An X-ray Study of the Pulsar Wind Nebulae Discovered in the Very High Energy Gamma-ray Band

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Abstract

We studied nature of the pulsar wind nebulae (PWNe) whose association to the TeV gamma-ray sources is suspected. A total of 16 PWNe was selected and their X-ray data were analyzed. We found that the parameters of the TeV associated PWNe are basically same as those not detected in the TeV band. Although the energy loss time scale of the X-ray emitting, high-energy electrons in the PWNe is only $\sim$2 kyr, we found that the size of the X-ray emission region of the TeV PWNe keeps increasing up to $\sim$100 kyr. Two possibilities are discussed for this continued increase of the X-ray sizes.

Key words: X-rays: pulsars — Pulsar wind nebulae — gamma rays: TeV — acceleration of particles

1. Introduction

The Galactic plane survey by the H.E.S.S. Cherenkov telescopes revealed the presence of about 50 VHE γ-ray sources in the TeV band (10^{12-13} eV; eg. Aharonian et al. 2005, 2006). They are suspected to be the acceleration site of the cosmic-ray protons, but surprisingly, many of them have no known counterpart in other wavelength. A pulsar wind nebula (PWN) is often found in the vicinity of the TeV sources, and their association is suspected. Therefore, we made systematic analysis of the PWNe possibly associated to the TeV sources (hereafter referred to as TeV PWNe) utilizing new and archival X-ray data. We picked up all such sources and a total of 16 sources was selected as listed in table 1. The list includes HESS J1837-069 / AX J1838–0655 and HESS J1809–193 / PSR J1809–1917, for which the new Suzaku data were obtained (Anada et al. 2009a; Anada et al. 2009b). Some of the data of these sources were used only partly because of the large ambiguity in the parameters of the pulsar, absence of extended nebula, etc. Details of the present analysis and its implication is described in Anada (2009).

2. Analysis and Results

2.1. Nature of the TeV PWNe

Because the TeV emission was significantly detected in the vicinity of only a part of the PWNe, it may reflect some unique properties of them. In order to check this possibility, we compared various parameters between the TeV PWNe and those not detected in the TeV band (Non-TeV PWNe). We selected 10 Non-TeV PWNe for comparison. We compared distributions of the spin-down luminosities and the X-ray photon indices, and the correlation between the X-ray luminosity and the characteristic age. However, we could not find statistically significant difference between the TeV PWNe and Non-TeV PWNe. This means that there is no intrinsic difference between the PWNe detected and not detected in the TeV band.

2.2. Spatial offsets of the PWNe

Although the PWNe are considered to be associated to the TeV sources, their X-ray locations are in many cases spatially offset from the TeV sources. We compared the offset with the age of the PWNe, which we considered to be same as the characteristic age of the associated pulsar. Here, we defined the offset as the lateral distance between the center of the TeV emission and the pulsar. We found that the offset tends to increase with the age of the PWNe, and can be explained by the kick velocity of the pulsar. The (transverse) kick velocity estimated from the offset is mostly less than 10^3 km/s and reach a few thousands km/s for the largest. These kick-velocities are not very different from those measured by the proper motions of the radio pulsars, which often exceed 10^3 km/s. Thus, the offset can be explained by the

Table 1. List of analyzed sources

HESS name	PWN/Pulsar name
HESS J1837–069[1)]	AX J1838.0–0655
HESS J1809–193[1)]	PSR J1809–1917
HESS J0835–455[2)]	Vela X
HESS J1420–607[2)]	K3/PSR J1420–6049
HESS J1514–591[2)]	MSH 15-52
HESS J1825–137[2)]	G18.0–0.7
HESS J1833–105[2)]	G21.5–0.9
HESS J1846–029[2)]	Kes 75
HESS J1718–385[2)]	PSR J1718–3825
HESS J1616–508[2)]	PSR J1617–5055
HESS J0534+220[3)]	Crab Nebula
HESS J1747–281[3)]	G0.9+0.1
HESS J1418–609[3)]	Rabbit
HESS J1804–216[3)]	PSR J1803–2137
HESS J1702–420[3)]	PSR J1702–4128
HESS J1303–631[3)]	PSR J1301–6305

[1)] New Suzaku data were acquired for the current study.

[2)] Archival data of Chandra, XMM-Newton and Suzaku were analyzed.

[3)] Parameters were taken from literature.

kick-velocity of the pulsar.

2.3. Spatial extents of the PWNe

High energy electrons responsible for the X-ray and γ-ray emission loose energy through the synchrotron radiation and inverse-Compton scattering, respectively. The energy loss time scales of electrons are $2(B/10\mu\mathrm{G})^{-3/2}(\epsilon_{\mathrm{syn}}/1\,\mathrm{keV})^{-1/2}$ kyr for the synchrotron X-ray emission, and $30(\epsilon_{\mathrm{IC}}/1\ \mathrm{TeV})^{-1/2}$ kyr for the TeV emission by inverse-Compton scattering of cosmic microwave background. Here, ϵ indicates the X/γ-ray photon energy. This means that the electron energy loss has significant impact on the X-ray emission, whereas little on the TeV emission, because the age of the PWNe studied here ranges between $\sim$1–100 kyr. In fact, we found that the X-ray luminosity tends to decrease with the age of PWN (i.e. characteristic age of the pulsar), while the TeV luminosities stay constant.

We also studied evolution of the spatial extents of the PWNe. The spatial extents in the TeV band were found to increase with the age of the PWNe, as expected from the diffusion of the energetic electrons with little energy loss. Interestingly, the spatial extent was also found to increase at least up to $\sim$100 kyr even in the X-ray band. Because the X-ray emitting electrons are expected to loose energy in $\sim$2 kyr, it is surprise that the source extent keeps increasing well beyond a few kyr.

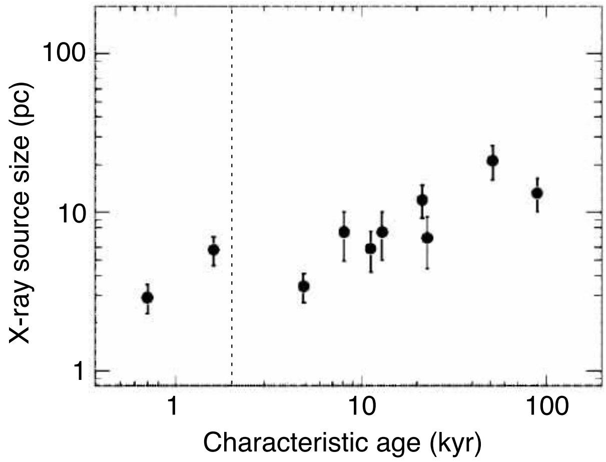

Fig. 1. Evolution of the emission region size in X-ray band. Although the X-ray emitting electrons loose energy typically in 2 kyr (indicated by a vertical broken line in the figure), size of the X-ray emission region keeps increasing well beyond a few kyr.

3. Discussion

We investigated nature of the PWNe detected in the TeV band systematically using the X-ray data. We found no significant difference between the properties of the TeV PWNe and the Non-TeV PWNe. This means that these two types of PWNe belong to intrinsically the same population. Although it is not clear what causes some PWNe bright in TeV, environmental difference could be one of the possibilities.

We unexpectedly found that the X-ray size of the PWNe keeps increasing up to $\sim$100 kyr. This cannot be explained naively as the energy loss time scale of X-ray emitting electrons is only $\sim$2 kyr. Therefore, nature of diffusion of energetic electrons needs to be changed with time. Two possibilities may be conceivable. One is evolution of the diffusion coefficient of electrons. If the turbulence at the termination shock becomes weaker with the pulsar's age, it may cause changes in the diffusion coefficient. The other is the evolusion of the advection speed, which depends on the σ parameter defined as the relative energy flux of particles to that of the magnetic field. In reality, both of these two mechanisms may be at work simultaneously in the termination shock of the PWNe.

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