THE VELA PULSAR AND TeV GAMMA-RAY EMISSION

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1. Introduction

Gamma-ray pulsars detected by EGRET are considered to be likely emitters of TeV gamma rays and, indeed, TeV gamma-ray emission has been detected from these pulsars, such as the Crab (Weekes et al. 1989; Tanimori et al. 1994), PSR B1706–44 (Kifune et al. 1995) and Vela (Yoshikoshi et al. 1997). The emission from these TeV sources is apparently unpulsed and the acceleration site for the progenitor electrons is probably the shock generated by the pulsar wind colliding with circumstellar matter. Of these TeV sources, Vela is the closest to us, at a distance of about 500 pc, and we can expect to resolve the structure of the pulsar wind and nebula better than in the other TeV sources. In the X-ray energy band, extended emission was detected by the *Einstein* satellite around the Vela compact nebula (Harnden et al. 1985), and later identified by the *ROSAT* satellite as an X-ray jet extending from the pulsar to the south-southwest direction (Markwardt and Ögelman 1995). The detection of Compton-boosted TeV gamma rays would provide direct and clear evidence of nonthermal electrons.

2. Observations

We have observed the Vela pulsar region with the 3.8 m telescope of the CANGAROO collaboration (Hara et al. 1993) every year since 1992 and reliable data were obtained in 1993, 1994, 1995 and 1997. Observation time and numbers of triggered events are summarized in Table 1. The on-source data from 1993 to 1995 amount to about 174 hr, of which about 119 hr of data remain after rejecting the data affected by clouds. Almost the same amount of off-source data has been taken night by night to estimate the background level due to cosmic rays. The 3.8 m mirror w

Table 1. Summary of the CANGAROO observations of Vela.

Year		$T_{\rm obs}$ (hr)	$N_{\rm events}$	$E_{\rm th}$ (TeV)
1993	ON	47.6	161,614	2.5 ± 1.0
	OFF	42.8	125,662	
1994	ON	69.7	295,732	2.5 ± 1.0
	OFF	61.9	227,122	
1995	ON	56.5	237,474	2.5 ± 1.0
	OFF	51.8	196,231	
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1997	ON	32.2	306,892	1.3 ± 0.5
	OFF	31.8	241,446	

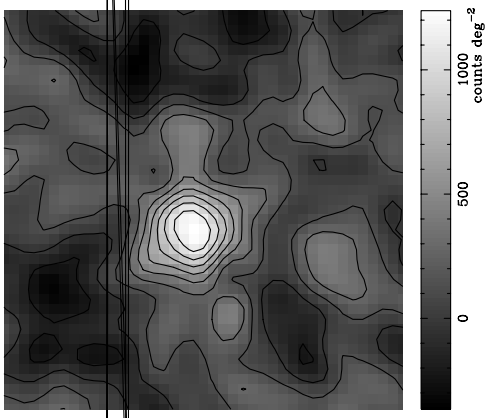
result, the threshold for the gamma-ray energy decreased from 2.5 ± 1.0 TeV to 1.3 ± 0.5 TeV[1]. The 1997 data are only for about 30 hr, which is shorter than any of the other years, but the number of events is roughly a half of the total amount of the previous data owing to the higher event rate in the lower energy region.

3. Results

We have detected an unpulsed gamma-ray signal from the Vela pulsar region at the 5.8 σ level using the 1993 to 1995 data (Yoshikoshi et al. 1997). The left of Fig. 1 shows the sky map of gamma-ray counts around the Vela pulsar for the 1993 to 1995 data. The gamma-ray signal was found in this sky map to be offset from the pulsar by about $0^\circ.13$ to the southeast. Almost the same analysis was applied to the 1997 data and a gamma-ray signal was again found with a significance of 4.1 σ. The sky map for the 1997 data is shown in the right of Fig. 1. The position of the maximum emission in the 1997 sky map is again found to be offset from the pulsar and agrees with the position of the 1993 to 1995 result within the statistical error ($\sim 0^\circ.04$). If these sky maps are combined together, the offset of the TeV source from the pulsar corresponds to about 4 σ.

We also estimated a preliminary differential spectrum of gamma rays from the TeV source near the Vela pulsar using the 1993 to 1995 data. The estimated spectral index is -2.9 ± 0.3, where the error is statistical only, and very steep compared with the other known TeV sources. The gamma-ray spectrum for the 1997 data is still under analysis.

1 Preliminary estimation.



Right

ASCA X-ray spectrum for the bright spot. As for the compact X-ray nebula surrounding the pulsar, a lower limit for the magnetic field can be estimated from the upper limit for the TeV gamma-ray luminosity from the pulsar position, i.e. $B \geq 5 \times 10^{-6} (U_{\rm ph}/0.24 \text{ eV cm}^{-3})^{1/2}$ G. This limit is compatible with an estimate obtained by de Jager et al. (1996) from a confinement condition for the progenitor electrons. A plausible scenario is thus that the TeV gamma-ray emission occurs from the X-ray bright spot offset $0^\circ.13$ from the pulsar to the southeast where there is sufficient density of relativistic electrons, but a smaller magnetic field.

5. Conclusions

We observed the Vela pulsar region in 1997 to confirm our previous results obtained from the 1993 to 1995 data and could detect TeV gamma rays with a significance of 4.1 σ. The position of the TeV emission is again offset from the Vela pulsar to the southeast and consistent with the position of the previous result. A preliminary gamma-ray spectrum for the TeV source was calculated for the 1993 to 1995 data and the estimated spectral index is -2.9 ± 0.3. A conservative upper limit for the magnetic field in the emission region was estimated to be about 4 μG by comparing TeV and X-ray luminosities.

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