Spatially resolved XMM-Newton analysis and a model of the nonthermal emission of MSH 15–52

F.M. Schöck1, I. Büsching2, O.C. de Jager2, P. Eger1, and M.J. Vorster2

1 Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Straße 1, 91058 Erlangen, Germany
2 Unit for Space Physics, North-West University, Potchefstroom, 2520, South Africa

Preprint online version: May 6, 2010

ABSTRACT

We present an X-ray analysis and a model of the nonthermal emission of the pulsar wind nebula (PWN) MSH 15–52. We analyzed XMM-Newton data to obtain the spatially resolved spectral parameters around the pulsar PSR B1509–58. A steepening of the fitted power-law spectra and decrease in the surface brightness is observed with increasing distance from the pulsar. In the second part of this paper, we introduce a model for the nonthermal emission, based on assuming the ideal magnetohydrodynamic limit. This model is used to constrain the parameters of the termination shock and the bulk velocity of the leptons in the PWN. Our model is able to reproduce the spatial variation of the X-ray spectra. The parameter ranges that we found agree well with the parameter estimates found by other authors with different approaches. In the last part of this paper, we calculate the inverse Compton emission from our model and compare it to the emission detected with the H.E.S.S. telescope system. Our model is able to reproduce the flux level observed with H.E.S.S., but not the spectral shape of the observed TeV γ-ray emission.

Key words. X-rays: individuals: MSH 15–52; ISM: supernova remnants; ISM: individual objects: MSH 15–52; ISM: jets and outflows

1. Introduction

MSH 15–52 (G320.4−1.2) is a complex supernova remnant (SNR) that was discovered in radio wavelengths by Mills et al. [1961]. Its radio appearance is dominated by two spots, a brighter one to the northwest and a fainter one to the southeast. The radio emission to the northwest coincides spatially with the H II region RCW 89. Situated inside the SNR is the energetic 150 ms pulsar PSR B1509–58, which was discovered by the Einstein satellite [Seward & Harnden 1982]. It has a spin-down luminosity of $E = 1.3 \times 10^{33}$ erg/s and a characteristic age of $\tau = 1.7$ kyr [Kaspi et al. 1994]. This makes the pulsar one of the youngest and most energetic known. Gaensler et al. [1999] concluded by a comparison of the radio and the X-ray emission that MSH 15–52, PSR B1509–58 and RCW 89 are associated objects and are located at a distance of $(5.2 \pm 1.4)$ kpc.

X-ray observations of the SNR have shown a pulsar wind nebula (PWN) powered by PSR B1509–58 (Trussoni et al. [1996], Tamura et al. [1996]). Observations with the Chandra satellite have revealed two outflow jets in the southeast and northwest directions, the latter terminating in the optical nebula RCW 89 [Gaensler et al. 2002, henceforth referred to as G02]. G02 derived a power-law photon index of $2.05 \pm 0.04$ and an absorption column density of $(9.5 \pm 0.3) \times 10^{21}$ cm$^{-2}$ for the diffuse PWN in the energy band of 0.5-10 keV. A detailed study of the innermost region of MSH 15–52 was performed by Yatsu et al. [2003, henceforth referred to as Y09] using an extended data set of Chandra observations. Their analysis revealed hints for a ring-like feature around the pulsar, which might correspond to a wind termination shock. The hard X-ray spectrum of the PWN was observed with the BeppoSAX and the INTEGRAL satellites. The PWN is clearly seen in the off-pulse component of the emission and the morphology corresponds nicely to the measurements at lower energies. In the energy band of 20-200 keV, the off-pulse emission from the PWN is fitted best by a power law with an index of 2.1 [Mineo et al. 2001, Forot et al. 2004].

In the very high-energy (VHE; 100 GeV-100 TeV) γ-ray domain, the PWN was observed by the High Energy Stereoscopic
Table 1. Details of the XMM-Newton EPIC PN observations on MSH 15−52.

| Observation ID | Exposures (ks) performed | Exposure time without background screening (1) | Net exposure time after background screening (2) |
|----------------|--------------------------|---------------------------------------------|-----------------------------------------------|
| 0207052001     | 23.135                   | 5.9                                         |                                               |
| 0302730201     | 16.130                   | 3.6                                         |                                               |
| 0302730301     | 8.235                    | 2.0                                         |                                               |

(1) Exposure time without background screening
(2) Net exposure time after background screening

Table 2. Extraction regions for the XMM-Newton spectral analysis of the source.

| Ring No. | Radius (arcsec) | No. of Obs. |
|----------|-----------------|-------------|
| 0        | 30              | 2           |
| 1        | 57              | 2           |
| 2        | 84              | 2           |
| 3        | 138             | 3           |
| 4        | 192             | 3           |
| 5        | 246             | 1           |
| 6        | 300             | 2           |

System (H.E.S.S.). The source is clearly extended beyond the point spread function (PSF) and shows a morphology comparable to what is seen in X-rays, extending northwest and southeast of the pulsar. The observed γ-ray emission is well-fitted by a power law with a photon index of 2.27 up to a photon energy of 40 TeV (Aharonian et al. 2005).

In the first part of this paper, we present an analysis of the XMM-Newton data of the PWN MSH 15−52. Its large effective area makes XMM-Newton ideally suited for the spectral analysis of extended sources. Our analysis thus provides a good measurement of the large-scale characteristics of MSH 15−52, compared to earlier high-resolution measurements of the inner region with the Chandra satellite. Following the XMM-Newton analysis, we introduce a model which is based on the assumption of the ideal magnetohydrodynamic limit to describe the observed emission in the X-ray domain. Fitting the spatially resolved X-ray emission with the model, we found optimum parameters for several scenarios that have been discussed by other authors. This allows us to constrain physical quantities of the PWN termination shock and the velocity profile of the PWN. In the last part, we also apply this model to make predictions for the VHE γ-ray emission as observed by the H.E.S.S. Cherenkov telescope array.

2. XMM-Newton Observations

The region around the SNR MSH 15−52 has been observed six times with XMM-Newton (Jansen et al. 2001) with the EPIC-MOS (Turner et al. 2001) and EPIC-PN (Strüder et al. 2001) cameras. These pointings were either centered north or southeast of the pulsar PSR B1509−58. During one of these pointings (Observation ID: 0312590101), all three cameras were operated in timing mode. Therefore, this observation will not be considered in the present paper. In order to study the morphology-dependent spectral characteristics of the extended emission, we require the whole area of our interest to be within the field of view (FoV). Only the three observations pointing towards the northern region matched this criterion. In each of them the detectors were operated in full-frame mode with medium optical blocking filters. The observations used in our analysis are listed in Table 1.

For the analysis of the X-ray data we used the XMM-Newton Science Analysis System (SAS) version 8.0.0 supported by tools from the FTOOLS package. For the spectral modeling, version 12.5.0 of the XSPEC software was used (Arnaud 1996). To screen the data from periods of high background-flaring activity, we used the 7 to 15 keV lightcurve provided by the standard SAS analysis chain extracted from the full FoV. Since a good understanding of the background is crucial for the analysis of extended sources, we applied a conservative background threshold of ten background counts per second for the definition of the good time intervals (GTI). Furthermore, we only analyzed the data of the PN camera since it is more sensitive than the MOS cameras. We selected good (FLAG= 0) single and double events (PATTERN<= 4). The innermost region used for the spectral analysis starts at a radius of 30 arcsec from the bright pulsar and therefore, pile-up is not an issue. All of the observations were affected by long periods of background flaring or full scientific buffer of the PN camera. This leads to rather short net exposures (see Table 1). However, the statistics are still sufficient to obtain spectra from all of the extraction regions as defined in the next section.

3. X-ray Spectra

We extracted spectra from annular regions centered on the pulsar position (R.A.: 15:13:55, Dec.: -59:08:08.8) to study the changes of the spectral properties. The regions can be seen on the XMM-Newton sky map (Fig. 1). We use full annuli in contrast to wedge shapes, to extract the integral flux for each radial distance. This is especially important for the modeling of the flux of the source, which is presented in Section 4. The parameters for the rings are listed in Table 2. The numbering scheme starts with ring 1, which is closest to the pulsar, and goes out to ring 6, for which the outer radius lies at a distance of 300 arcseconds from the pulsar position. Beyond the distance of 300 arcseconds the emission seems to bend sideways significantly. Since the model (see Sec. 4) assumes a radial symmetry, we did not extract spectra for any regions beyond this distance.

In order to avoid systematic effects from the CCD borders, we extracted the spectra for each detector CCD separately. The background for each CCD was estimated using infield background regions from the same chip. This minimizes systematic uncertainties on the flux, compared to a background estimation from blank-sky observations. The effective areas and energy responses for each detector CCD were calculated by weighting the contribution from each pixel with the flux using a detector map from the FTOOLS package. For the spectral modeling, version 8.0.0 of the XSPEC package was used.
Table 3. Results obtained by fitting a power-law spectrum to the XMM-Newton data of MSH 15–52.

| Ring No. | $\Gamma$ | Flux $(10^{-12}$ erg cm$^{-2}$ s$^{-1})$ | Surface Brightness $(10^{-17}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2})$ | $\chi^2$/dof |
|---------|---------|-------------------------------------|-----------------------------------------------|---------------|
| 1       | 1.66 ± 0.02 | 12.0 ± 0.3                          | 162 ± 4.5                                      | 147/161       |
| 2       | 1.78 ± 0.03 | 10.0 ± 0.3                           | 92 ± 3.0                                       | 161/147       |
| 3       | 1.88 ± 0.02 | 2.9 ± 0.07                           | 9.2 ± 0.2                                      | 431/459       |
| 4       | 1.96 ± 0.02 | 3.1 ± 0.09                           | 6.1 ± 0.2                                      | 356/536       |
| 5       | 2.07 ± 0.05 | 2.4 ± 0.1                            | 3.4 ± 0.2                                      | 97/156        |
| 6       | 2.24 ± 0.28 | 0.4 ± 0.2                            | 0.5 ± 0.3                                      | 62/107        |

Fig. 2. Spectrum and power-law fit for the first extraction region (ring 1). Two observations were used for the analysis of this region (cf. Table 2). The resulting fit parameters are listed in Table 3.

The resulting parameters for the spectral analysis of each ring are listed in Table 3. The data are fitted very well by pure power laws. Due to the increasing size of the extraction region and the constant area of the infield background, the statistical uncertainty of the spectra of the outer regions is greater, resulting in a lower value of $\chi^2$/dof. We obtain an absorption density of $N_H = (1.15 \pm 0.03) \times 10^{21}$ cm$^{-2}$ using the abundance tables of Wilms et al. (2000). This is in good agreement with results of previous X-ray analyses of this source (see e.g. G02). The extended emission of MSH 15–52 shows variation in the spectra of the different regions versus the mean distance of the extraction regions to the pulsar. A steepening of the spectrum is observed with increasing distance.

Fig. 3. Spectral index of the power-law fit to the XMM-Newton data of the different regions versus the mean distance of the extraction regions to the pulsar. A steepening of the spectrum is observed with increasing distance.

4. The Model

4.1. Injection Spectrum

At the termination shock of the pulsar wind, particles are accelerated and injected into the PWN (Gaensler & Slane 2006). In our model, we assume a certain particle injection spectrum at the termination shock and propagate the particles radially outward. The shape of the spectrum is chosen based on observational constraints rather than on a detailed physical model, which would be beyond the scope of our model. We assume that the particle injection spectrum $Q(E, t)$ at the shock radius $R_S$ follows a power-law distribution. Earlier papers on the modeling of PWN concluded that the injection spectrum should follow a broken power law.

...
In this expression, \( \kappa \) is the compression ratio at the shock and \( \sigma \) is the magnetization parameter (ratio of the magnetic energy flux to the particle energy flux). The second condition comes into effect for strong magnetic fields. In this case the maximum lepton energy is limited by the synchrotron emission that the lepton radiates. Thus, the maximum energy is limited to

\[
e_{e,\text{max}} < 43.84 B^{-1/2} \text{erg},
\]

where \( B \) is the magnetic field strength in Gauss. The lower \( E_{e,\text{min}} \) obtained with the two limits is then used for Eq. [(1)](#).
we find that the spatial variation of the X-ray and TeV spectra is already adequately described by this parametrization, so that an introduction of additional free parameters would not necessarily give more information about the system.

The next step is to look at the change of the lepton spectrum as the particles propagate away from the pulsar wind shock. The particles lose energy due to adiabatic losses and synchrotron radiation in the magnetic field of the PWN. The total energy loss of the particles is given by (cf. [de Jager & Harding 1992]):

\[
\frac{dE}{dt} = -E \nabla \cdot \mathbf{v}_\perp(r) - 2.368 \times 10^{-3} (B_0(r)E)^{2},
\]

where the first part represents the adiabatic losses and the second part the energy losses due to synchrotron radiation.

4.3. Emission Spectra

The parameters of the lepton population and the magnetic field are described for all locations in the PWN by the Eqs. [5] to [8]. With this information, we are able to calculate the spectra of the synchrotron and inverse Compton radiation emitted by the leptons. For the calculation of the two emission processes, we use the standard equations by Blumenthal & Gould (1970).

By comparing the measured synchrotron spectra with the calculated spectra we are able to constrain the free parameters of our model.

5. Parameter Optimization

The optimization of the parameters of the model, as introduced in Section 4, was carried out by dividing the PWN into a number of shells. As discussed in the previous section, the values of \( v \) and \( B \) are known for every location in the PWN, thus enabling us to calculate the amount of energy lost by a particle during its propagation from the shock to a specified shell. This, in turn, allows us to calculate the lepton spectrum that enters a shell, as well as the change in the lepton spectrum as it propagates through the shell. To calculate the corresponding nonthermal spectra, the initial lepton spectrum is used. This is sufficient, provided that the size of the shells is chosen small enough. The modified spectrum is then used as the injection spectrum for the following shell. For the first shell, the lepton spectrum is calculated by making use of Eq. [1] i.e. the lepton injection spectrum at the shock.

Since our modeling focuses only on the X-ray synchrotron component, we use a single power law, with \( E > E_0 \), for the lepton injection spectrum. The index of the lepton spectrum is derived from measurements of the photon spectrum close to the termination shock with the Chandra X-ray telescope, which yielded a photon index of around 1.5 (Y09). Assuming that the lepton population emitting this spectrum has not undergone any significant cooling, the spectral index of the lepton spectrum is then equal to 2, which we adopt for our optimizations. G02 concluded that the spectral break between the comparatively flat radio spectrum and the steeper synchrotron spectrum is just below the X-ray band. Thus it is reasonable to assume \( E_{\min} \) to be of order 1 erg. Since only the logarithm of \( E_{\min} \) contributes to the normalization of the spectrum, a variation of \( E_{\min} \) does not change the spectral shape and has little effect on the total flux.

The remaining free parameters of the model are the shock radius \( R_S \), the bulk velocity of the leptons at the shock \( v_S \), the index of the velocity profile \( \alpha \), the conversion efficiency of spin-down luminosity into lepton energy \( \eta \) and the parameter \( \xi \), which links the magnetization \( \sigma \) and the compression \( \kappa \) of the shock. The parameters \( R_S \) and \( v_S \) are restricted by the observations of G02 and Y09, whereas the other parameters are left unconstrained for the optimization. To determine the optimum fit to the synchrotron spectra for the different scenarios, we minimized the \( \chi^2 \) test statistic for the XMM-Newton data points and the calculated model flux points.

For PSR B1509−58, G02 and Y09 both estimated the termination shock radius using Chandra data, but do not find consistent results. G02 favor a scenario in which a feature at 0.5 pc corresponds to an internal structure in the termination shock. They also estimated the \( \sigma \) value for several compact knots of emission less than 0.5 pc away from the pulsar and concluded that the transition to a particle-dominated wind should occur at a distance less than 0.1 pc from the pulsar. Y09 analyzed a considerably larger data set of Chandra observations and used image enhancement techniques to resolve the detailed structure of the inner region around PSR B1509−58. According to their results, the termination shock is located at a distance of \( 9^{+4}_{−2} \) pc from the pulsar, which corresponds to a termination shock radius of \( R_S = 0.225 \) pc. For the magnetization parameter, Y09 derived a value of \( \sigma = 0.01 \), which is about a factor of 2 greater than the result obtained by G02.

Based on the two analyses, we considered three scenarios with different values for \( R_S \) for the optimization procedure of our model. In Scenario I we assume that the termination shock is unresolved in the Chandra observations by G02 and Y09 and thus is at a distance closer than 0.1 pc from the pulsar. For Scenario II we assume a distance of \( R_S = 0.5 \) pc, while for Scenario III we adopt the value of \( R_S = 0.225 \) pc, as stated by Y09.

G02 and Y09 both assume a shock velocity of \( v_S \approx c/3 \). The same value was also found for other PWN, e.g. the Crab Nebula (Kennel & Coroniti 1984a). Furthermore, this shock velocity is in good agreement with the lower limit that G02 determined from the energetics of the PWN. Therefore, we also adopted this value for our calculations. We do not constrain the remaining parameters \( \alpha \), \( \eta \) and \( \xi \), except for the straightforward assumption that the conversion efficiency \( \eta \) should be in the interval \( 0 < \eta < 1 \). Table 4 gives an overview of the three scenarios and the constraints on the parameters, which we used for the modeling described in the next section.

| Parameter | Scenario I | Scenario II | Scenario III |
|-----------|------------|-------------|--------------|
| \( R_S \) [pc] | < 0.1 | 0.5 | 0.225 |
| \( v_S \) [c] | 1/3 | | |
| \( \alpha \) | no constraint | | |
| \( \eta \) | 0 | | |
| \( \xi \) | no constraint | | |

6. Results of the Modeling

Using the model and the parameter constraints described in the previous section, we calculated the optimum parameters for the three scenarios defined in Section 5. The results of the optimization show that the Scenarios II and III (larger shock radius) yield a better fit to the data than Scenario I (small shock radius). For Scenario I we do not have a fixed value for \( R_S \). We thus leave it as...
a free parameter for the simulations. The best fit for this scenario is obtained for a value of $R_S = 0.1$ pc which is the upper limit for $R_S$ (see Table 4). However, even the best fit of Scenario I does not give a satisfactory result. Due to the small shock radius, the synchrotron cooling is very efficient and leads to a strong cutoff in the X-ray spectra for the outer rings, which is not consistent with the observed emission.

The results obtained for Scenario II yield a better fit to the data. In this scenario the shock radius is considerably larger. Thus, the leptons accelerated at the termination shock suffer from less synchrotron cooling up to ring 1 of the XMM-Newton measurement. Figure 5 shows as an example the data and model synchrotron spectra for rings 1 and 6 for the optimum set of parameters found in Scenario II. Even the best-fit model spectrum deviates significantly from the XMM-Newton spectrum, but this is expected due to the simplifications of our model. The general trend, however, reproduces the spectral shape and the observed flux level. The spectral index with increasing distance of the extraction region from the pulsar is plotted in Fig. 6. The best-fit model is able to reproduce the variation of the spectral index. As shown in Fig. 7 the change in surface brightness with increasing distance of the extraction regions to the pulsar is also reproduced. For Scenario III we also get a good fit to the data. Figure 8 shows the spectra for the optimum set of parameters found in Scenario III, again for rings 1 and 6. The spectral index and the surface brightness with increasing distance can be seen in Figs. 9 and 10. The shape is also reproduced well for this scenario.

The results obtained for Scenarios II and III constrain the range of the model parameters. Since the parameters are correlated, it is only possible to state parameter ranges. For Scenario II we found that the index of the velocity profile is in the range of $\alpha = 0.4 - 0.6$. The conversion efficiency is greater than 0.3 for this scenario and $\xi$ ranges between 0.3 and 1.3. The compression ratio $\kappa$ varies between 1 and 3 for relativistic shocks. We can thus translate the range of $\xi$ to the result that $\sigma > 0.01$, which is a factor of 2 more than the lower limit derived by G02. For Scenario III, we found the same range for $\alpha$ and $\eta$, but a narrower lower limit on the magnetization parameter, $\sigma > 0.005$. This is lower than the limit that Y09 found in their estimate based on the equipartition assumption. In summary, we can state that our results support a shock radius of the order of $0.2 - 0.5$ pc. However, we are not able to favor one scenario above the other. For the conversion efficiency, we found a lower limit of $\eta > 0.3$ for Scenario II and III. This agrees very well with the result of the time-dependent one-zone model by Zhang et al. (2008). The magnetic field estimates for MSH15–52 range between 8 $\mu$G (G02) and 25 $\mu$G (Zhang et al. 2008). The spatial evolution of the magnetic field with distance for our model can be seen in Fig. 11. Our predictions for the magnetic field in the PWN agree with the estimates from the other authors. The lower limit of $\sigma > 0.005$ on the magnetization parameter agrees very well with the observational results obtained with the Chandra satellite by G02 and Y09, which both state a lower limit of the same value as we derive with our model.

7. Implications for the TeV $\gamma$-ray Emission

Based on the optimized parameters described in the previous section, we calculated the IC emission for our model to com-
Fig. 8. Data and model spectra for the ring 1 and 6 regions for Scenario III. The shaded regions mark the error bands of the XMM-Newton measurement of ring 1 and 6. For ring 1 the error band is very narrow and thus hardly visible.

Fig. 9. Spectral indices of power-law fits to the XMM-Newton data of the different regions in the energy range of 0.5-9.0 keV. The model points shown are calculated for the best fit of Scenario III and use the same energy range for the fit.

Fig. 10. Variation of the surface brightness for the XMM-Newton data and the model in the energy range of 0.5-9.0 keV. The model points shown are calculated for the best fit of Scenario III.

Fig. 11. Spatial evolution of the magnetic field with distance from the pulsar. The two solid lines denote the upper and lower range of values of the magnetic field strength for Scenario II (based on the range for $\alpha$ and $\xi$ that is found in the optimization). The two dashed lines mark the upper and lower limit of $B$ for Scenario III.

Fig. 12. Variation of the surface brightness for the XMM-Newton data and the model in the energy range of 0.5-9.0 keV. The model points shown are calculated for the best fit of Scenario III.

Fig. 13 shows the spectral index for the IC emission with increasing distance of the region from the pulsar, where it can be seen that the index steepens by $\Delta \Gamma \approx 0.15$.

Fig. 14 shows a plot of the spectral energy distribution (SED) of MSH 15−52 in the X-ray and TeV $\gamma$-ray band. The presented experimental data in the X-ray band are the sum of the emission of the shells from the XMM-Newton analysis (see...
We analyzed XMM-Newton data of the SNR MSH 15–52 to derive the spatially resolved spectral parameters of the inner region of the source. For this analysis we extracted spectra from six annuli centered on PSR B1509–58. A steepening of the X-ray spectrum with increasing distance from the pulsar is observed. The surface brightness in the XMM-Newton range drops by three orders of magnitude from the inner region close to PSR B1509–58 up to the last ring used in our analysis (at a distance of 300 arcsec from the pulsar). The spectra of all rings are fitted well with power laws.

We then introduced a numerical model to describe the spatial evolution of the lepton population and the magnetic field within the PWN. Our model is based on the parameters of the termination shock. We fitted the calculated model spectra to the XMM-Newton data to constrain the parameters of our model. The results of our optimizations suggest a termination shock in the range of 0.225 to 0.5 pc (Scenarios II and III in this work), which are the values derived from different analyses by G02 and Y09. However, the results of the optimizations of our model do not favor one scenario over the other. For the magnetization pa-
Fig. 15. Surface brightness of the IC emission with increasing distance from the pulsar. The surface brightness was calculated for a power-law fit to the data in an energy range of 300 GeV to 30 TeV. Plotted is the emission from the model calculations with the best fit parameters for Scenario II for a conversion efficiency $\eta = 0.4$.

The integrated emission of $7 \times 10^{35}$ erg s$^{-1}$ amounts to roughly $4\%$ of the current spin-down luminosity of PSR B1509−58. However, when making this comparison one has to be aware that the integrated emission comes from a population of leptons with different lifetimes and cannot be directly linked to the current spin-down luminosity. Furthermore, there is also significant emission at X-ray and TeV energies outside the central 0.1° region considered in our modeling approach, which increases the percentage of lepton energy converted to radiation (see Figs. 14 and 15).

In summary, we show that our radially symmetric model of the PWN MSH 15−52 readily describes the nonthermal emission seen in the X-ray band. Despite the simplifying assumptions of our model, the change in spectral index and surface brightness can be reproduced. The model is also able to predict the flux level of the observed emission in VHE $\gamma$-rays, however, the exact shape of the spectrum is not reproduced. For the future, an application of the model introduced in this paper to other PWN should be interesting to obtain a broader view on the underlying physics in PWN.

Acknowledgements. We would like to thank the anonymous referee for the constructive comments. They helped to improve the article significantly.

References

Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005, A&A, 435, L17
Arnaud, K. A. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes, 17
Blumenthal, G. R. & Gould, R. J. 1970, Reviews of Modern Physics, 42, 237
de Jager, O. C. & Djourados, A.-A.; A., 2009, Neutron Stars and Pulsars, ASSL 357, Springer, ed. Becker, W., 451
de Jager, O. C. & Harding, A. K. 1992, ApJ, 396, 161
Forot, M., Herrnser, W., Renaud, M., et al. 2006, ApJ, 651, L45
Gaensler, B. M., Arons, J., Kaspi, V. M., et al. 2002, ApJ, 569, 878
Gaensler, B. M., Brazier, K. T. S., Manchester, R. N., Johnston, S., & Green, A. J. 1999, MNRAS, 305, 724
Gaensler, B. M. & Slane, P. O. 2006, ARA&A, 44, 17
Jansen, F., Lumb, D., Altieri, B., et al. 2001, A&A, 365, L1
Kaspi, V. M., Manchester, R. N., Siegman, B., Johnston, S., & Lyne, A. G. 1994, ApJ, 422, L83
Kenne, C. F. & Coroniti, F. V. 1984a, ApJ, 283, 694
Kenne, C. F. & Coroniti, F. V. 1984b, ApJ, 283, 710
Mills, B. Y., Snee, O. B., & Hill, E. R. 1961, Australian Journal of Physics, 14, 497
Mineo, T., Cusumano, G., Maccarone, M. C., et al. 2001, A&A, 380, 695
Reynolds, S. P. & Chevalier, R. A. 1984, ApJ, 278, 630
Sefako, R. R. & de Jager, O. C. 2003, ApJ, 593, 1013
Seward, F. D. & Harnden, Jr., F. R. 1982, ApJ, 256, L45
Strüder, L., Briel, U., Dennerl, K., et al. 2001, A&A, 365, L18
Tamura, K., Kawai, N., Yoshida, A., & Brinkmann, W. 1996, PASJ, 48, L33
Trussoni, E., Massaglia, S., Cauccio, S., Brinkmann, W., & Aschenbach, B. 1996, A&A, 306, 581
Turner, M. J. L., Abbey, A., Arnaud, M., et al. 2001, A&A, 365, L27
Venter, C. C. & de Jager, O. C. 2007, in Proceedings of the 363. WE-Heraeus Seminar on Neutron Stars and Pulsars 40 years after the discovery, Edited by W. Becker and H. H. Huang. MPE-Report 291. ISSN 0178-0719. Published by the Max Planck Institut für extraterrestrische Physik, Garching bei München, Germany, 2007., p.40, ed. W. Becker & H. H. Huang, 40
Wagner, R. M., Landfors, E. J., Sillanpää, A., et al. 2009, ArXiv e-prints
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914
Yatsu, Y., Kawai, N., Shibata, S., & Brinkmann, W. 2009, PASJ, 61, 129
Zhang, L., Chen, S. B., & Fang, J. 2008, ApJ, 676, 1210