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Citation: [AIP Conf. Proc. 1505](#), 337 (2012); doi: 10.1063/1.4772266

View online: <http://dx.doi.org/10.1063/1.4772266>

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A Model to Reproduce the Emission of Young Pulsar Wind Nebulae

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Abstract. We present a radially symmetric leptonic model which allows to reproduce the spectral properties of the X-ray emission of several regions inside a young PWN. Using the optimized model parameter values obtained from the X-ray analysis, it is possible to calculate the IC emission of the lepton population and compare it with the data in the very high-energy range ($E > 100\text{ GeV}$). This method has been applied to three young PWNe, namely MSH15–52, G0.9+0.1, and G21.5–0.9.

Keywords: supernova remnants – X-rays: individuals (MSH15–52, G0.9+0.1, G21.5–0.9) – radiation mechanism: non-thermal

PACS: 98.38.Mz

INTRODUCTION

Young pulsar wind nebulae (PWNe) are known as strong photon emitters over a wide energy band, ranging from radio over X-rays up to very high-energy (VHE, $E > 100\text{ GeV}$) γ -rays. The emission of PWNe is likely caused by synchrotron and inverse Compton (IC) radiation of highly energetic leptons. Most of the current models try to explain the observed radiation with a single lepton population (so-called one-zone models). While in many cases such an approach already yields physically reasonable parameter results, it does not make use of, nor describe, the spatial properties of the source considered. In the following, we present the results of a spatially resolved X-ray spectroscopy and modeling of the PWNe MSH15–52 (G320.4–1.2), G0.9+0.1, and G21.5–0.9. Due to the limited length of this publication, we only show the figures for G21.5–0.9. The count maps and plots for MSH15–52 and G0.9+0.1 can be found in [1] and [2]. The reader is also referred to these two publications for a more detailed treatment of the X-ray analysis and applied modeling.

THE SOURCES

All three selected PWNe have been detected in X-rays as well as in VHE γ -rays, and are powered by pulsars with a very large spin-down luminosity. Some main physical characteristics of the selected PWNe are listed in Table 1. Notably, MSH15–52 is more extended in X-rays than the other two analyzed PWNe. This source is also the only

TABLE 1. Characteristics of the selected PWNe. Values were taken from [3] and [4] (MSH15–52), [5] (G0.9+0.1), and [6] (G21.5–0.9), respectively.

	MSH15–52	G0.9+0.1	G21.5–0.9
Pulsar characteristic age [years]	1700	5300	4800
Pulsar spin-down luminosity [erg/s]	1.8×10^{37}	4.3×10^{37}	3.3×10^{37}
Distance [kpc]	5.2 ± 1.4	8–16	4.7 ± 0.4
Inner PWN extent in X-rays [arcmin]	10	1.5	1.5

FIGURE 1. Smoothed *Chandra* count map of G21.5–0.9. The annuli chosen for the extraction of the X-ray spectra are encompassed by dashed cyan lines.

one of the sample which does not appear point-like in VHE γ -rays, allowing a better comparison of the emission in these two energy ranges.

X-RAY ANALYSIS

We analyzed publicly available X-ray data from *XMM-Newton* (MSH15–52, G0.9+0.1) and *Chandra* (G21.5–0.9). For MSH15–52 and G21.5–0.9, we extracted spectra of annuli which were centered on the respective pulsar position. As the position of the pulsar powering G0.9+0.1 exhibits a high uncertainty ([5]), the annuli were centered on the region of brightest emission in this case. The smoothed X-ray count map of G21.5–0.9 together with the annuli chosen for the extraction of the X-ray spectra is shown in Fig. 1. The width and number of annuli for each PWN was set according to the available statistics. We fitted a power law to each of the spectra in order to derive the unabsorbed surface brightness and spectral index. To increase the statistical significance, the absorption column density was fixed to the value obtained for the whole source in each case. The evolution of the surface brightness of G21.5–0.9 is shown in the left panel of Fig. 2. As already expected from the count map, the surface brightness decreases with growing distance to the pulsar. The other two selected PWNe show a similar behavior. The dependence of the spectral index from the distance to the pulsar,

FIGURE 2. Spectral characteristics of the annulus-shaped regions for the case of G21.5–0.9. The energy range is 1 – 10 keV. In both plots, the blue and red points correspond to the results obtained with the optimized parameters of *Scenario I* and *Scenario II*, respectively (see Section "The Model"). The *Chandra* data is indicated by black crosses. *Left panel:* Evolution of the surface brightness with increasing angular distance to the pulsar. *Right panel:* Spectral index plotted over the distance to the pulsar.

again for G21.5–0.9, is shown in the right panel of Fig. 2. The spectral index within the annuli increases with growing distance to the pulsar for all three sources.

THE MODEL

In order to comprehend the spectral properties of the PWNe, we modeled the observed emission in the X-ray energy range with a radially-symmetric leptonic scenario. We assumed a continuous outflow of leptons from the pulsar (called the pulsar wind). These leptons are shocked and accelerated at the termination shock and hence injected into the PWN. For the spectral shape of the injected leptons, we assumed a power law for all three sources (*Scenario I*). In addition to that, we separately modeled G0.9+0.1 and G21.5–0.9 with an injection spectrum that consists of a relativistic Maxwellian, followed by a cut-off power law tail (*Scenario II*, see [7] and [2]). After the injection, the leptons are assumed to propagate radially outwards and, during this process, lose energy due to adiabatic expansion and synchrotron emission. The energy losses as well as the synchrotron emission have been calculated for the given parameters of the model. The parameters were then optimized so that the surface brightness and spectral index of the synchrotron emission matches the one of the measured X-ray data. Using the optimized parameter values, we calculated the IC radiation of the leptons and compared it with the published VHE γ -ray data.

RESULTS

The results of the modeling of G21.5–0.9 are also given in Fig. 2. The adopted model is well able to reproduce the evolution of the surface brightness and spectral index for all three PWNe. Whereas in the case of G0.9+0.1 the evolution of the spectral index can

FIGURE 3. Spectral energy distribution of G21.5–0.9. Definitions regarding the different components are given in the figure legend. The *Integral* and H.E.S.S. data were taken from [8] and [9], respectively.

be better reproduced with *Scenario II*, *Scenario I* performs slightly better than *Scenario II* in the case of G21.5–0.9. The overall spectral energy distribution of G21.5–0.9 is shown in Fig. 3. As the model parameters were optimized to match the X-ray data, the agreement is very good in that energy range. The predicted flux in the VHE range is underestimated especially in the low-energy part of the spectrum. This is however partly expected since the model does not account for the IC emission of older leptons which are not energetic enough to emit X-rays anymore.

CONCLUSION

We performed an extensive analysis of the non-thermal emission of the three young PWNe MSH15–52, G0.9+0.1, and G21.5–0.9. Furthermore we applied a spatially resolved model of the sources in X-rays and VHE γ -rays. Whereas the evolution of the surface brightness and spectral index in X-rays can be well reproduced, the modeled IC emission is generally underestimated (especially at lower energies).

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