textit{Chandra}. The derived \textit{Chandra} and \textit{XMM-Newton} temperature of $T^\infty \simeq (6.4-7.1) \times 10^5$ K at its age of $\sim 10^4$ years is below the standard cooling curve.

INTRODUCTION

The Vela pulsar is one of the best-studied pulsars in the radio band. It has an 89 millisecond period and the spin-down parameters indicate that the Vela pulsar is about $10^4$ years old with magnetic field $3 \times 10^{12}$ G. Nevertheless, multi-wavelength observations in the past two decades showed the Vela pulsar is a strong source at all wavelengths from the radio to the gamma-ray band. In the X-ray band, thermal emission was discovered by \textit{ROSAT} (\textsuperscript{1993}). \textit{ROSAT} observation also revealed a peculiar pulse profile with three peaks in the soft X-ray band. Non-thermal emission from its surrounding nebula is dominant at higher energies.

Recent \textit{Chandra} observations revealed even more complex properties of the Vela pulsar and its nebula. With its high angular resolution, a \textit{Chandra} image showed detailed structure in the surrounding nebula (\textsuperscript{2001a}). No spectral features were found in the high energy resolution \textit{Chandra} LETGS spectra of the resolved pulsar emission. No detection of spectral features excludes the presence of heavy element atmospheres on the surface (\textsuperscript{2001b}).

The Vela pulsar is also a strong source of non-thermal emission in the optical, X-ray and gamma-ray bands. The non-thermal component from the pulsar was resolved for the first time by \textit{Chandra} (\textsuperscript{2001a}). Recent \textit{RXTE} observations revealed complex timing properties associated with non-thermal emission from the pulsar, showing energy-dependent multiple peaks in folded lightcurves (\textsuperscript{1999}, \textsuperscript{2002}). However, the origin of the peaks in the soft X-ray band, whether thermal or non-thermal, has yet to be determined.

\textit{XMM-Newton} observation of the Vela pulsar was performed with a 90 ksec exposure time on 1 Dec 2000. \textit{XMM-Newton} is sensitive to faint sources such as isolated neutron stars due to its large effective area. Since the nebula turned out to be compact $\sim 10-20''$ (\textsuperscript{2001}), the imaging capability of \textit{XMM-Newton} cannot resolve the pulsar from the nebula. Therefore, the thermal component dominates at $E \lesssim 1$ keV and the nebula emission is dominant at $E \gtrsim 1$ keV in \textit{XMM-Newton} spectra. We could not spatially resolve the non-thermal emission from the pulsar or study different components of the nebula. Instead, using the \textit{XMM-Newton} data, we did the following: (1) a spectral fit to high sensitivity European Photon Imaging Camera (EPIC) (\textsuperscript{2001}) data was used to determine thermal properties with high accuracy, (2) a search for spectral features in high resolution Reflection Grating Spectrometer (RGS) (\textsuperscript{2001}) data was performed. All the data were processed by version 5.3.3 of the Scientific Analysis System (SAS) pipeline (\textsuperscript{2003}).
EPIC PHASE-AVERAGED SPECTRAL ANALYSIS

We analyzed EPIC-PN data to determine the global features of the X-ray spectrum. Source data were extracted from a circular region with radius \( r = 1' \) and events with CCD pattern 0 were selected. Such a source area includes more than 90% of the source counts at energies up to \( \sim 5 \) keV. However, the extracted spectra are heavily contaminated by nebular emission at \( E \gtrsim 1 \) keV. Unlike the recent Chandra results which resolved the pulsar emission from its nebula emission (Pavlov et al., 2001a), our analysis focuses on thermal emission from the pulsar at \( E \lesssim 1 \) keV. Systematic errors from nebular contamination are discussed later in this section. Background spectra were reduced from an annulus region between \( r = 1' \) and \( r = 2' \). Total EPIC-PN count rate from the \( r < 1' \) region after subtracting background was 27.0 cts/sec.

We rebinned the data so that each spectral bin contained more than 25 counts. For the following spectral analysis, we used ready-made Response Matrix Files (RMFs) and Auxiliary Response Files (ARFs) generated by the SAS tool “arfgen”. For spectral fitting, we adopted a two-component model comprised of a thermal and non-thermal (power-law) spectrum. We applied two different thermal models to the data: a blackbody model (BB+PL model) and a magnetized hydrogen atmosphere model provided by V. Zavlin (Zavlin, 2003) at \( B = 10^{12} \) G (H+PL model). When we fitted a hydrogen atmosphere model, we fixed the neutron star mass and radius to \( 1.4 M_\odot \) and 10 km. Both thermal models fit the data well, yielding \( \chi^2 \simeq 1.1 \) (Figure 1 and Table 1). Figure 2 shows an \( N_H-T^{\infty} \) contour plot with fixed power-law index and radius. Hydrogen atmospheres are in general harder than a blackbody since free-free absorption dominates in the X-ray band. Therefore, the temperature fitted by a magnetized hydrogen atmosphere model is lower than a blackbody fit (hence a larger radius for the hydrogen atmosphere fit).

The derived distance \( (d = 256 \pm 50 \) pc) is consistent with the distance from the parallax measurement \( (d = 294^{+76}_{-60} \) pc).
Fig. 2. Contour plot in $N_H-T^\infty$ plane. Blackbody (top) and hydrogen atmosphere at $B = 10^{12}$ G (bottom).

For hydrogen atmosphere models, $T^\infty$ and $R^\infty/d$ depend on other input parameters (e.g. $M$ and $R$) weakly (Zavlin et al., 1998). The apparent radius corresponding to the measured distance is inferred to be $R^\infty/d_{294} = 15.0^{+6.5}_{-5.1}$ km where $d_{294}$ is the distance in units of 294 pc.

We note that non-thermal spectra from the pulsar (obtained by Chandra observation) are about two orders of magnitude weaker than the nebular spectra, so the power-law component observed by XMM-Newton is dominated by the nebular contribution. The fitted power-law index ($\gamma \approx 1.6$) probably represents a superposition of different nebular components, which were resolved by the Chandra observation (Pavlov et al., 2001b). The estimated luminosity of the power-law component in the EPIC-PN data is consistent with the Chandra result for the nebula ($L_{\text{neb}} = 8.3 \times 10^{32}$ ergs s$^{-1}$ for $d = 294$ pc) (Pavlov et al., 2001b).

The derived parameters from both the blackbody and magnetized hydrogen atmosphere fit are in good agreement with the Chandra results. However, since the angular resolution of XMM-Newton is poorer than that of Chandra,
Table 1. Fitted parameters to XMM-Newton EPIC-PN spectra (pulsar plus nebula) in comparison with Chandra data (pulsar only).

| Parameter          | EPIC-PN         | Chandra          |
|--------------------|-----------------|------------------|
| \( N_H \) \( [10^{20} \text{ cm}^{-2}] \) | \( 1.44^{+0.88}_{-0.85} \) | \( 2.2 \pm 0.3 \) |
| \( T^{\infty} \) \( [10^6 \text{ K}] \) | \( 1.46^{+0.02}_{-0.02} \) | \( 1.50 \pm 0.05 \) |
| \( R^{\infty} \) [km]\(^{a}\) | \( 2.50^{+0.14}_{-0.14} \) | \( 2.5 \pm 0.2 \) |
| \( L_{th}^{\infty} \) \( [10^{32} \text{ erg s}^{-1}]^{a} \) | \( 2.02^{+0.34}_{-0.33} \) | \( 2.1 \pm 0.3 \) |
| \( \gamma^{b} \) | \( 1.64^{+0.08}_{-0.08} \) | \( 2.7 \pm 0.4 \) |
| \( L_{pl}^{\infty} \) \( [10^{32} \text{ erg s}^{-1}]^{a,b} \) | \( 8.56^{+0.11}_{-0.14} \) | \( 0.58 \pm 0.08 \) |
| \( \chi^2_{\nu} \) | 1.16 | 1.1 |

Magnetized H atmosphere \(^{c}\) + Power-law

| Parameter          | EPIC-PN         | Chandra          |
|--------------------|-----------------|------------------|
| \( N_H \) \( [10^{20} \text{ cm}^{-2}] \) | \( 2.50^{+0.14}_{-0.17} \) | \( 3.3 \pm 0.3 \) |
| \( T^{\infty} \) \( [10^6 \text{ K}] \) | \( 0.674^{+0.034}_{-0.033} \) | \( 0.68 \pm 0.03 \) |
| \( d \) [pc]       | \( 256^{+44}_{-43} \) | \( 210 \pm 20 \) |
| \( L_{th}^{\infty} \) \( [10^{32} \text{ erg s}^{-1}]^{a} \) | \( 3.35^{+1.78}_{-1.77} \) | \( 5.2 \pm 0.4 \) |
| \( \gamma^{b} \) | \( 1.59^{+0.12}_{-0.12} \) | \( 1.5 \pm 0.3 \) |
| \( L_{pl}^{\infty} \) \( [10^{32} \text{ erg s}^{-1}]^{a,b} \) | \( 8.27^{+0.14}_{-0.14} \) | \( 0.21 \pm 0.06 \) |
| \( \chi^2_{\nu} \) | 1.08 | 1.0 |

Errors for EPIC-PN data are 1 sigma level including both statistical and systematic uncertainty. For luminosity of non-thermal component in the range of 2–10 keV \( (L_{pl}) \), the error refers only to the statistical uncertainty since the smaller extracted region picks up less nebular emission.

\(^{a}\) We assumed the distance is 294 pc from the latest parallax measurement \[^{[Caraveo et al. 2001]}\]. We rescaled the Chandra results in Table 1 in Pavlov et al. (2001a) to \( d = 294 \) pc.

\(^{b}\) Note that these parameters are different from the Chandra results in comparison. However, the fitted parameters to the XMM-Newton data is dominated by the nebular component, while Pavlov et al. (2001a) extracted spectra from the pulsar.

\(^{c}\) We fixed the neutron star mass to \( 1.4M_{\odot} \) and the radius to \( 10 \) km for spectral fitting. Here \( B = 10^{12} \) G.

our fitting parameters can be affected by systematic errors due to the nebular contamination. These errors are, in general, larger than the statistical ones. In order to estimate such errors, we examined the variations in the hydrogen atmosphere and blackbody parameters by using as extraction regions annuli of various radii; the errors reported in Table 1 reflect both statistical and systematic uncertainties. We can see that, when considering the effect on the nebular contamination, Chandra and XMM-Newton temperatures are in agreement at 1-sigma level.

SEARCH FOR SPECTRAL FEATURES IN RGS DATA

Reflection Grating Spectrometer data were taken in “spectroscopy” mode in order to take full advantage of the high spectral resolution. First, we extracted the 95% Point Spread Function (PSF) of the source region for both RGS 1 and 2 data. The background spectrum was reduced from outside the 98% PSF region. We generated responses by the SAS command “rgsrmfgen”. Total count rate was 1.0 cts/sec for both RGS 1 and 2 data. We extracted smaller regions of the source (50% and 70% PSF region) to maximize the number of thermal photons compared to nebular emission.
Fig. 3. XMM-Newton/RGS spectra fit by Hydrogen+Power-law model. The spectra were extracted from the 70% Point Spread Function (PSF) region.

The results obtained with XMM-Newton for the Vela pulsar are in agreement with previous findings by Chandra (Pavlov et al., 2001a,b). The RGS data indicate that the thermal spectrum is featureless, and the EPIC-PN spectrum is well fitted by a magnetized hydrogen atmosphere model with $B = 10^{12}$ G. As it has been found with Chandra, with respect to a fit with the simple blackbody, the atmospheric model has the advantage that it gives a radius for the emitting region compatible with neutron star equations of state. Also, when Chandra data are fitted with an atmospheric model, the index of the power-law component above $\sim 1$ keV is remarkably consistent with that of the PL observed at optical and hard X-ray wavelengths. The power-law component observed with XMM-Newton is dominated by the nebular emission and the value of $L_{\text{pl}} \sim 8 \times 10^{32}$ erg s$^{-1}$ is again consistent with that observed by
The presence of hydrogen is not surprising since a tiny amount of hydrogen constitutes an optically-thick layer in the atmosphere (Zavlin & Pavlov, 2002). Hydrogen could be accumulated on the surface by accretion or generated by spallation of fallback material (Bildsten et al., 1992). The derived large radius from the H+PL model implies that the thermal emission originates from the whole surface.

There is an important implication for the neutron star physics which is consistent with the Chandra and XMM-Newton results. Surface temperature for a given age reflects cooling processes via neutrino emission in the core. Recent studies show that neutron star cooling curves are dependent on various factors such as proton-to-neutron ratio, neutron star mass, magnetic field strength, neutron superfluidity and presence of exotic matter. Among various proposed models, a model which assumes normal composition ($n$, $p$ and $e$) and the indirect URCA process was often quoted as the standard cooling model. The standard cooling model fits most cooling neutron stars, although recent X-ray observations found several neutron stars have surface temperatures below the standard cooling curve (Slane et al., 2002). For the Vela pulsar, the derived Chandra and XMM-Newton temperature of $T^\infty \simeq (6.4-7.1) \times 10^5$ K at its age $\sim 10^4$ years is below the standard cooling curve (Tsuruta et al., 2002).

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