PHASE-RESOLVED SPECTROSCOPY OF THE VELA PULSAR WITH XMM-NEWTON¹

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ABSTRACT

The ∼10⁴ yr old Vela Pulsar represents the bridge between the young Crab-like and the middle-aged rotation-powered pulsars. Its multiwavelength behavior is due to the superposition of different spectral components. We take advantage of the unprecedented harvest of photons collected by XMM-Newton to assess the Vela Pulsar spectral shape and to study the pulsar spectrum as a function of its rotational phase. As for the middle-aged pulsars Geminga, PSR B0656+14, and PSR B1055−52 (the “Three Musketeers”), the phase-integrated spectrum of Vela is well described by a three-component model, consisting of two blackbodies (T_bb = [1.06 ± 0.03] × 10⁶ K, R_bb = 5.1 ±0.4 km, T_BB = 2.16 ±0.06 × 10⁶ K, T_FB = 0.73 ±0.99 km) plus a power law (γ = 2.2 ±0.4). The relative contributions of the three components are seen to vary as a function of the pulsar rotational phase. The two blackbodies have a shallow ∼7%-9% modulation. The cooler blackbody, possibly related to the bulk of the neutron star surface, has a complex modulation, with two peaks per period, separated by ∼0.35 in phase, the radio pulse occurring exactly in between. The hotter blackbody, possibly originating from a hot polar region, has a nearly sinusoidal modulation, with a single, broad maximum aligned with the second peak of the cooler blackbody, trailing the radio pulse by ∼0.15 in phase. The nonthermal component, magnetospheric in origin, is present only during 20% of the pulsar phase and appears to be opposite to the radio pulse. XMM-Newton phase-resolved spectroscopy unveils the link between the thermally emitting surface of the neutron star and its charge-filled magnetosphere, probing emission geometry as a function of the pulsar rotation. This is a fundamental piece of information for future three-dimensional modeling of the pulsar magnetosphere.

Subject headings: pulsars: general — pulsars: individual (Vela) — stars: neutron — X-rays: stars

Online material: color figures

1. INTRODUCTION

The Vela pulsar is one of the best scrutinized neutron stars. It was the first pulsating radio source observed in the southern hemisphere (Large et al. 1968), and the swing of the polarization vector during the radio pulse provided evidence for a rotational origin of the radio emission (Radhakrishnan et al. 1969). Moreover, the position of the pulsar, close to the center of the Vela SNR, confirmed the association of pulsars with rotating neutron stars born from massive stars’ collapse.

About 10 years after the radio discovery, Wallace et al. (1977) detected a pulsating optical source of V ∼ 23.6: at least four peaks are present in the optical (Gouiffès 1998) and UV (Romani et al. 2005) light curves, as well as in the hard X-ray energy range (Harding et al. 2002). HST observations (Caraveo et al. 2001) of the optical counterpart have allowed the direct measurement of the pulsar distance (294±76 pc), later confirmed and refined through radio observations (287±17 pc; Dodson et al. 2003). PSR B0833−45 is also a bright γ-ray source: pulsations were detected by SAS 2 (Thompson et al. 1975), COS B (Bennett et al. 1977; Kanbach et al. 1980; Grenier et al. 1988), and the Compton Gamma Ray Observatory (CGRO). Kanbach et al. (1994), using EGRET, were able to perform spectroscopic analysis of different phase intervals of the double-peaked γ-ray pulsar emission.

Röntgensatellit (ROSAT) detection of soft X-ray pulsations (Oegelman et al. 1993) was the last piece of the Vela multiwavelength puzzle. It turned out to be a difficult observation since X-rays from the neutron star are embedded in the bright pulsar wind nebula (PWN), located near the center of the Vela SNR. A blackbody with temperature ∼(1.5–1.6) × 10⁶ K and a radius of 3–4 km could describe the ROSAT spectrum, while the nebular emission, clearly nonthermal, could be ascribed to synchrotron emission originating from the interaction of the high-energy particle pulsar wind with the interstellar medium. Chandra observations of the Vela pulsar provided high-resolution images of the X-ray nebula surrounding the neutron star. The nebula turns out to be quite complex, with spectacular arc and jetlike features (Helfand et al. 2001; Pavlov et al. 2003) reminiscent of those observed around the Crab. The thermal nature of the pulsar spectrum inferred from ROSAT data was confirmed. While high-resolution spectra failed to show absorption features, a nonthermal harder tail was found in ACIS-S spectra (Pavlov et al. 2001b).

Analyzing XMM-Newton observations, Mori et al. (2004) found the same thermal radiation. However, in their preliminary analysis, they studied only the pulsar phase-averaged thermal emission below ∼1 keV. Since thermal emission is a very distinctive character of middle-aged pulsars (Geminga, PSR B0656+14, and PSR B1055−52; Becker & Truemper 1997), Vela’s (τ ∼ 11,400 yr; ˙ E ∼ 7 × 10³⁶ ergs s⁻¹) spectral properties make it more similar to an older specimen than to younger ones. In this paper we provide further evidence in favor of this classification, taking advantage of XMM-Newton statistics to perform phase-resolved spectroscopy of the Vela pulsar.

2. THE DATA

We use data collected by XMM-Newton and Chandra, exploiting the characteristics of both observatories. While XMM-Newton

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observations provide an unprecedented harvest of photons from the Vela pulsar and its PWN, the instrument point-spread function (PSF; 6.6" FWHM), however, does not allow us to disentangle the pulsar emission from the extended one. Accounting for the bright PWN contribution is mandatory to unveil the PSR emission properties. Thus, the high-resolution image obtained by Chandra is crucial to have a clear view of the Vela pulsar and its surrounding nebular emission.

2.1. XMM-Newton EPIC Data

XMM-Newton observed PSR B0833−45 on 2000 December 2–3. Owing to the high flux of the source, to reduce photon pileup, pn and MOS2 were used in “Small Window” mode, while MOS1 operated in “Large Window.” In the XMM-Newton Science Archive there are two data sets (ID 0111080101 and 0111080201), separated by about 1.5 hr, that cover a time span of 41,100 and 61,800 s, respectively. The raw data were first processed with standard pipeline tasks of the XMM-Newton Science Analysis Software (SAS, ver. 6.5.0), and then the soft proton flares were removed using the standard prescription of De Luca & Molendi (2004). The two data sets were merged using the SAS task merge. Table 1 summarizes good-time intervals and total exposure time for the three EPIC detectors.

Table 1: Journal of XMM-Newton Observations

| ObsID          | Date    | MJD | Observation Time (ks) | Instrument (Mode) | Good Time (s) | Live Time (s) |
|----------------|---------|-----|-----------------------|-------------------|---------------|---------------|
| 0111080101     | 2000 Dec 1 | 51,879 | 41.11                 | pn (SW)           | 37590         | 26366         |
| 0111080101     | 2000 Dec 1 | 51,879 | 41.11                 | MOS1 (SW)         | 37648         | 37241         |
| 0111080101     | 2000 Dec 1 | 51,879 | 41.11                 | MOS2 (LW)         | 37694         | 36597         |
| 0111080201     | 2000 Dec 2 | 51,880 | 61.81                 | pn (SW)           | 50887         | 53693         |
| 0111080201     | 2000 Dec 2 | 51,880 | 61.81                 | MOS1 (SW)         | 49067         | 48524         |
| 0111080201     | 2000 Dec 2 | 51,880 | 61.81                 | MOS2 (LW)         | 50410         | 48940         |

Notes.—For the two different XMM-Newton data sets are listed the start date of the observation in standard UTC time and in Modified Julian Day (MJD), the total observation time, the instrument that performed the observation and the operational mode (SW=Small Window; LW=Large Window), the good-time intervals after removing the soft proton flares, and the live time after correction for charge transferring and readout time.

2.2. Chandra HRC and ACIS Data

To get a clear view of the spatial distribution of the bright nebular emission, we analyzed the two Chandra HRC-Imaging (HRC-I) archive observations of the Vela pulsar, performed after the 2000 January glitch. A third observation, taken on 2002 January, was also available. All these observations were reprocessed with CIAO3 version 3.2, applying aspect solution, and degap correction, as well as reducing tap-ringing distortion. The resulting image (Fig. 2) shows the well-known structure of the Vela PWN: the two “arcs” and the “jet/counterjet” feature protruding from the point source (Helfand et al. 2001; Pavlov et al. 2003).

3. SPECTRAL ANALYSIS

To perform the spectral analysis of the XMM-Newton data on the Vela pulsar, we exploit both the spectral and temporal resolution of the EPIC pn camera. To disentangle the PSR photons from the PWN ones, we take advantage of their different space distribution; while the PSR photons follow the instrument PSF, the nebular ones do not.

To estimate the nebular contribution in the EPIC pn event file, we perform the following:

1. Extract spectra from concentric annular regions of increasing radii.
2. Determine the PSR contribution in each spectrum as a function of the PSF and of the encircled energy fraction (EEF).
3. Determine the PWN contribution in each spectrum using a surface brightness map of the nebular emission derived from Chandra data.
4. Fit all the spectra at once with a two-component (PSR+PWN) model whose normalization ratios are fixed following the two previous steps.

Fig. 1.—EPIC pn image of the Vela pulsar. The plus sign marks the radio position, and the box marks the region covered by the Chandra image of Fig. 2. The spectral extraction regions (§ 3.1) are also marked. [See the electronic edition of the Journal for a color version of this figure.]
In the following section we describe in detail each step.

3.1. EPIC pn Phase-averaged Spectra

We extract spectra from the merged EPIC pn event file, with FLAG 0 and PATTERN 0–4, from a 10″ radius circle centered on the pulsar position, as well as from three annular (10″–20″, 20″–30″, 30″–40″) regions (see Fig. 1). No evidence for photon pileup is found in the data. All the spectra are shown in Figure 3, where their composite nature is clearly visible: while at lower energies the thermal spectrum prevails, with the flux values in the four different extraction regions proportional to EEF, at higher energies almost all the photons detected are produced by the PWN and the flux values are proportional to the spatial distribution of the nebula surface brightness. Since the background estimate will be provided by the spectral fitting, we avoid background subtraction. We chose the energy range 0.2–10 keV and rebinned the spectra in order to have at least 30 counts per spectral bin and no more than 3 spectral bins per energy resolution interval. Owing to the extended nature of the diffuse nebular emission, we generated effective area files with the prescription for extended sources, without modeling the PSF distribution of the source counts.

3.2. EEF from XMM-Newton Telescopes’ PSF

The XMM-Newton telescopes’ radially averaged PSF profile at distance $r$ from the aim point is well described by the King’s profile (Gondoin et al. 1998):

$$\text{PSF}(r) = A \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\alpha}, \quad (1)$$

where the core radius $r_c$ and the slope $\alpha$ vary as a function of the photon energy and off-axis angle and $A$ is a constant normalization factor. The calibration files provide the values of $r_c$ and $\alpha$, for different photon energies and off-axis angles.

Since the Vela pulsar thermal spectrum peaks at about 0.5 keV and the source is always at the center of the field of view, we used the parameters $r_c = 1.59$ and $\alpha = 5.504$, corresponding to an energy of 475 eV and an offset angle of $0.0^\circ$.

The EEF, i.e., the fraction of energy collected within a certain radius $R$ from the source distribution centroid, is simply the integral of equation (1) times the radius over the radius, normalized at $5^\prime$:

$$\text{EEF}(R) = \frac{1 - \left\{ 1/ \left[ 1 + (R/5.504')^2 \right]^{1.59-1} \right\} 1.59-1}{1 - \left\{ 1/ \left[ 1 + (5'/5.504')^2 \right]^{1.59-1} \right\} 1.59-1}. \quad (2)$$

Since the source is not strictly monochromatic, we calculated the fraction of energy encircled in the spectra extraction regions also for 250 and 800 eV, in order to obtain a “confidence interval.”

3.3. Surface Brightness Map of the PWN from Chandra Data

We used Chandra data to produce a surface brightness map of the nebular emission. In the Chandra HRC images more than 97% of the pulsar counts fall within 3″ from the centroid of the distribution (Weisskopf et al. 2002 and references therein). Thus, outside this small region, the images represent a good approximation of the brightness spatial distribution in the energy range 0.1–10 keV.

Since we needed an estimate of the PWN flux in the proximity of the position of the pulsar, a two-dimensional model of a pointlike source flux distribution was obtained with a simulation performed with ChaRT7 and MARX.8 A two-dimensional fitting was then performed on the HRC images with the addition of a spatially constant contribution from the PWN. Best-fit count rates found for the region between 2.64″ and 3.46″, corresponding to 20–26 pixels, are reported in Table 2 for the three different HRC-I exposures. Following the criterion by Helfand et al. (2001), the region inside 3.46″, 26 pixels, was excised from all images and replaced with a Poissonian distribution with a mean value equal to the best-fit count rate.

In order to take into account the angular resolution of the XMM-Newton telescopes, the maps obtained were convolved with a Lorentzian kernel of $\Gamma = 7.125''$, corresponding to an FWHM of the distribution of 6.6″, the nominal FWHM of the XMM-Newton mirrors.

7 See http://cxc.harvard.edu/chart/.
8 See http://space.mit.edu/CXC/MARX/.

Fig. 2.—Chandra HRC image of the Vela pulsar. [See the electronic edition of the Journal for a color version of this figure.]
Finally, the convolved image was used to compute the encircled PWN fraction in each extraction region of our XMM-Newton image.

3.4. Background Estimate from Spectral Fitting

The XMM-Newton spectra extracted from the four annuli (Fig. 3) were fitted simultaneously using the following combination: (interstellar absorption) × [ρ (PSR model) + ε (PWN model)], where ρ and ε are the PSR and PWN encircled fractions within the i-th extraction region (see §§ 3.2 and 3.3). The interstellar absorption does not depend on i. The PWN model is a power law whose index γi is allowed to vary among different regions, while the model describing the PSR emission does not depend on i. Our approach simultaneously resolves the PSR and PWN emission and computes best-fit parameters for both the PWN and the PSR models (described in the following sections).

The spectral fitting was performed with XSPEC version 11.3, in the energy range 0.2–10 keV. The values of the coefficients are given in Table 3 and represent the different contribution of each region to the total flux of the pointlike and diffuse emission. Uncertainties on the pulsar as well as on the nebular coefficients arise from the following caveats:

1. The pulsar spectrum is far from monochromatic.
2. The XMM-Newton PSF is known within an uncertainty of ~2% (Kirsch 2006).
3. The PWN emission is known to be highly variable over a small timescale (Pavlov et al. 2001a).
4. The Lorentzian kernel differs from the telescope PSF.
5. The HRC efficiency differs from the pn one, and also the telescopes’ effective areas have different dependencies on the energy of the incoming photons.

Thus, to account for all uncertainties, an overall systematic error of 5% has been added.

3.4.1. EPIC pn Vela Pulsar Wind Nebula Spectrum

The overall (absorption+PSR+PWN) best-fit model, summarized in Table 5, allows us to determine the nebular background flux and photon index for all spectra. In particular, we found that the inner circle contains 7.60 ± 0.04 counts s⁻¹ from the PSR and 2.58 ± 0.02 counts s⁻¹ from the PWN (note that only 58% of the pulsar counts are contained in this region; see Tables 3 and 4).

From Table 5 we can see that the nonthermal nebular emission, whose photon indices in the four concentric regions are γ1, γ2, γ3, and γ4, becomes softer as the distance from the pulsar increases. The result is consistent with Chandra ACIS spectra obtained from the 2000 November 30 observation (see also Kargaltsev & Pavlov 2004). The power-law normalization yields the PWN flux within 40″ from the PSR in the EPIC pn data; its value turns out to be $F_{\gamma} = (4.26 ± 0.03) \times 10^{-11}$ erg cm⁻² s⁻¹ in the range 1–8 keV. A large part of the PWN lies outside such a region. In order to estimate the flux of the remaining portion of the PWN inside the pn field of view, we extracted a spectrum from the whole detector, excluding the 40″ circle centered on the PSR, as well as a stripe affected by PSR out-of-time events.

### Table 2

| Extraction Region | EPIC pn Counts (0.2–10 keV) |
|-------------------|-----------------------------|
| 10″               | 471592 (160114)             |
| 10″–20″           | 164272 (355540)             |
| 20″–30″           | 54544 (363174)              |
| 30″–40″           | 36491 (247743)              |

Note.—Number of photons collected by the EPIC pn in the different spectra extraction regions, emitted from the Vela pulsar and from its PWN, as derived from best-fit spectral model fluxes.

### Table 3

| Extraction Region | Total Number of Photons | PSR EEF (%) | PWN Flux (counts) |
|-------------------|-------------------------|-------------|-------------------|
| 10″               | 671021                  | 0.582342    | 17729.6985        |
| 10″–20″           | 541089                  | 0.25818     | 40692.9075        |
| 20″–30″           | 431813                  | 0.0770648   | 42880.3005        |
| 30″–40″           | 293991                  | 0.0377001   | 29622.9375        |

Notes.—Total number of photons collected by the EPIC pn in the different spectra extraction regions. Also shown are XMM-Newton EEF and the PWN counts estimated on the Chandra HRC surface brightness map (degraded to the XMM-Newton angular resolution). The PWN parameters $\epsilon_i$ used in the fit are proportional to such counts. We assumed $\epsilon_I = 1$. These values have been used to compute the PSR and PWN coefficients for the spectral fitting.

### Table 4

| Extraction Region | PSR Flux (counts) | PWN Flux (counts) | EPIC pn Counts (0.2–10 keV) |
|-------------------|-------------------|-------------------|-----------------------------|
| 10″               | 160114            | 471592            | 631711                      |
| 10″–20″           | 355540            | 164272            | 519824                      |
| 20″–30″           | 363174            | 54544             | 417689                      |
| 30″–40″           | 247743            | 36491             | 284238                      |

Notes.—Photons collected by the EPIC pn in the different spectra extraction regions, emitted from the Vela pulsar and from its PWN, as derived from best-fit spectral model fluxes.
Ad hoc response matrix and effective area files were generated. We fitted an absorbed power-law model to the spectrum in the range 2–8 keV, which yielded a best-fit photon index of 1.6 ± 0.02 and an unabsorbed 1–8 keV flux of (1.5 ± 0.02) × 10^{-11} ergs cm^{-2} s^{-1}, corresponding to a luminosity of $L_X = (5.74 ± 0.04) \times 10^{32}$ ergs s^{-1} at the parallactic distance (∼287 pc). Such value is in good agreement with Kargaltsev et al. (2002).

3.5. EPIC pn Vela Pulsar Spectrum

The spectral distribution of the ∼500,000 Vela PSR photons detected in the inner 10'' radius region can be described as the superposition of different components. A simple blackbody thermal model does not fit well the observed spectra, which appear to the CCD readout and converted to the solar system barycenter photon arrival times were corrected for the discrete sampling due to the solar system barycenter with the SAS task barycen. Source counts were extracted from the same region used for spectral analysis after subtraction of the non-point-source contribution.

Epoch folding yields a strong signal at the pulsar frequency. Following the prescription of Leahy (1987) for high-accuracy period determination and error evaluation, we found $P_{101} = 0.08933185 ± 0.00000001$ s and $P_{201} = 0.089331857 ± 0.0000000007$ s, respectively, for observations 01108101 and 01108201.

Table 7. Vela Radio Ephemeris

| Parameter | Value |
|-----------|-------|
| $t_0$ (MJD) | 51881.000000049 |
| $f$ (Hz) | 11.1942146219182 |
| $P$ (s) | 0.0893318588016 |
| $F$ (Hz s^{-1}) | -1.56297 × 10^{-11} |
| $P$ (s^{-1}) | 1.24728 × 10^{-13} |

Note.—R. Dodson (2006, private communication).
were then merged and folded using the radio $f$ and $\dot{f}$, to align in phase X-ray and radio light curves.

The overall (0.2–10 keV) X-ray light curve shows three broad peaks per period marked XS1, XS2, and XS3 in Figure 5. The first and highest peak is phase aligned with the first $\gamma$-ray peak and follows the radio peak by $\sim 0.15$ in phase. The second one, the lowest in this energy range, reaches its maximum at $\varphi = 0.45$–0.50 and corresponds to the RXTE Peak 2-Soft (Harding et al. 2002) and UV P2, (Romani et al. 2005). The third peak, which has an intermediate intensity, occurs at $\varphi = 0.80$–0.85; it appears in the soft X-ray light curve and is not present at any other wavelength. The nebular background emission accounts for 25.5% of the observed flux; the net count rate has a pulsed fraction of 9.2% $\pm$ 0.3% (where pulsed fraction is defined as the ratio between number of counts above the minimum and total number of counts).

We note the presence of a pulsed signal also at energies above 2 keV, where the contribution from the two-blackbody thermal emission model used to describe the Vela spectrum is negligible. This would imply a nonthermal origin for the pulsed emission above 2 keV, a component that was hidden by the nebular emission in the phase-integrated spectrum. We estimated the 2–8 keV Vela light curve to be about 100% pulsed. However, we stress that, in such an energy range, the source signal counts for a small fraction ($\sim 5\%$) of the photons detected, so that a small error in the background estimate would translate into a big uncertainty in the pulsed fraction.

Figure 6 summarizes the multiwavelength behavior of the Vela pulsar. Significant differences are seen in the pulse profile emerging from the two energy-resolved EPIC pn light curves: in the energy range 2–8 keV the second peak is stronger than at lower energies and the third peak is not observable; the phase interval $0.7 < \varphi < 1.2$ appears more complex at energies above 2 keV, with three distinct peaks, two coinciding with the optical third and fourth peak, and one phase aligned with the first hard X-ray and $\gamma$-ray peak.

5. PHASE-RESOLVED SPECTRAL ANALYSIS

Since in the XMM-Newton domain the pulse shape of the Vela pulsar changes with energy, we expect a variation of the spectral shape as a function of the PSR rotation. To study such a modulation, we extract spectra from 20 different phase intervals. The spectra were rebinned in order to have at least 30 counts bin$^{-1}$. Following the approach of Caraveo et al. (2004) and De Luca et al. (2005), we have compared the phase-resolved spectra with the two-blackbody best-fit model using the two normalization coefficients as free parameters.

Such an approach works well for all the phase-resolved spectra except for that encompassing phase interval $0.45 < \varphi < 0.55$, which is characterized by high-energy residuals, impossible to account for with the two-blackbody model. The spectrum of such a phase interval is shown in Figure 7.

Leaving the temperature of the two blackbodies and the hydrogen column density fixed to the values found above, a power law with photon index $2.2^{+0.4}_{-0.3}$ is required to fit the spectrum (Fig. 8) for the $0.45 < \varphi < 0.55$ interval. The normalization of the power law is $\sim 10$ times lower than the nebular emission in this phase interval; thus, its contribution to the phase-integrated spectrum is $\sim 100$ times lower than the nebular one and it cannot be seen in the total Vela spectrum.

Following the detection of a nonthermal component, we decided to perform spectral fitting with a three-component source model (two blackbodies + power law) plus the background model to account for the nebular emission. As in the previous case, the blackbody temperatures where fixed to the values best fitting the total Vela spectrum while a power-law photon index of 2.2 was used. The best-fitting parameters are given in Table 8, while an animated version of the phase-resolved spectra can be found online.$^9$

![Fig. 5.—Folded light curve of the Vela pulsar in the 0.2–10.0 keV energy range as observed with the EPIC pn camera. Two rotational periods are represented for clarity. Phase 0 corresponds to the radio peak.](image)

![Fig. 6.—Multiwavelength light curves of the Vela pulsar from radio to $\gamma$-rays (Harding et al. 2002; Kanbach 2002). Two rotational periods are represented for clarity. In the EPIC pn light curves, error bars are also plotted.](image)

$^9$ See http://www.iasf-milano.inaf.it/~deluca/vela/.
From the blackbody emissions, we can compute blackbody radii (at parallactic distance). In Figure 9 we reported the variation of blackbody radii and power-law normalization as a function of the rotational phase. The hotter blackbody presents a low modulation, with a single broad peak per period. The cooler one shows a more complex modulation with possibly two peaks per period, with a small “dip” between them, well aligned with the radio pulse. The colder component first maximum ($R \approx 5.5 \text{ km}$) trails the radio pulse phase by about 10 ms ($\sim 0.10$–0.15 in phase).

After such maximum, the emitting area suddenly decreases to reach its minimum ($R \approx 4.7 \text{ km}$), at $\varphi \simeq 0.30$, the same phase of the absolute minimum of the Vela soft X-ray flux; the cool blackbody radius then slowly grows and reaches its second and more pronounced maximum ($R \approx 5.5 \text{ km}$) at phase $0.8$–0.85 responsible for the third XMM-Newton light-curve peak, which is not seen in hard X-rays, nor in the UV or optical light curves.

The hotter blackbody peaks, with a maximum radius of about 0.77 km, at the same phase of the first cool blackbody peak, trailing by 0.1–0.15 in phase the radio pulse, long known to mark the pulsar polar region. The minimum of the hot blackbody emission occurs at about 180° from the maximum and trails the minimum of the cooler emission by $\sim 0.3$ in phase. The transition from the minimum to the maximum state is not symmetric, as the growth is sharper than the descent.

The nonthermal emission is present with a narrow peak between $\varphi \sim 0.4$ and $\varphi \sim 0.6$, between the two thermal emissions’ minima. The power-law normalization is found to be consistent with zero in all other phase intervals. Such a nonthermal component is responsible for the second peak observed in the 2–8 keV EPIC light curve and seems to be connected with the narrow “spike” in the near-UV/far-UV light curves and with the “Peak 2-Soft” detected with RXTE. The power-law photon index also agrees with the value found in RXTE phase-resolved spectroscopy (Harding et al. 2002) in the same phase interval. The peak corresponds to the “Leading Wing 2” in the EGRET energy range.

6. DISCUSSION

Considering the different spectral components identified in the EPIC pn data, we note that the maximum extension of the hotter thermally emitting region is observed when looking at the polar region of the neutron star. The radius of this blackbody component is in agreement with the radius of a polar cap within a simple magnetic dipole model (Goldreich & Julian 1969). For the rotational velocity of the Vela pulsar, the polar cap radius would be $R_{PC} = R(R\Omega/c)^{1/2} = 0.485 \text{ km}$. Harding & Muslimov (2002) made an estimate of the energetics for a hot spot reheated by curvature particle downflow: with the Vela parameters the bolometric luminosity would be $L = 6.01 \times 10^{31} \text{ ergs s}^{-1}$ and the temperature $T = 2.66 \times 10^6 \text{ K}$. Both values agree with what we found. Since the Vela pulsar is known to be an inclined rotator, a terrestrial observer would face a single polar region during rotation. Assuming that the hot component is produced by the polar cap region heated by return current, the gravitational bending (Page 1995) would result in a shallow modulation of the emitting surface, in agreement with our results.

The cooler blackbody would represent the radiation from the remaining part of the star surface. The radius inferred from the phase-averaged spectrum is too small to fit in any proposed equation of state for a star composed mainly of neutrons. We also observe a $\sim 10\%$ modulation of this spectral component as a function of the rotational phase. Magnetospheric reprocessing of the thermal photons emitted from the surface could provide a phase-dependent “obscuration” of a fraction of the neutron star surface, depending on magnetic field configuration and viewing geometry. The phenomenon of the magnetospheric “blanket,” e.g., cyclotron resonance scattering by plasma at a few stellar radii (Ruderman 2003), originally proposed by Halpern & Ruderman (1993) as an explanation of the soft thermal emission of Geminga, could provide the physical basis for the observation of a phase-dependent emitting area.

Anisotropic heat transfer from the interior of the neutron star would also provide a surface temperature far from uniform, with the polar regions hotter than the equatorial ones (Greenstein & Hartke 1983). Such nonuniform temperature distribution would result in a modulated X-ray thermal flux. Alternatively, using a uniform surface temperature approximation, this translates into a modulation of the emitting surfaces. Page (1995) shows that in such a case a modulation of a few percent is expected, owing to gravitational light bending. However, such a modulation would have to be phase aligned with that of the hotter component. The complicated modulation we observe for the cool blackbody component is not easy to reconcile with such a picture, pointing to a more complex surface temperature distribution and/or to magnetospheric reprocessing as discussed above.
TABLE 8

RESULTS OF PHASE-RESOLVED SPECTROSCOPY

| Phase   | bb Radius (km) | BB Radius (km) | PL Norm ($\gamma$ s$^{-1}$ cm$^{-2}$ keV$^{-1}$) | $\chi^2$ (dof) |
|---------|----------------|----------------|-----------------------------------------------|----------------|
| 0.00-0.05 | 5.12 ± 0.06 | 0.73 ± 0.02 | (1.6 ± 1.2) $\times$ 10$^{-4}$ | 1.00 (136) |
| 0.05-0.10 | 5.22 ± 0.06 | 0.75 ± 0.01 | 0 | 0.99 (137) |
| 0.10-0.15 | 5.33 ± 0.06 | 0.77 ± 0.02 | 0 | 1.10 (137) |
| 0.15-0.20 | 5.27 ± 0.06 | 0.77 ± 0.02 | (1.9 ± 1.2) $\times$ 10$^{-4}$ | 1.10 (143) |
| 0.20-0.25 | 5.11 ± 0.06 | 0.75 ± 0.01 | 0 | 1.28 (137) |
| 0.25-0.30 | 4.80 ± 0.06 | 0.76 ± 0.01 | 0 | 1.41 (133) |
| 0.30-0.35 | 4.73 ± 0.06 | 0.74 ± 0.02 | 0 | 1.10 (134) |
| 0.35-0.40 | 4.84 ± 0.06 | 0.73 ± 0.02 | 0 | 1.51 (138) |
| 0.40-0.45 | 4.88 ± 0.06 | 0.73 ± 0.02 | (1.8 ± 1.2) $\times$ 10$^{-4}$ | 1.17 (138) |
| 0.45-0.50 | 4.88 ± 0.06 | 0.72 ± 0.02 | (5.7 ± 1.2) $\times$ 10$^{-4}$ | 0.84 (140) |
| 0.50-0.55 | 4.87 ± 0.06 | 0.69 ± 0.02 | (5.0 ± 1.2) $\times$ 10$^{-4}$ | 1.13 (144) |
| 0.55-0.60 | 5.08 ± 0.06 | 0.66 ± 0.02 | (2.0 ± 1.2) $\times$ 10$^{-4}$ | 1.03 (139) |
| 0.60-0.65 | 5.09 ± 0.06 | 0.65 ± 0.02 | 0 | 1.08 (138) |
| 0.65-0.70 | 5.13 ± 0.06 | 0.71 ± 0.01 | 0 | 1.08 (137) |
| 0.70-0.75 | 5.18 ± 0.06 | 0.75 ± 0.01 | 0 | 1.26 (136) |
| 0.75-0.80 | 5.38 ± 0.06 | 0.73 ± 0.01 | 0 | 1.08 (134) |
| 0.80-0.85 | 5.46 ± 0.06 | 0.74 ± 0.01 | 0 | 1.09 (133) |
| 0.85-0.90 | 5.33 ± 0.06 | 0.71 ± 0.02 | (5.0 ± 1.2) $\times$ 10$^{-5}$ | 1.27 (134) |
| 0.90-0.95 | 5.16 ± 0.06 | 0.72 ± 0.02 | (0.3 ± 1.2) $\times$ 10$^{-5}$ | 1.14 (136) |
| 0.95-1.00 | 5.05 ± 0.06 | 0.75 ± 0.01 | 0 | 1.11 (134) |

Notes.—Cool blackbody (bb) and hot blackbody (BB) radius and power-law normalization as a function of the rotational phase. Temperatures of both blackbody components were fixed at the best-fit values for the phase-integrated spectrum. The power-law photon index was left as a free parameter in the 0.45–0.55 phase interval (best-fit value of 2.2 ± 0.4). For the remaining part of the cycle the photon index was fixed at the best-fit value for the 0.45–0.55 phase interval. For the radius computation we assumed 58% of the energy emitted encircled in the 1000 radius region and a parallactic distance of 287 pc. Errors are computed at a 90% confidence level for a single interesting parameter.

Fig. 9.—Variation of the three spectral components (cool and hot blackbody radius and power-law normalization) as a function of the rotational phase. Two rotational periods are plotted for clarity. [See the electronic edition of the Journal for a color version of this figure.]
The nonthermal component detected in a small phase interval 180° from the radio pulse, when the thermal components are at their minimum, might be produced by particles accelerated in the star magnetosphere.

7. CONCLUSIONS

The spectral analysis of the XMM-Newton data of the Vela pulsar confirms the thermal nature of its emission pointing toward an X-ray phenomenology similar to that seen in older neutron stars. Both the overall spectral shape and the phase-resolved behavior are reminiscent of what has been found for middle-aged pulsars such as Geminga, PSR B0656+14, and PSR B1055−52, affectionately called the “Three Musketeers” in view of their similarities (Becker & Truemper 1997). Indeed, the Three Musketeers could be described, even with some caveats, with a simple common phenomenological model in which the differences in the variations of the “hot spot” emitting areas as a function of the rotational phase could be ascribed to the different viewing geometries of the three neutron stars, which are known to be different: orthogonal rotator seen perpendicular to the rotational axis for PSR B1055−52 and almost aligned for PSR B0656+14 (for a full description of such a picture see, e.g., De Luca et al. 2005).

While Vela is certainly hotter than the older musketeers, its overall blackbody-emitting radius is rather small, leading to a low luminosity, well below the value expected in the standard cooling scenario described by Tsuruta et al. (2002). Using a hydrogen atmosphere eases the radius problem but, yielding lower cooling scenario described by Tsuruta et al. (2002). Using a hydrogen atmosphere eases the radius problem but, yielding lower cooling scenario described by Tsuruta et al. (2002).

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