EXTENDED HARD X-RAY EMISSION FROM THE VELA PULSAR WIND NEBULA

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ABSTRACT

The nebula powered by the Vela pulsar is one of the best examples of an evolved pulsar wind nebula, allowing access to the particle injection history and the interaction with the supernova ejecta. We report on the INTEGRAL discovery of extended emission above 18 keV from the Vela nebula. The northern side has no known counterparts and it appears larger and more significant than the southern one, which is in turn partially coincident with the cocoon, the soft X-ray, and TeV filament toward the center of the remnant. We also present the spectrum of the Vela nebula in the 18–400 keV energy range as measured by IBIS/ISGRI and SPI on board the INTEGRAL satellite. The apparent discrepancy between IBIS/ISGRI, SPI, and previous measurements is understood in terms of the point-spread function, supporting the hypothesis of a nebula more diffuse than previously thought. A break at \( \sim 25 \) keV is found in the spectrum within 6' from the pulsar after including the Suzaku XIS data. Interpreted as a cooling break, this points out that the inner nebula is composed of electrons injected in the last \( \sim 2000 \) years. Broadband modeling also implies a magnetic field higher than 10 \( \mu \)G in this region. Finally, we discuss the nature of the northern emission, which might be due to fresh particles injected after the passage of the reverse shock.

Key words: ISM: individual objects (Vela PWN) – ISM: supernova remnants – pulsars: general – pulsars: individual (PSR B0833–45) – X-rays: general

1. INTRODUCTION

Pulsar wind nebulae (PWNe) are the non-thermal bubbles inflated by the winds of rotation-powered pulsars. Recent observations have allowed the arrangement of the variety of their morphologies in an evolutionary sequence resulting from the interaction with their surroundings (Gaensler & Slane 2006). A very complex phase occurs after the host remnant evolves into the Sedov–Taylor phase (\( \sim 10 \) kyr after the pulsar birth), when a reverse shock propagates inward into the supernova ejecta and eventually collides with the PWN (van der Swaluw et al. 2001). Located at a distance of 290 pc (Dodson et al. 2003), the PWN powered by the Vela pulsar (PSR B0833–45, with spin-down luminosity \( \dot{E} = 6.9 \times 10^{36} \) erg s\(^{-1}\)) is the best example of a PWN (Blondin et al. 2001). This explanation has been confirmed by the detection of extended TeV emission matching the cocoon (Aharonian et al. 2006), with the brightness peak offset from the pulsar, and of thermal X-ray emission suggesting mixing with the shocked ejecta (LaMassa et al. 2008). However, an additional particle population, older and less energetic, is needed to explain the multiwavelength spectrum of Vela X (de Jager et al. 2008), complemented by the recent GeV detections by AGILE (Pellizzoni et al. 2010) and Fermi (Abdo et al. 2010). The angular resolution of IBIS/ISGRI on board the INTEGRAL observatory (Winkler et al. 2010) combined with its large field of view allows us for the first time to address the problem of the full morphology of the hard X-ray nebula. Here, we report on the INTEGRAL identification of extended hard X-ray emission from Vela.

2. OBSERVATIONS AND ANALYSIS

2.1. IBIS/ISGRI Imaging

We analyzed all public INTEGRAL pointings within 12' from the Vela pulsar. We first analyzed the data from IBIS (Ubertini et al. 2003), the coded mask imager on board INTEGRAL, and in particular of its low energy detector ISGRI (15 keV–1 MeV; Lebrun et al. 2003). The IBIS/ISGRI data have been collected from 1976 pointings between 2003 March and 2008 July, for a total exposure time of 5.6 Ms. In the 18–40 keV mosaicked image (Figure 1), obtained with the Offline Scientific Analysis (Goldwurm et al. 2003) software v.8, we found a 110\( \sigma \) point-like source at the pulsar position. The point-spread function (hereafter PSF) encompasses the pulsar, the Chandra PWN, and part of the fainter region.
An extended emission in the NE/SW direction is also visible in the image, spanning ~50’ on both sides. After subtraction of the point-like source by fitting it with a two-dimensional Gaussian profile ($\sigma = 6'2$), the NE side appears larger and more significant than the SW side, which is coincident with the ROSAT and H.E.S.S. cocoon (Figure 1, second and third panels). The extended emission also matches the one found by the Birmingham Spacelab 2 telescope in 2.5–10 keV (Figure 1, fourth panel). The individual pixels of the IBIS/ISGRI feature are at the $\sim 3\sigma$ significance level. Such a large cluster of low-significance pixels is not observed in the rest of the image, and it is not reminiscent of IBIS/ISGRI coding noise. After smoothing, it is the only residual excess besides the known point sources. A further evidence of extended hard X-ray emission beyond the inner PWN is provided by the spectral analysis.

2.2. INTEGRAL Spectral Analysis

We extracted the IBIS/ISGRI spectrum of the point-like source from mosaicked images in narrow energy bands between 18 and 400 keV (Figure 2). To account for the evolution of the instrument response, we produced an average of the responses weighted by the on-source exposures in their respective validity epochs. All the spectra in this work have been fitted using Xspec v.11.3 (Arnaud 1996), and the uncertainties are reported at the 90% confidence level. A best fit with a single power-law model yielded a photon index $\Gamma_{\text{ISGRI}} = 2.00 \pm 0.04$ and a flux

$$ F = (4.76 \pm 0.09) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ in the 20–40 keV range} \left( \chi^2_{\text{red}} = 1.16/16 \text{ dof} \right). $$

This spectrum is $\sim 50$ times higher than the phase-averaged one of the Vela pulsar at 20 keV (W. Hermsen & L. Kuiper 2011, private communication; Harding et al. 2002). Therefore, the IBIS/ISGRI emission is dominated by the nebula.

We also analyzed the data from the INTEGRAL spectrometer SPI (20 keV–8 MeV; Vedrenne et al. 2003) collected simultaneously with the IBIS data. SPI spectra have been extracted using the SPIROS package (Skinner & Connell 2003) within the OSA analysis software. The SPI data are best fitted ($\chi^2_{\text{red}} = 0.7/10 \text{ dof}$) by a power-law model in the 20–300 keV range with photon index $\Gamma_{\text{SPI}} = 2.15 \pm 0.15$, compatible within the errors with the IBIS/ISGRI one, but with a higher flux.

$$ F = (9.1 \pm 0.6) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ in 20–40 keV, with respect to IBIS/ISGRI}. $$

A joint fit to the IBIS/ISGRI and SPI spectra with a single power law yields a compatible photon index, but it requires a renormalization constant of 1.8 to recover the higher SPI flux. Such a discrepancy cannot be accounted for by an intercalibration factor, which is in the 0.8–1.2 range for IBIS/ISGRI and SPI (e.g., Jourdain et al. 2008; Bouchet et al. 2009).

The photon index measured by BeppoSAX/Phoswich Detection System (PDS) in the same energy range ($\Gamma_{\text{PDS}} = 2.00 \pm 0.05$; Mangano et al. 2005) is consistent with both spectral indices derived above, whereas the flux lies between the IBIS/ISGRI and SPI one. As shown in Figure 3, the IBIS/ISGRI, BeppoSAX/PDS, and SPI fluxes correlate with the respective PSF radii (half-width at half-maximum, HWHM: 6', 39', and 1.3), suggesting that each instrument samples a different portion of the nebula. Due to the coded mask deconvolution of IBIS/ISGRI, optimized for point sources, the reconstructed flux of an extended source of 60' radius is lower than the real one by a factor $\sim 50$ (Renaud et al. 2006). Therefore, a flux of $4.3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ (the difference between the SPI and ISGRI fluxes) from such a source would be measured as low as } 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ by IBIS/ISGRI, close to its sensitivity limit.}

To support the hypothesis that an extended source is present in the IBIS/ISGRI data but diluted by the coded mask deconvolution, we refined the analysis following the method developed by Renaud et al. (2006) for analyzing emission from extended sources.

We extracted the IBIS/ISGRI count rates from concentric circles centered on the pulsar with radii up to 80', and converted them into flux by assuming a photon index as for the point-like source. This integrated flux as a function of the extraction radius does not reach a plateau after 15', as expected for a point-like source, but slowly increases up to $\sim 60'$ (Figure 3). The integrated IBIS/ISGRI flux also recovers the BeppoSAX/PDS and SPI fluxes at radii comparable with their

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8 As the PDS had no imaging capabilities, this is the HWHM of the instrumental angular response (Frontera et al. 1997).
Figure 2. Combined Suzaku/XIS0-1-3 (blue, green, and red) and IBIS/ISGRI (black) spectra of the Vela PWN within 6′ from the pulsar fitted to the model with a Band component described in Section 2.3. The data have been graphically rebinned for clarity. The lower panel shows residuals from the best fit in units of 1σ.

Figure 3. IBIS/ISGRI flux in the 20–100 keV band integrated at varying extraction radii (open triangles), along with the BeppoSAX/PDS and SPI fluxes in the same band (filled circles). In this case the integration radius is given by their PSF (39 and 1:3 for BeppoSAX/PDS and SPI, respectively). The origin of the x-axis corresponds to the pulsar position. The expected (dotted line) and measured (the bright binary pulsar Vela X-1 rescaled, open squares) profiles for a truly point source are also shown.
PSFs. This confirms the detection of extended hard X-ray emission beyond the inner PWN.

2.3. IBIS/ISGRI and Suzaku/XIS Combined Spectrum

The MECS and PDS instruments on board BeppoSAX allowed us to measure a break at energy 12.5 ± 1.5 keV (Mangano et al. 2005). However, the different angular resolution of the two instruments required the authors to combine the PDS spectrum rescaled by an intercalibration factor with the MECS spectrum extracted from a 15′ radius region. With a much smaller PSF, INTEGRAL IBIS/ISGRI can be combined with Suzaku/XIS on the same extraction radius.

Suzaku observed the Vela pulsar and PWN on 2006 July 10 and 11. Event files from version 2.0.6.13 of the Suzaku pipeline were used and spectra were extracted using XSELECT. Response matrices and ancillary response files were generated for each XIS using XISRMFGEN and XISIMARFGEN version 2007 May 14. The data of the XIS2 camera were not considered because of a more uncertain calibration. The effective exposure time for each XIS is about 60.3 ks. The source photons are extracted from a circular region with a radius of 6′ to match the IBIS/ISGRI PSF. Background photons are extracted from blank sky observations within the same region as the source.

We modeled the pulsar contribution by introducing two black bodies corrected by the interstellar absorption, with fixed parameters as measured by XMM-Newton (Manzali et al. 2007). An absorbed non-equilibrium plasma emission model (VMEKAL) is also included to account for the thermal supernova remnant; fixing the abundances as in LaMassa et al. (2008), we derived a temperature of $k_B T = 0.214^{+0.003}_{-0.005}$ keV. The XIS spectra show a bright power-law component with photon index and flux (Table 1) compatible with the MECS at the same radius (Mangano et al. 2005). It is connected to the IBIS/ISGRI spectrum, confirming that the IBIS/ISGRI flux is due to the PWN. However, a spectral break is required to simultaneously fit the XIS and the IBIS/ISGRI data. The break is located at energies ($27 \pm 3$ keV) higher than the one derived by BeppoSAX. A simultaneous fit with a single power law is statistically rejected ($\chi^2$ of 11252 for 6245 dof).

We also refined the spectral fit by replacing the broken power law with a Band model, an empirical four-parameter model consisting of two power-law components smoothly joined by an exponential rollover (Band et al. 1993). The fitted parameters are compatible with the ones derived with the broken power-law model (Table 1), for a comparable $\chi^2$. Notably, the two power laws intersect at 25 ± 7 keV, which corresponds to the break energy in the broken power-law model. In the next section we adopt the Band model, as a gradual transition should be more representative of the change of slope around a cooling break (e.g., Kardashev 1962).

3. DISCUSSION

Thanks to the deep INTEGRAL exposure, we were able to discover diffuse emission above 20 keV beyond the inner Vela PWN. Such emission is resolved in two different regions: a southern hot spot coincident with the Vela cocoon, notably with the peak of the TeV brightness profile measured by H.E.S.S., and a more extended northern emission, without any counterpart at other wavelengths and outside Vela X. However, recent Suzaku/XIS observations showed non-thermal emission below 10 keV in a region located at the boundary of the IBIS northern emission (Katsuda et al. 2011). We then compared the IBIS spectrum to the ones of BeppoSAX/PDS and SPI, and explained the flux differences by their different PSFs, which sample different portions of the nebula, confirming a large extension (∼1° radius) at hard X-rays.

We also reported on the spectrum within 6′ from the pulsar using the IBIS/ISGRI and the XIS telescopes. This is the first broadband X-ray spectrum of the Vela PWN taken within a region with the same angular extension below and above 10 keV. The change of slope around 25 keV ($\Delta \Gamma = 0.59 ± 0.15$ for the Band model) is compatible with the standard value of 0.5 expected from a cooling break occurring in a continuously injected electron distribution affected by radiative losses. Indeed, the XIS and IBIS/ISGRI photon indices (∼1.6 and ∼2.2) are compatible with the synchrotron spectrum of a shock-accelerated electron distribution in the uncooled and cooled regime, respectively (e.g., Chevalier 2000). In this framework, the cooling energy is expected to decrease with time that is at increasing integration radii from the pulsar. The lower break energy measured by BeppoSAX MECS and PDS on a larger angular extension may indicate a cooling break propagating along the flow. Indeed, the cooling energy in the cocoon is expected around 1 keV (LaMassa et al. 2008). The similar photon indices found by IBIS, BeppoSAX/PDS, and SPI suggest that the radiative losses above 20 keV already balance the injection rate within the region enclosed by the IBIS/ISGRI PSF.

The measurement of a cooling energy at ∼25 keV in the photon spectrum allows us to set an upper limit on the time (residence time) spent by the particles in the region within 6′ from the pulsar, corresponding to a distance of 0.5 $d_{200}$ pc. Accounting for synchrotron losses and inverse Compton losses in the Thomson regime, the cooling frequency as a function of the residence time $t$ can be written as

$$v_c(t) = \frac{81 m_e^5 c^9}{32 \pi e^4 (1 + U_{ph}/U_B)^2 B^3 t^2},$$

where $U_{ph}$ and $U_B$ are the photon field and magnetic energy densities, respectively. Equation (1) coincides with the cooling frequency calculated assuming only synchrotron losses (e.g., Chevalier 2000) for $B \gg \sqrt{8\pi U_{ph}}$. Solving it for $t$, the residence time has a maximum occurring for a magnetic field $B = \sqrt{8\pi U_{ph}/3}$ independently from the cooling frequency. Such a magnetic field amounts to 1.9 $\mu$G when the target photons are provided by the cosmic microwave background.

Table 1

| Parameter | Broken Power Law | Band |
|-----------|-----------------|------|
| $\Gamma_1$ | 1.64±0.05 | 1.61±0.02 |
| $\Gamma_2$ | 2.07 ± 0.05 | 2.2±0.1 |
| $E_b$ (keV) | 27 ± 3 | ... |
| $E_b$ (keV) | ¥ | ... |
| $E_b$ (keV) | ¥ | ... |
| $\chi^2$/dof | 1.03 (6235) | 1.03 (6235) |

Notes. Best-fit spectral parameters of the combined Suzaku/XIS-IBIS/ISGRI data within 6′ from the Vela pulsar. The uncertainties are at the 90% confidence level.

$E_b$ is the folding energy in the Band model. The two power laws intersect at $(\Gamma_2 - \Gamma_1) e^{-1} E_b = 25 ± 7$ keV, which corresponds to the break energy in the broken power-law model $E_b$.

$\Gamma_1$ Flux in the 20–100 keV energy band in units of $10^{-10}$ erg cm$^{-2}$ s$^{-1}$.
(CMB) radiation ($U_{\text{ph}} = 0.26 \text{ eV cm}^{-3}$). For a cooling energy of 25 keV ($\nu_c = 6 \times 10^{18} \text{ Hz}$), the residence time of electrons is 1650 yr in this case, and shorter for any different intensity of the magnetic field and any additional photon field. Therefore, the electrons radiating in X-rays in the considered region cannot be older than 1650 yr. We conclude that those injected before have flowed out of the region within 6′ from the pulsar. This requires a moderate average velocity (>300 $d_{290} \text{ km s}^{-1}$).

We explored the hypothesis that particles of all energies remain in this region for the residence time which yields a cooling break at 25 keV for a given $B$. This is done by means of a time-dependent one-zone model of the spectral energy distribution (SED; see Figure 4). The injection spectrum is composed of a relativistic Maxwellian (Sironi & Spitkovsky 2009) and a cutoff power law with index 2.2. The radiative losses depend on a magnetic field of constant intensity $B$ and a target photon field taken at the Vela position according to Moskalenko et al. (2006). The cutoff energy is fixed by $B$ through the condition that the acceleration rate equals the cooling rate (de Jager et al. 1996). The shape of the distribution is constant, whereas the normalization is proportional to the pulsar spin-down power:

$$N = \frac{\eta \dot{E}}{\Gamma_c m_e c^2}, \quad (2)$$

where $\eta$ is the fraction of $\dot{E}$ converted into the wind energy and $\Gamma_c$ is the average Lorentz factor fixed by the energy conservation. Such an injection rate decreases in time following $E(t) = E_0 (1 + t/t_{\text{dec}})^{-\beta}$, where $E_0$ is the initial spin-down power, $t_{\text{dec}}$ is the spin-down timescale, and $\beta = (n + 1)/(n - 1)$ for a braking index $n$ (Pacini & Salvati 1973).

The SED in Figure 4 is reproduced by this simple model for a range of values of $B$. The upper limit on the integral flux above 1 TeV implies a firm lower limit on the magnetic field, $B > 10 \mu G$, higher than the one estimated in the cocoon (de Jager et al. 2008). This result depends on the relative intensity of the synchrotron and Compton peaks, which is not affected by the conversion efficiency $\eta$ (1.3% for $B = 10 \mu G$). It is also nearly irrespective of $t_{\text{dec}}$ and $n$: given the short evolution time, a manifold break around the cooling energy due to the pulsar spin-down (Gelfand et al. 2009) is not evident. The extrapolation of the X-ray spectrum at lower energies falls squarely on the measured radio fluxes of the compact PWN. A fine tuning is obtained adopting a relativistic Maxwellian with a temperature of 3 GeV for $B = 10 \mu G$; alternatively, a low-energy break in the injected electron population is required at GeV energies, as found in young PWNe (e.g., Bucciantini et al. 2011). Additional measurements between radio and X-ray frequencies are needed to exclude a more complex spectrum (e.g., Slane et al. 2008).

The fact that diffuse hard X-ray emission is detected beyond 6′ from the pulsar in the northern direction strengthens the hypothesis of particle leakage. Unlike the southern hot spot, which may simply be the high-energy counterpart of the X-ray cocoon, the northern emission may be generated by particles injected after the transit of the supernova reverse shock (~3 kyr ago; Blondin et al. 2001). The original PWN is then set apart from the pulsar, becoming a relic, while the latter forms a new PWN in subsonic expansion inside the supernova remnant (van der Swaluw et al. 2004). To understand the nature of the northern emission it will be crucial to extend the X-ray mapping of the Vela PWN with XMM-Newton and Suzaku and with the forthcoming focusing telescopes at higher energy X-rays (NuSTAR and ASTRO-H).

Based on observations with INTEGRAL, an ESA mission with instruments and science data center funded by ESA member states, Czech Republic, and Poland, and with the participation of Russia and the USA. ISGRI has been realized and maintained in

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**Figure 4** SED of the Vela PWN emission within 6′ from the pulsar, fitted with the model described in the text. The Suzaku XIS and INTEGRAL IBIS/ISGRI spectra are shown in red and blue, respectively. The radio fluxes of the inner Vela PWN are shown (Dodson et al. 2003; Hales et al. 2004, orange and green circles, respectively). The upper limit (99.9%) on the integral flux above 1 TeV within 6′ from the pulsar is also shown (purple arrow, assuming a photon index of 2; Aharonian et al. 2006). The measurements of the large-scale PWN are reported in gray for comparison: Vela X in radio (Alvarez et al. 2001; Abdo et al. 2010), at GeV energies (Abdo et al. 2010), and the TeV cocoon (Aharonian et al. 2006). The total (synchrotron and IC) model spectrum is indicated with a thick (thin) solid line. The IC emission is computed taking into account the CMB (dashed line), dust (dot-dashed line), and starlight (dotted line). The magnetic field is 10 $\mu G$. 

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9 We tested $t_{\text{dec}}$ between 100 yr and 1000 yr, and both $n = 3$ (dipolar rotator model) and $n = 1.6$ (measured; Dodson et al. 2007). $E_0$ has been chosen to yield $\dot{E} = 6.9 \times 10^{36} \text{ erg s}^{-1}$ at the present time.
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Facilities: INTEGRAL (IBIS/ISGRI, SPI), Suzaku (XIS)

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 713, 146
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, A&A, 448, L43
Alvarez, H., Aparici, I., May, J., & Reich, P. 2001, A&A, 372, 636
Arnaud, K. A. 1996, Astron. Data Anal. Softw. Syst. V, 101, 17
Band, D., Matteson, J., Ford, L., et al. 1993, ApJ, 413, 281
Blondin, J. M., Chevalier, R. A., & Frierson, D. M. 2001, ApJ, 563, 806
Bouchet, L., del Santo, M., Jourdain, E., et al. 2009, ApJ, 693, 1871
Bucciantini, N., Arons, J., & Amato, E. 2011, MNRAS, 410, 381
Chevalier, R. A. 2000, ApJ, 539, L45
de Jager, O. C., Harding, A. K., Michelson, P. F., et al. 1996, ApJ, 457, 253
de Jager, O. C., Slane, P. O., & LaMassa, S. 2008, ApJ, 689, L125
Dodson, R., Legge, D., Reynolds, J. E., & McCulloch, P. M. 2003, ApJ, 596, 1137
Dodson, R., Lewis, D., & McCulloch, P. 2007, Ap&SS, 308, 585
Dodson, R., Lewis, D., McConnell, D., & Deshpande, A. A. 2003, MNRAS, 343, 116
Frontera, F., Costa, E., dal Fiume, D., et al. 1997, A&AS, 122, 357
Gaensler, B. M., & Slane, P. O. 2006, ARA&A, 44, 17
Gelfand, J. D., Slane, P. O., & Zhang, W. 2009, ApJ, 703, 2051
Goldwurm, A., David, P., Foschini, L., et al. 2003, A&A, 411, L223
Hales, A. S., Casassus, S., Alvarez, H., et al. 2004, ApJ, 613, 977
Harding, A. K., Strickman, M. S., Gwinn, C., et al. 2002, ApJ, 576, 376
Helfand, D. J., Gotthelf, E. V., & Halpern, J. P. 2001, ApJ, 556, 380
Jourdain, E., Görtz, D., Westergaard, N. J., Natalucci, L., & Roques, J. P. 2008, in Proc. 7th Integral Workshop, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=67
Kardashev, N. S. 1962, SvA, 6, 317
Katsuda, S., et al. 2011, PASJ, in press (arXiv:1103.4872)
LaMassa, S. M., Slane, P. O., & de Jager, O. C. 2008, ApJ, 689, L121
Lebrun, F., Leray, J. P., Lavocat, P., et al. 2003, A&A, 411, L141
Mangano, V., Massaro, E., Bocchino, F., Minco, T., & Cusumano, G. 2005, A&A, 436, 917
Manzali, A., De Luca, A., & Caraveo, P. A. 2007, ApJ, 669, 570
Markwardt, C. B., & Ogelman, H. B 1995, Nature, 375, 40
Moskalenko, I. V., Porter, T. A., & Strong, A. W. 2006, ApJ, 640, L155
Pacini, F., & Salvati, M. 1973, ApJ, 186, 249
Pavlov, G. G., Kargaltsev, O. Y., Sanwal, D., & Garmire, G. P. 2001, ApJ, 554, L189
Pavlov, G. G., Teter, M. A., Kargaltsev, O., & Sanwal, D. 2003, ApJ, 591, 1157
Pellizzoni, A., Trois, A., Tavani, M., et al. 2010, Science, 327, 663
Renaud, M., Gros, A., Lebrun, F., et al. 2006, A&A, 456, 389
Rishbeth, H. 1958, Aust. J. Phys., 11, 550
Sironi, L., & Spitkovsky, A. 2009, ApJ, 698, 1523
Skinner, G., & Connell, P. 2003, A&A, 411, L123
Slane, P., Helfand, D. J., Reynolds, S. P., et al. 2008, ApJ, 676, L33
Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L131
van der Swaluw, E., Achterberg, A., Gallant, Y. A., & Tóth, G. 2001, A&A, 380, 309
van der Swaluw, E., Downes, T. P., & Keegan, R. 2004, A&A, 420, 937
Vedrenne, G., Roques, J.-P., Schönfelder, V., et al. 2003, A&A, 411, L63
Willmore, A. P., Eyles, C. J., Skinner, G. K., & Watt, M. P. 1992, MNRAS, 254, 139
Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, A&A, 411, L1