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

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Abstract

We have observed PSR 1706−44 using the CANGAROO-II 10m telescope in 2000 and 2001. The differential spectrum of gamma rays between 0.5 to 4 TeV is obtained and is found to be consistent with previous results. In addition, we analyzed *Chandra* archive data, to derive the X-ray spectra of both the pulsar and the nebula. As compared with the X-ray spectrum, the TeV gamma-ray spectrum seems difficult to explain by a conventional synchrotron nebula model based on the Crab nebula.

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 $\cdot$ s^{-1}. Two estimates have been made for the distance from the Earth: 1.8 kpc from a free-electron model of the Galaxy [19], and 2.4–3.2 kpc from H I absorption [12]. PSR 1706−44 has been observed over a wide energy band from radio to TeV gamma-ray energies. The CANGAROO group has detected TeV gamma rays from the region of the pulsar with high statistics using the CANGAROO 3.8m telescope [11], which was confirmed by the Durham Mark 6 telescope [4]. On the other hand, in the X-ray band only weak unpulsed components were 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. Based on non-thermal radiations of pulsar-nebula systems, it is widely believed that the unpulsed X-rays are due to synchrotron radiation and the TeV gamma rays due to IC scattering of 2.7 K cosmic microwave background (CMB) photons from the same high energy electrons in the nebula. However, in this case, the large observed TeV gamma-ray

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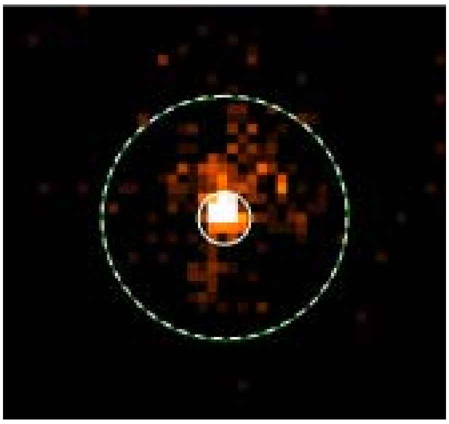

Fig. 1. ACIS image of PSR 1706−44. One pixel is equal to 0.4920 ± 0.0001 arcsec.

intensity and the weak X-ray synchrotron emission result in a very weak derived magnetic field in the nebula of $1\,\mu$G, which is weaker than the Galactic magnetic field [1]. In addition, it would be difficult for such a weak magnetic field to produce the observed synchrotron nebula. Therefore, Aharonian et al. [1] proposed that the region producing TeV gamma-rays may be more extended than the X-ray nebula.

In order to study this further, we observed PSR 1706−44 again, using the CANGAROO-II 10 m telescope, and obtained the spectrum between 0.5 to 4 TeV. In addition, we analyzed *Chandra X-Ray Observatory (Chandra)* archive data, and derived the nebula size and X-ray spectra of both the pulsar and the nebula in the keV range. Since these results cover a wider energy range, we have been better able to derive model parameters. Here, we discuss the gamma-ray emission mechanisms of PSR 1706−44 based on this multi-wavelength spectrum.

2. Observation and Analysis of X-ray Data

PSR 1706−44 was observed with the High-Resolution Camera (HRC-I) and with the Advanced CCD Imaging Spectrometer spectroscopy array (ACIS-S) in 2000. Exposure times were 45,867 and 14,262 s, respectively. Details on the detectors are given by Weisskopf et al. [21]. We used the *Chandra* Interactive Analysis of Observations (CIAO) version 2.1 and FTOOLS version 4.2 for the Level 2 data. Figure 1. shows the ACIS image of PSR 1706−44. A faint X-ray nebula is clearly seen. From this radial profile, the size of the X-ray nebula is within about $14''$.

From the ACIS image shown in Fig. 1., we extracted the pulsar and the nebula spectra, separately. The radii of region to extract the spectra are $1.2''$ and

$6''$ for the pulsar and the nebula, respectively. The background is taken from the circle 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 power-law plus black-body better than with a power-law only. The absorption of the pulsar was fixed at the obtained value of $5.9^{+3.5}_{-2.5}\mathrm{cm}^{-2}$ for the nebula. The best-fit temperature and photon index of the pulsar are $0.14^{+0.02}_{-0.01}$ keV and $2.0^{+0.39}_{-0.72}$. As inferred from ACIS and HRC images, the spectrum of the pulsar is found to be much softer than that of the nebula.

3. Observation and Analysis of Gamma-ray Data

Observations of PSR 1706−44 were carried out with the CANGAROO-II 10m telescope in 2000 and 2001. The details of the 10 m telescope are described elsewhere [10][14][18]. The total observation times for both ON-source and OFF-source were about 30 hours in each year. We observed PSR 1706−44 near its culmination at a zenith angle of $\sim 18°$. In order to avoid the bright stars near PSR 1706−44, the center of camera was shifted from PSR 1706−44 by $0.°1$ in all observations. The imaging camera of CANGAROO-II has 552 pixels, each of which is a half-inch photomultiplier (PMT). The event trigger requires at least 4 PMTs detecting $\sim$3 photoelectrons. Using the timing information, each event is corrected for the time jitter. After these calibrations, a "cluster" cut is applied, retaining only PMTs exceeding $\sim$3.8 photoelectrons and having more than 4 adjacent hits.

The analysis of the data was based on conventional "Imaging Technique" [9]. In this analysis, "Distance", "Length", "Width", and "Alpha" were used. In order to avoid systematic effects when applying the image parameter cuts, we used the maximum likelihood method [5]. For each event, the probabilities for a gamma-ray origin and proton origin were calculated, where each probability was defined as the product of each probability density function (PDF) obtained from the distribution of the imaging parameters. The PDFs for gamma rays and for protons are calculated using simulated gamma-ray events and OFF-source events, respectively, with the energy dependence of the imaging parameters taken into account. Here, we have used log-likelihoods for the gamma rays (L_g) and background (L_{BG}) events. These are the same as the χ^2, are are obtained from the PDFs $L_g = -2\Sigma log(Prob_g)$ and $L_{BG} = -2\Sigma log(Prob_{BG})$, where $Prob_g$ and $Prob_{BG}$ mean the PDFs for gamma rays and background events, respectively.
Using these χ^2 minimizing results, gamma-ray–like events can be enhanced, and proton–like events are suppressed. In this analysis, we selected events satisfying both L_g >5.8 and L_{BG} <8.0.

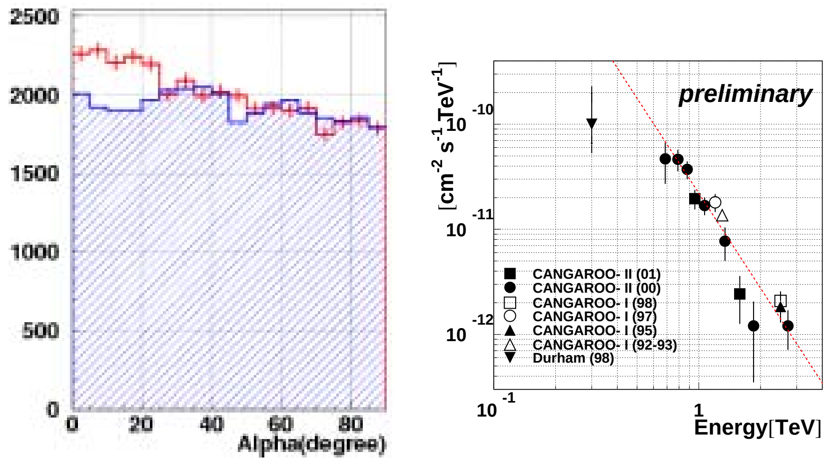

Fig. 2. Alpha distribution in 0.5 to 4 TeV for ON source (the solid line) and OFF source (the hatched histograms) data (left), and the preliminary differential spectrum of PSR 1706−44 (right).

Figure 2. (left) show "Alpha" distributions of the 2001 data, where the energy range is 0.5 to 4 TeV. The significance of the excess is calculated for alpha $< 15°$. The number of excess events are 772±119 ($6.5\,\sigma$). 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. 2.(right). The broken line is an $\mathrm{E}^{-3.0}$ spectrum. The obtained flux is consistent with all previous results, where previous integral fluxes are converted to differential fluxes assuming a power-law index of −2.5. Consistency with the Durham result requires a break in the spectrum near 1 TeV.

4. Result and Discussion

We are in process of combining the two years data, and checking the appropriate combination of cuts which does not deform the shape of the alpha distribution. Thus far, we have obtained the preliminary differential flux of gamma rays between 0.5 to 4 TeV. Above 1 TeV, the flux is steep and the estimated index is –3.0. This result is consistent with previous results [11][15]. 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 IC mechanism. In addition, we obtained X-ray spectra of the pulsar and the nebula, individually. These spectra are fitted with a power-law plus black-body, and power-law, respectively. The obtained nebula spectrum is very hard and the photon index is found to be 1.5. These results are consistent with Gotthelf et al.

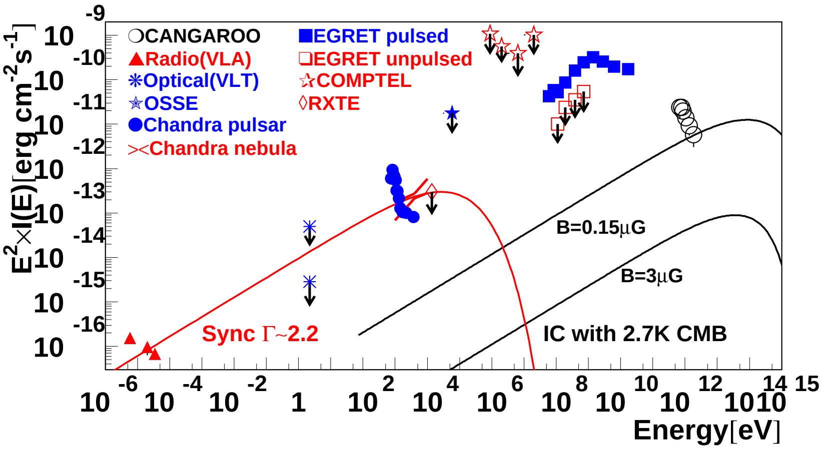

Fig. 3. Multi-wavelength spectrum of PSR 1706−44. The X-ray flux is corrected for absorption. The closed marks indicate pulsed or pulsar components and the opened marks indicate unpulsed or nebula components. References for this figure are followings: Radio [7], Optical [13], RXTE [16], OSSE [17], COMPTEL [3], EGRET [20].

[8].

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. 3.). The closed marks indicate pulsed or pulsar components and the opened marks indicate unpulsed or nebula components. The X-ray flux of the pulsar and the nebula components obtained by *Chandra* are corrected for absorption, and plotted by closed circles (pulsar) and region allowed by the range of possible spectral indices (nebula). The TeV gamma-ray fluxes from CANGAROO-II are plotted by open circles. 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. Since the intensity of the pulsar obtained by *Chandra* is consistent with the *ROSAT* result, the peak intensity of the detected TeV gamma-ray flux is more than ten times stronger than that of X-ray flux from the nebula. Considering these results, 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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