The TeV gamma-ray emission mechanism of PSR 1706−44 based on the multi-wavelength spectrum

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Abstract

PSR 1706−44 has been observed at energies above several hundred GeV in 2000 and 2001 using the CANGAROO-II 10 m telescope. Above 1 TeV, the spectrum is a steep power-law, which is consistent with previous results. However, the spectral index seems to change around 1 TeV and becomes much flatter at lower energies. In addition, we analyzed *Chandra X-Ray Observatory* (*Chandra*) archival data to derive the X-ray spectra of the pulsar and the nebula, separately. The obtained X-ray spectrum indicates that the synchrotron peak energy appears to be above 10 keV. Combining the new results from CANGAROO-II and *Chandra* data, the detailed unpulsed multi-wavelength spectrum from radio to TeV energies was obtained. The new results put severe restrictions on both the magnetic field of the nebula and the maximum energy of parent electrons, which make it difficult to explain the TeV gamma-ray emission by the conventional synchrotron nebula model.

1. Introduction

PSR 1706−44 (257.°43, −44.°48) is a young pulsar with a period of 102 ms, and a large spin-down luminosity of 3.0×10^{36} erg · s^{-1}. The CANGAROO group detected TeV gamma rays from the region of the pulsar with high statistics using the CANGAROO 3.8 m telescope [11], which was confirmed by the Durham Mark 6 telescope [4]. On the other hand, in the X-ray band only weak unpulsed emission was detected by *ROSAT* [2] and *ASCA* [6]. From these results, the intensity of TeV gamma-ray radiation was found to be ten times larger than that of the X-ray synchrotron radiation. In order to study this further, we observed PSR 1706−44 again using the CANGAROO-II 10 m telescope.

2. Observation and Analysis of Gamma-ray and X-ray Data

Observations of PSR 1706−44 were carried out with the 10 m telescope in 2000 and 2001. The details of the 10 m telescope are given elsewhere [10]

pp. 2493–2496

[15] [18]. The total times for both ON-source and OFF-source observations were about 30 hours in each year. In order to avoid bright stars near PSR 1706−44, the tracking center was shifted from PSR 1706−44 by 0.°1 in all observations. After the timing calibrations, a "cluster" cut is applied, retaining only PMTs having more than 4 adjacent hits. We used the conventional "Imaging Technique" [9], taking into account the energy dependence of parameters. The details of these analysis methods are described elsewhere [12] [13]. The significance of the excess is calculated for alpha $< 15°$, and the number of excess events is 772 ± 119 ($6.5\,\sigma$) in the range 0.5 to 4 TeV. The Alpha distribution for 2001 data is similar to that for 2000. Combining the 2000 and 2001 data, the differential spectrum of PSR 1706−44 between 0.5 and 4 TeV is shown in Fig. 1. (left). The broken line is an $E^{-3.0}$ spectrum. The obtained flux is consistent with all previous results [11], where previous integral fluxes are converted to differential fluxes assuming a power-law index of −2.5. There is evidence for a break in the spectrum, with the observed power-law index changing by >1.0 between 0.8 and 1.2 TeV. This would be expected in the case of the inverse Compton (IC) mechanism.

In order to investigate the size of the TeV emission region around PSR 1706−44, the significance map [11] was obtained from the distribution of the detection significance. The resulting map around PSR 1706−44 for 2000 data is shown in Fig. 1. (middle). The position of PSR 1706−44 is shifted to the center of this map (0,0) considering the shift due to the bright star. Since the point spread function (PSF) of this telescope is 0.°2 in radius, the chance probability for the accidental coincidence of the significance above 4 σ is negligible. Figure 1. (right) shows the polarized radio intensity map of the supernova remnant G323.1−2.3 from observations with the Australia Telescope Compact Array (ATCA) [5] with the PSF of PSR 1706−44 superimposed. These results indicate that the gamma rays come from a point-like region consistent with the pulsar instead of from the whole SNR G323.1−2.3.

In addition, we analyzed *Chandra* archive data. PSR 1706−44 was observed with the Advanced CCD Imaging Spectrometer spectroscopy array (ACIS-S) in 2000, with an exposure time of 14,262 s. From the ACIS image, a faint X-ray nebula is clearly seen, with a size of around 14″. We extracted the pulsar and the nebula spectra, separately. The radii of the regions to extract the spectra are 1.2″ and 6″ for the pulsar and the nebula, respectively. The background is taken from the annulus between 6″ and 60″ from the center of the source. The nebula spectrum can be well fitted with a power-law of $1.4^{+0.34}_{-0.30}$. The pulsar spectrum can be fitted with a power-law plus black-body spectrum better than with a power-law spectrum only. The absorption of the pulsar was fixed at the value of $5.9^{+3.5}_{-2.5}\mathrm{cm}^{-2}$ obtained for the nebula. The best-fit temperature and photon index of the pulsar are $0.14^{+0.02}_{-0.01}$ keV and $2.0^{+0.39}_{-0.72}$. These results are consistent with Gotthelf et al. [8].

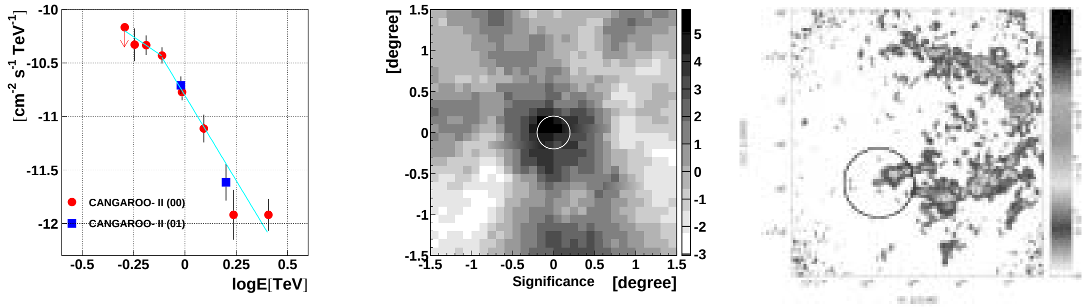

Fig. 1. The preliminary differential spectrum of PSR 1706−44 (left), the contour map of the statistical significance around PSR 1706−44 (right), and ATCA image of the G323.1−2.3 polarised intensity [5].

3. Result and Discussion

Combining the new results from *Chandra* and CANGAROO-II data, we obtained the multi-wavelength spectrum of PSR 1706−44 from radio to TeV gamma-rays (Fig. 2.). The X-ray intensity from the nebula is found to be one third of the *ROSAT* observation [2], and its hard spectrum indicates that the X-ray synchrotron peak energy must be higher than 10 keV. The peak intensity of the detected TeV gamma-ray flux is more than ten times stronger than that of the X-ray flux from the nebula. The best fit synchrotron and IC (on the 2.7 K CMB) spectra are shown by the solid lines in Fig. 2., where the magnetic fields of the emission regions of TeV gamma rays are 3 and 0.15 μG. If unpulsed X-rays and TeV gamma rays radiate due to the IC scattering of the 2.7 K CMB by the same multi-TeV electrons in the nebula, the magnetic field of the nebula is estimated to be very weak, $<0.1\mu$G, and the maximum energy of the expected IC spectrum is much higher than the result of CANGAROO-II. With such a weak magnetic field, it seems difficult for an X-ray synchrotron nebula to be produced. Furthermore the nebula size, within 14″, is too small to radiate such strong TeV gamma rays. In a previous unpulsed gamma-ray radiation model of PSR 1706−44, Aharonian *et al.* [1] proposed that the region producing TeV gamma rays was more extended than the X-ray nebula. Using the previous unpulsed fluxes obtained by *ROSAT* and the CANGAROO 3.8 m telescope, this model resulted in the conclusion that the energy of parent electrons was restricted to ~ 20 TeV from the peak energy of IC spectrum, assuming a magnetic field of the X-ray nebula of 20μG. These values are quite reasonable. However, considering the new *Chandra* result that the peak energy of the IC spectrum seems to be 10 keV, the mangetic field of the X-ray nebula is restricted higher than 100 μG or the energy of parent electrons has to be above 100 TeV. Both values are unacceptable. Therefore, the TeV gamma-ray flux is difficult to explain by a Synchrotron–IC (2.7 K CMB) model in the nebula.

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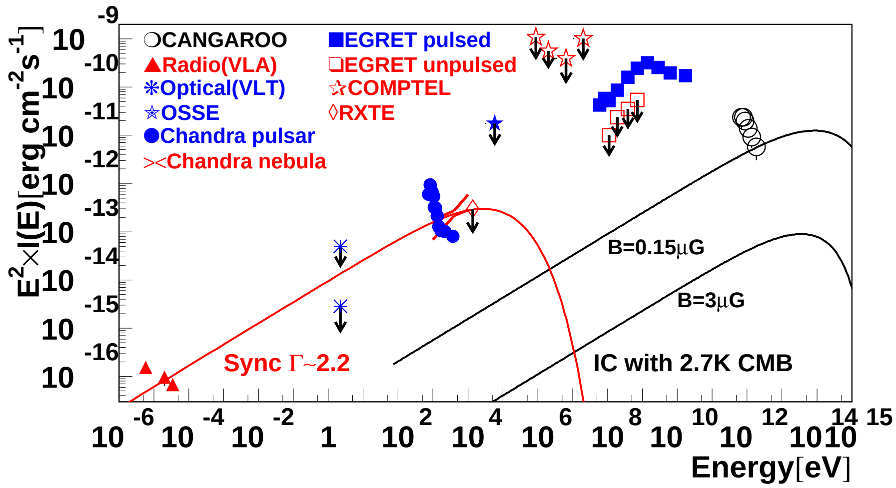

Fig. 2. Multi-wavelength spectrum of PSR 1706−44. The X-ray flux is corrected for absorption. The closed marks indicate pulsed or pulsar components and the opened marks indicate unpulsed or nebula components. References for this figure are followings: Radio [7], Optical [14], RXTE [16], OSSE [17], COMPTEL [3], and EGRET [19].

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