

PROBING THE RADIO TO X-RAY CONNECTION OF THE VELA X PULSAR WIND NEBULA WITH *FERMI* LAT AND H.E.S.S.

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Received 2008 July 4; accepted 2008 October 10; published 2008 November 13

ABSTRACT

Morphologically, it appears as if the Vela X pulsar wind nebula (PWN) consists of two emission regions: whereas X-ray (~ 1 keV) and very high energy (VHE) H.E.S.S. γ -ray observations appear to define a cocoon-type shape south of the pulsar, radio observations reveal an extended area of size $2^\circ \times 3^\circ$ (including the cocoon area), also south of the Vela pulsar. Since no wide field of view (FoV) observations of the synchrotron emission between radio and X-rays are available, we do not know how the lepton (e^\pm) spectra of these two components connect or how the morphology changes with energy. Currently, we find that two distinct lepton spectra describe the respective radio and X-ray/VHE γ -ray spectra, with a field strength of $5 \mu\text{G}$ self-consistently describing a radiation spectral break (or energy maximum) in the multi-TeV domain as observed by H.E.S.S. (if interpreted as IC radiation), while predicting the total hard X-ray flux above 20 keV (measured by the wide FoV *INTEGRAL* instrument) within a factor of 2. If this same field strength is also representative of the radio structure (including filaments), the implied IC component corresponding to the highest radio frequencies should reveal a relatively bright high-energy γ -ray structure, and *Fermi* LAT should be able to resolve it. A higher field strength in the filaments would, however, imply fewer leptons in Vela X and hence a fainter *Fermi* LAT signal.

Subject headings: gamma rays: theory — ISM: jets and outflows — pulsars: individual (Vela X) — radiation mechanisms: nonthermal — supernova remnants

1. INTRODUCTION

The Vela-Puppis region was first identified as a bright radio region by McGee et al. (1955). Rishbeth (1958) compared Vela X, Y, and Z (the radio counterparts of the Vela supernova remnant [SNR]) and remarked that Vela X is the most prominent radio feature, with the specific distinction of having an almost flat radio spectrum.

A total Vela X radio energy spectrum of the form $F_\nu \propto \nu^{-0.39 \pm 0.03}$ was measured by Alvarez et al. (2001), based on flux measurements up to 8.4 GHz. However, between 8.4 and 30 GHz, Hales et al. (2004) resolved the filamentary and PWN structures and found that the spectra are overall harder: whereas the PWN spectrum is $F_\nu \propto \nu^{0.1 \pm 0.06}$, the filamentary spectrum is of the form $F_\nu \propto \nu^{-0.28 \pm 0.09}$.

Following EGRET observations of the Vela region, de Jager et al. (1996a) showed that the observation of inverse Compton (IC) scattered high-energy (HE) γ -rays from the electron component producing this radio component should allow us to constrain the maximum radio frequency and associated field strength. This electron component should IC scatter three target photon components: the cosmic microwave background radiation (CMBR) field, the Galactic far-infrared radiation (FIR) field produced by reradiation of dust grains, and the local starlight field (Porter et al. 2007).

Further insight into the nature of Vela X was gained by the detection of a cocoon of X-ray emission south of the Vela pulsar by *ROSAT* (Markwardt & Ögelman 1995). The X-ray data (with limited energy extent up to 2.4 keV) were shown to be con-

sistent with a thermal origin, but recently LaMassa et al. (2008) used *XMM-Newton* observations of the southern head of this cocoon to show that the addition of a nonthermal synchrotron component with photon index as steep as ~ 2.3 is favored by the data. By rescaling the H.E.S.S. flux relative to the *XMM-Newton* FoV, a field strength of $5 \mu\text{G}$ was found. Milne (1995) also identified a bright radio filament running along this cocoon, and models for such filaments require a strong thermal component, pulsar-generated magnetic flux, and relativistic particles (Reynolds 1988).

Conclusive proof for the existence of relativistic particles in the X-ray cocoon was revealed by H.E.S.S. observations of the Vela region (Aharonian et al. 2006). In fact, H.E.S.S. detected a spectral maximum from Vela X, which allows us to probe the low-energy spectral component, as well as the energy at which the spectral turnover occurs. An overlay of the H.E.S.S. image in Figure 8 of de Jager & Djannati-Ataï (2008) shows the overlap of the VHE γ -ray cocoon and the bright radio filament referred to by Milne (1995). While a hadronic interpretation was suggested by Horns et al. (2006), de Jager (2007) and de Jager & Djannati-Ataï (2008) reviewed evidence in favor of a leptonic IC origin. Recently, LaMassa et al. (2008) also found that the thermal particle density at the head of the cocoon where bright VHE γ -ray emission was found is only 0.1 cm^{-3} —a factor of 6 lower than the lower limit employed by Horns et al. (2006). This places more stringent constraints on the brightness of a hadronic signal from Vela X.

Mangano et al. (2005) derived an X-ray photon index of 1.50 ± 0.02 within a distance of $0.5'$ from the pulsar. This index represents the uncooled (by synchrotron losses) electron spectral index injected into the PWN, since a steepening is observed for

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distances greater than $0.5'$. The corresponding uncooled postshocked electron spectral index of 2.0 is also consistent with the prebreak spectral index detected by H.E.S.S., if the signal from the latter has an inverse Compton origin.

De Jager (2007) has shown that Vela X most likely consists of a two-component nonthermal spectrum; from Figure 2 of de Jager (2007), the lepton spectrum corresponding to the VHE γ -ray spectrum only connects to the radio lepton spectrum if the field strength of the radio structure is $>200 \mu\text{G}$, if we extrapolate the uncooled lepton index of 2.0 toward the radio domain. However, the field strength in the radio filaments is more likely to be in the range $10\text{--}50 \mu\text{G}$ (Milne 1995).

The observation of an X-ray photon index >2.0 in the cocoon by LaMassa et al. (2008) may be due to synchrotron cooling inside the X-ray band (below 7 keV); to test this we need hard X-ray observations with a FoV covering the full size of Vela X. Only *INTEGRAL* (20–300 keV) has a large enough FoV to cover the extended Vela X (and by default cocoon) region. However, only pointlike unpulsed emission centered on the pulsar (consistent with the $12'$ PSF) with a photon index of -1.86 ± 0.03 was detected by *INTEGRAL* (L. Kuiper 2007, private communication). Thus, synchrotron burnoff must have terminated most emission above 20 keV at distances $>12'$ from the pulsar to levels consistent with the sensitivity of *INTEGRAL*. This spectrum is consistent with the *OSSE* spectrum reported by de Jager et al. (1996b), covering at least the total cocoon region. The *BeppoSAX* PDS, with a FoV of 1.3° (FWHM), also observed the Vela pulsar above 20 keV, covering most of the cocoon region (Mangano et al. 2005). Although the observed photon index of the nebula is slightly steeper (2.00 ± 0.05), the energy flux is comparable to that of *INTEGRAL*.

In this paper we construct a time-dependent postshocked injection spectrum $Q(E,t)$ (where E is the lepton energy). This spectrum consists of two components (as motivated above): $Q_R(E,t)$ as source for the extended radio emission, and $Q_X(E,t)$ as source for the X-ray and VHE γ -ray emission, confined mostly to the cocoon region. In this paper *Fermi* LAT observations should be able to test the spectral connection between Q_X and Q_R .

These two distinct source spectra are normalized to the time-averaged spin-down power, giving conversion efficiencies η_R and η_X of spin-down power to leptons. The time-dependent transport equation with synchrotron losses is then solved to produce the present time electron spectra dN_R/dE and dN_X/dE . The field strength required for the synchrotron loss term is obtained from H.E.S.S. observations, if we assume that the VHE γ -ray signal is the result of IC scattering. Since H.E.S.S. measured the spectral energy maximum, we find the magnetic field strength that reproduces the observed multi-TeV spectral break, so that dN_X/dE is uniquely determined in the energy range 5–100 TeV. We then show that this same dN_X/dE (with B derived from the VHE spectral break) also predicts the total hard X-ray flux from the PWN measured by *INTEGRAL* correctly within a factor of 2. For $\eta_R < 1$ we also show that dN_R/dE (with the above-mentioned B) reproduces the total integrated radio flux, which in turn predicts a high-energy γ -ray component, which can be tested with *Fermi* LAT.

2. DOUBLE SOURCE SPECTRUM OF VELA X

In the discussion below we neglect (to a first order) the effect of adiabatic cooling on the spectrum (Pacini & Salvati 1973), since the reverse shock (applicable to Vela X) is expected to have adiabatically heated the particles during the PWN crushing

phase. Energy losses due to adiabatic cooling during the pre-crushing phase is then partially canceled during the crushing phase (S. E. S. Ferreira & O. C. de Jager 2008, in preparation).

Let $Q_R(E,t)$ and $Q_X(E,t)$ be the respective source spectra corresponding to the radio and X-ray synchrotron components, and $L(t)$ be the time-dependent spin-down power, of which fractions η_R and η_X are converted to these two components. Based on the discussion in § 1, we model these source spectra as

$$Q_R(E,t) = Q_{0,R}(t)(E/E_{\max,R})^{-p} \quad (1)$$

$$Q_X(E,t) = Q_{0,X}(t)(E/E_{\max,X})^{-2}, \quad (2)$$

for $E_{\min,R} < E < E_{\max,R}$ and $E_{\min,X} < E < E_{\max,X}$ in the two respective equations. These upper and lower limits are currently weakly constrained by observations. The radio spectral index of 0.39 requires a particle index of $p = 0.39 \times 2 + 1 = 1.78$, whereas an X-ray (VHE γ -ray) lepton spectral index of 2 would reproduce the uncooled photon spectral index of 1.5. By requiring the total energy in each respective component to be a fraction $\eta_R < 1$ and $\eta_X < 1$ (with $\eta_R + \eta_X \leq 1$) of the spin-down power, we can show that (with the minimum electron energy for the radio component much smaller than the corresponding maximum),

$$Q_R(E,t) \sim \left[\frac{\eta_R L(t)(2-p)}{E_{\max,R}^{2-p}} \right] E^{-p}, \quad (3)$$

$$Q_X(E,t) = \left[\frac{\eta_X L(t)}{\ln(E_{\max,X}/E_{\min,X})} \right] E^{-2}. \quad (4)$$

Neglecting adiabatic losses (as discussed above), but including radiation losses with timescale $\tau_{\text{rad}}(E) = E/(dE/dt)_{\text{rad}}$, where $(dE/dt)_{\text{rad}}$ is the sum of the synchrotron and IC (Klein-Nishina effects included) energy-loss rates, the transport equation can be solved to give the present day (age T) total particle spectrum for each component $i = R, X$ as (see, e.g., Zhang et al. 2008)

$$\frac{dN_i(E,T)}{dE} = \int_0^T Q_i(E,t) \exp\left[-\frac{T-t}{\tau_{\text{rad}}(E)}\right] dt. \quad (5)$$

This expression effectively allows leptons to be accumulated over time T in the nebula. The resulting spectrum dN/dE is, however, modulated (steepened) at the high-energy tail by radiation losses.

Since radiation losses are negligible for the radio component, the integral over the source term Q_R yields the change in rotational kinetic energy [$\Delta KE_{\text{rot}} = I(\Omega_0^2 - \Omega^2)/2$] since birth, as shown by de Jager (2008), so that (for $p < 2$)

$$\frac{dN_R(E,T)}{dE} = \frac{\bar{\eta}_R(2-p)\Delta KE_{\text{rot}}}{E_{\max,R}^{2-p}} E^{-p}. \quad (6)$$

The term $\bar{\eta}_R$ is the time-averaged conversion efficiency. Van der Swaluw & Wu (2001) found that a pulsar birth period of $P_0 = 40\text{--}50$ ms is required to reproduce the observed ratio (~ 0.25) between the PWN and SNR radius. The recently measured pulsar braking index $n = 1.6 \pm 0.1$ (Dodson et al. 2007) implies an age between $T = 11$ and 15 kyr, given the above-mentioned range for P_0 . This range of values (or exact choice of braking index) do not change our conclusions significantly.

TABLE 1
PARAMETERS ASSOCIATED WITH THE TWO LEPTON COMPONENTS OF
VELA X

Band	η	p	E_{\min}	E_{\max} (eV)	ν_{\max} (Hz)	E_{tot} (erg)
Radio	0.35	1.78	$m_e c^2$	2×10^{10}	10^{10}	3×10^{48}
Radio	0.45	1.78	$m_e c^2$	6×10^{10}	10^{11}	4×10^{48}
X-ray	0.003	2.0	$m_e c^2$	3×10^{15}	2×10^{20}	2×10^{46}

NOTES.—For a pulsar birth period of 40 ms, and an assumed braking index of 2.5, to give an age of 11 kyr. E_{tot} is the total lepton energy between E_{\min} and E_{\max} .

3. PARTICLE, SYNCHROTRON, AND IC SPECTRA OF THE COCOON

The lepton spectrum for the X-ray/VHE γ -ray emission region (mostly the cocoon region) derived from equation (5) (parameters in Table 1) is constrained by the following information: an injection (uncooled) lepton spectral index of 2.0 as discussed in § 1, the IC normalization of the VHE cocoon spectrum as provided by H.E.S.S. (Aharonian et al. 2006), the multi-TeV break energy observed by H.E.S.S., spin-down from $P_0 = 40$ ms to the current period of 89 ms within time T (~ 11 – 15 kyr), an implied time-averaged conversion efficiency of $\bar{\eta}_x = 3 \times 10^{-3}$, and a field strength of $5 \mu\text{G}$ to reproduce the observed VHE break energy.

It is clear that this model IC spectrum agrees relatively well with H.E.S.S. measurements (Fig. 1, thick solid line at very high γ -ray energies). The CMBR mostly contributes to this spectrum, whereas higher energy contributions from the galactic FIR and starlight photon fields are suppressed due to Klein-Nishina effects. However, in the next section we will see

that the latter two radiation fields contribute significantly to the high-energy IC γ -ray counterpart of the radio spectrum, where the IC scattering is in the Thomson limit.

The lepton spectrum of the cocoon, if self-consistent, should be able to predict the total X-ray spectrum from Vela X. From Figure 1 it is clear that the model synchrotron spectrum shows a radiation break around 1 keV (~ 2 to 3×10^{17} Hz) and predicts the 20–300 keV *INTEGRAL* flux within a factor of 2, although with a steeper spectrum. The latter is expected to harden if we allow the field strength to increase toward the pulsar in a more sophisticated model incorporating a spatial dependence as well.

4. PARTICLE, SYNCHROTRON, AND IC SPECTRA OF THE TOTAL VELA X PWN

To first order we assumed the same field strength (5×10^{-6} G) in the entire Vela X structure as found for the cocoon (LaMassa et al. 2008). This may not be the case, but by comparing *Fermi* LAT with high-frequency radio observations we should be able to measure the field strength in this extended structure if the high-frequency (radio) cutoff or turnover can be independently determined. In this case, synchrotron cooling is negligible, and the steady state spectrum is given by equation (6). To reproduce the absolute radio flux (for a particle index of $p = 1.78$), we had to assume efficiencies of $\eta_R = 0.35$ and 0.45, corresponding to assumed spectral cutoffs of 10^{10} and 10^{11} Hz, respectively. The leptonic parameters corresponding to the latter cutoff is listed in Table 1 as “radio.” From Figure 1 it is clear that the maximum frequency should be $>10^{10}$ Hz.

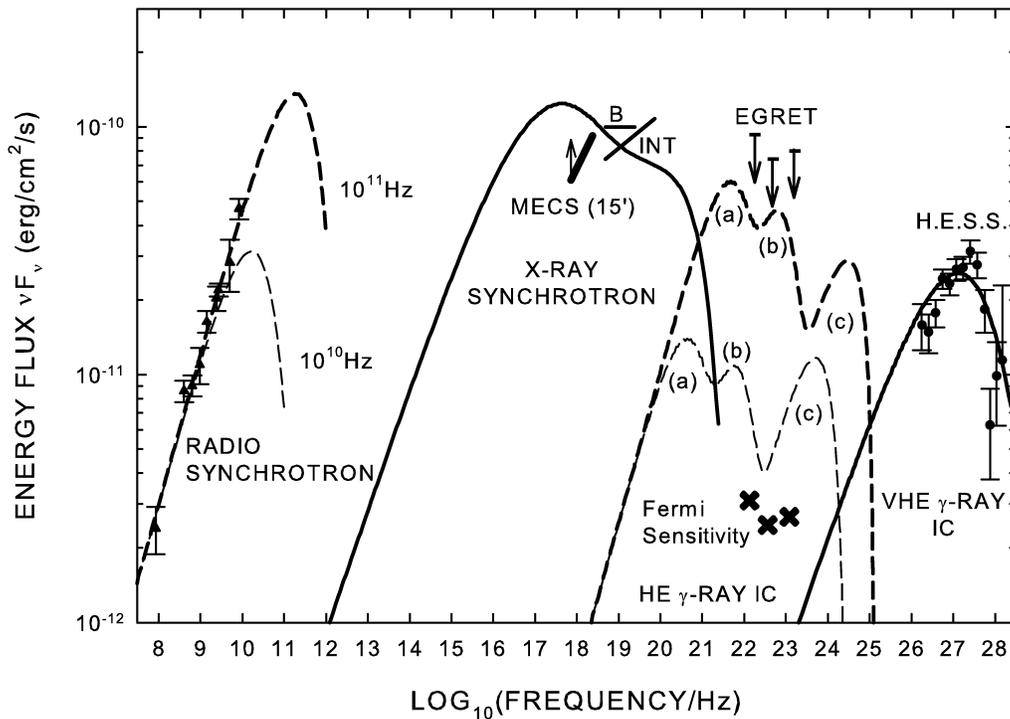


FIG. 1.—Dashed lines: Radio synchrotron and high-energy (HE) IC γ -ray spectra of the total $2^\circ \times 3^\circ$ Vela X structure corresponding to synchrotron cutoffs of 10^{10} Hz (thick dashed line) and 10^{11} Hz (thin dashed line). Also shown are HE IC γ -ray features from scattering on (a) the CMBR, (b) FIR, and (c) starlight. Thick solid lines: The X-ray synchrotron and VHE γ -ray IC spectra including spin evolution. Triangles: Radio flux measurements from Alvarez et al. (2001). Circles: H.E.S.S. data from Aharonian et al. (2006). Short thick solid lines: *INTEGRAL* (“INT”) data from L. Kuiper (2007, private communication), *BeppoSAX* “MECS” shown as a lower limit for an extraction radius of $15'$ and PDS (“B”) from Mangano et al. (2005). Arrows: EGRET Vela X ULs from de Jager et al. (1996a). Crosses: *Fermi* LAT 1 yr sensitivity from EGRET ULs, scaled down by $\times 30$.

While the lack of high-frequency radio measurements prohibits a clear constraint on the cutoff of this component, *Fermi* LAT observations can constrain the maximum of the spectral energy distribution of leptons in the radio nebula. As an example, we employ cutoffs at the above-mentioned two frequencies to calculate the corresponding expected high-energy γ -ray spectra. These predictions are shown by dashed lines in Figure 1 (marked “HE γ -ray IC”). The hard lepton spectrum followed by an assumed cutoff at an electron energy $E_{\text{max,R}} = \gamma_{\text{max,R}} mc^2$ should produce broad γ -ray features at three energies $3.6\gamma_{\text{max,R}}^2 kT_i$, corresponding to temperatures $T_i = 2.7$ K (CMBR), 25 K (FIR), and ~ 4000 to ~ 8000 K (starlight).

Although these energy densities are comparable in the local neighborhood (Porter et al. 2007), we investigate deviations at the location of Vela X. The IRAS-Vela shell (IVS) of dark clouds and cometary globules centered on ($\ell = 259.85^\circ$, $b = -8.25^\circ$), with a radius of $(5.1^\circ \pm 0.2^\circ)$ and annular rms width of $\sim 2^\circ$, is located at a distance of ~ 400 pc (Testori et al. 2006). With a $100 \mu\text{m}$ IRAS ring flux of ~ 10 MJy sr^{-1} we obtain a luminosity of $\sim 10^{38}$ erg s^{-1} , and assuming a distance of $r = 100$ pc between the IVS center and Vela X, we obtain an additional FIR energy density of $0.002(100 \text{ pc}/r)^2 \text{ eV cm}^{-3}$ at Vela X, which is well below our assumed local averaged energy density. Other potential target photon fields from the Vela molecular ridge and Gum Nebula are located directly behind the Vela pulsar (Sahu 1992), so that the contribution from these local clouds would be severely suppressed by the head-on-tail effect of the IC process, since the $(1 - \cos \theta)^2$ term (with θ small) in the energy-loss rate term is much less than unity.

Furthermore, fluctuations in the local distribution of stars can also produce deviations in the starlight energy density at Vela X. To investigate this, we extracted the *Hipparcos* catalog of $\sim 118,000$ stars, of which $\sim 73,000$ have parallax measurements at the $>3 \sigma$ detection level. This subset was used to calculate the starlight energy density at any three-dimensional field point within ~ 300 pc from Earth. Within ~ 20 pc from Earth we obtain a value of $U_{\text{rad}} = 0.24 \text{ eV cm}^{-3}$, consistent with Porter et al. (2007), whereas a value of $U_{\text{rad}} = 0.44 \pm 0.12 \text{ eV cm}^{-3}$ is obtained for the Vela PWN, with the error reflecting the uncertainty in the distance to the Vela pulsar (Dodson et al. 2003). This mean value (0.44 eV cm^{-3}) was used in Figure 1, but assuming a mean temperature of 7500 K to account for the stellar types contributing to this excess.

While the *Fermi* LAT Web page² only lists sensitivities for

² http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.

point sources, we scale the actual EGRET upper limits for the Vela X extended source (extracted from the unpulsed sky maps) obtained by de Jager et al. (1996a) by a factor of 30 downward to account for the improved *Fermi* LAT sensitivity in the same energy bands, for an integration time of 1 yr, employing the sky map corresponding to the full pulse phase after subtracting the point-spread function. The EGRET integral flux upper limits and *Fermi* LAT sensitivities are shown in Figure 1.

5. DISCUSSION AND CONCLUSIONS

In this paper we have shown that a pulsar birth period of ~ 40 ms (to reproduce the observed ratio of PWN to SNR radii), spinning down within 11–15 kyr to the present period of 89 ms while converting $\eta_X \sim 0.3\%$ of its spin-down power to leptons (e^\pm) in the PWN with a spectral index of 2, would reproduce the observed H.E.S.S. flux in the Vela X cocoon via the IC process. A nebular averaged field strength of $5 \mu\text{G}$ would also reproduce the observed TeV spectral break. Furthermore, this same spectrum predicts the *BeppoSAX* PDS and *INTEGRAL* total fluxes within a factor of 2.

Assuming the same $5 \mu\text{G}$ field strength in the much larger $2^\circ \times 3^\circ$ Vela X radio nebula, we need to invoke a second e^\pm component with electron spectral index 1.78 and a much larger conversion efficiency $\eta_R \sim 0.4$ to reproduce the observed total radio spectrum up to at least 8.9 MHz and possibly 30 MHz. This spectrum should cut off or steepen significantly to meet the less energetic cocoon spectrum.

The implication of this second (radio) component is the prediction of an IC component at HE γ -rays covering the same $2^\circ \times 3^\circ$ area south of the pulsar. The visibility of this component in the HE γ -ray domain for *Fermi* LAT is further improved due to the existence of the local FIR and starlight target photon fields, scattered by the highest energy leptons in this second component up to ~ 10 GeV γ -rays (in the Thomson limit), where *Fermi* LAT has good sensitivity.

If the electrons radiating the radio component are trapped in compressed regions (e.g., filaments) with field strength $\gg 5 \mu\text{G}$, we would require fewer leptons and hence lower efficiency η_R to reproduce the radio emission. A HE γ -ray flux measurement, or upper limit thereof, will provide constraints on this field and hence η_R .

P. O. Slane acknowledges support from NASA contract NAS8-39073. The referee is thanked for useful comments.

REFERENCES

- Aharonian, F. A., et al. (H.E.S.S. Collaboration), 2006, *A&A*, 448, L43
 Alvarez, H., Aparici, J., May, J., & Reich, P. 2001, *A&A*, 372, 636
 de Jager, O. C. 2007, *ApJ*, 658, 1177
 ———. 2008, *ApJ*, 678, L113
 de Jager, O. C., & Djannati-Ataï, A. 2008, in *Neutron Stars and Pulsars: 40 Years After Their Discovery*, ed. W. Becker (Berlin: Springer), in press (arXiv:0803.0116)
 de Jager, O. C., Harding, A. K., Sreekumar, P., & Strickman, M. 1996a, *A&AS*, 120, 441
 de Jager, O. C., Harding, A. K., & Strickman, M. S. 1996b, *ApJ*, 460, 729
 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
 Hales, A. S., et al. 2004, *ApJ*, 613, 977
 Horns, D., et al. 2006, *A&A*, 451, L51
 LaMassa, S., Slane, P. O., & de Jager, O. C. 2008, *ApJL*, 689, in press
 Mangano, V., Massaro, E., Bocchino, F., Mineo, T., & Cusumano, G. 2005, *A&A*, 436, 917
 Markwardt, C. B., & Ögelman, H. 1995, *Nature*, 375, 40
 McGee, R. X., Slee, O. B., & Stanley, G. J. 1955, *Australian J. Phys.*, 8, 347
 Milne, D. K. 1995, *MNRAS*, 277, 1435
 Pacini, F., & Salvati, M. 1973, *ApJ*, 186, 249
 Porter, T. A., Digel, S. W., Grenier, I. A., Moskalenko, I. V., & Strong, A. W. 2007, in *Proc. 30th Int. Cosmic-Ray Conf. (Merida, Mexico)* (arXiv:0706.0221)
 Reynolds, S.P. 1988, *ApJ*, 327, 853
 Rishbeth, H. 1958, *Australian J. Phys.*, 11, 550
 Sahu, M. S. 1992, Ph.D. thesis, Univ. Groningen
 Testori, J. C., Arnal, E. M., Morras, R., Bajaja, E., Pöppel, W. G. L., & Reich, P. 2006, *A&A*, 458, 163
 van der Swaluw, E., & Wu, Y. 2001, *ApJ*, 555, L49
 Zhang, L., Chen, S. B., & Fang, J. 2008, *ApJ*, 676, 1210