Recent Results from the CANGAROO 3.8 m Telescope

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Abstract. We observed the shell-type supernova remnant (SNR) RX J1713.7–3946 and the X-ray binaries Cen X-3 and Vela X-1 at TeV energies in 1998 using the CANGAROO 3.8 m telescope. Preliminary results of data analyses on these objects are summarized here. We also estimated a spectrum of the Vela pulsar region using 116 hr data taken by the 3.8 m telescope during 1994 and 1997. The two data sets having different mirror reflectivities give consistent results and the photon index of the best-fit power-law spectrum is -2.4 ± 0.2.

INTRODUCTION

The 3.8 m telescope of CANGAROO [1] started to observe southern TeV gamma-ray sources in 1992 from Woomera, South Australia and has detected gamma-ray signals from three pulsar nebulae (Crab [2], Vela [3], PSR 1706–44 [4]) and a SNR (SN 1006 [5]) so far. These results give direct evidence of particle acceleration up to at least multi-TeV energies in our galaxy and activated discussions on non-thermal phenomena in such objects. The important role of the 3.8 m telescope will be taken over by the new 7 m telescope of the CANGAROO II project [6–8], which was completed in March 1999. The 3.8 m telescope has not been in operation since October 1998 to concentrate to the construction of the 7 m telescope. In 1998, before stopping the 3.8 m telescope, we observed two important objects; RX J1713.7–3946 which is a very similar SNR to SN 1006, and Cen X-3 from which a 400 GeV gamma-ray signal was recently detected by the Durham group [9]. Preliminary results on these objects are summarized in the next section. We also present a new result on the spectrum of the Vela pulsar region obtained using all available data taken by the 3.8 m telescope so far as well as the details of the analysis.

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TABLE 1. Summary of new results from the CANGAROO 3.8 m telescope.

Object	$T_{\rm obs}$ (hr)	Flux ($\times 10^{-12}$ cm^{-2} s^{-1})
SNR		
RX J1713.7–3946	42	~ 3 (>2 TeV, preliminary)
W 28	58	< 8.8 (> 1.5 TeV$^{\rm a}$)
X-ray binary		
Cen X-3	17	< 5.2 (> 2 TeV, preliminary)
Vela X-1	12	< 5.5 (> 2 TeV, preliminary)
Pulsar nebula		
Vela pulsar region	116	$2.6\ (E/2\ \mathrm{TeV})^{-2.4}\ \mathrm{TeV}^{-1}$

[a] A different definition of the energy threshold is used (see [13]).

NEW RESULTS FROM THE 3.8 M TELESCOPE

In the recent CANGAROO observations, we have given the highest priority to RX J1713.7–3946, which is a shell-type SNR recently discovered by *ROSAT*. Subsequent observations of this SNR by *ASCA* revealed non-thermal hard X-ray emission from its northeastern rim, which is even brighter than that from SN 1006 [10]. We could accumulate about 42 hr on-source data on RX J1713.7–3946 and a preliminary analysis of the data shows a 5σ excess of the on-source events over the background [11]. The gamma-ray flux derived is shown in Table 1.

Another SNR, W 28, has also been thought to be a possible TeV gamma-ray emitter since it includes pulsars and an unidentified EGRET source. However, we have detected no significant signal from W 28 so far in spite of the long exposure time [12]. Rowell et al. recently reanalyzed all of our data on W 28 taking into account the positions of the possible sources in the field of view [13].

Following the detection of an unpulsed signal from Cen X-3 by the Durham group, we observed the X-ray binaries Cen X-3 and Vela X-1 in February and March 1998. Our preliminary analyses show no evidence of TeV emission from either source. The calculated 3σ upper limits to the TeV fluxes (> 2 TeV) are shown in Table 1. The upper limit for Cen X-3 does not conflict with the Durham flux if we assume a power-law model and the photon index is smaller than -2.0.

The CANGAROO result on the Vela pulsar region using the data taken during 1993 and 1995 has already been reported by Yoshikoshi et al. [3]. An unpulsed TeV gamma-ray signal from the Vela pulsar region was found at the 5.8σ level, with the TeV source being offset from the Vela pulsar to the southeast by about $0^\circ.13$. We observed the same field in 1997 with the recoated 3.8 m mirror (the reflectivity was improved from about 45% to 75% on average) and again found a significant gamma-ray signal at a consistent position. The statistical significance of the total signal increased to 6.8σ and using these data we have estimated the spectrum of this source. Table 2 summarizes the data used in this analysis. The 1993 data were not used here since they are more contaminated by electronic noise. The image analysis procedure is almost the same as that described in [3] but the

TABLE 2. Summary of the data set of the Vela pulsar region used to estimate the spectrum.

Year	T_{ON} (hr)	N_{ON}	T_{OFF} (hr)	N_{OFF}	Reflectivity (%)
1994	41.9	194,795	41.9	162,029	45
1995	44.9	183,262	44.9	169,425	45
- - - - - - - - - - - - - - - - - Mirror recoating - - - - - - - - - - - - - - - - -					
1997	28.8	291,567	23.3	189,792	75

gamma-ray selection criteria based on the image parameters were slightly changed so as to avoid the overcut of gamma-ray events in the higher energy region. The 1994 to 1995 data and the 1997 data were separately analyzed owing to the different reflectivities.

If we observe a gamma-ray source having an intrinsic source spectrum $f(E)$, the observed gamma-ray rate $r(E)$ is represented by the following convolution function;

$$r(E) = \int_0^\infty f(E')A(E')P(E;E')dE', \tag{1}$$

where $A(E)$ and $P(E;E')$ are the effective area including the efficiency of the gamma-ray selections and the response function of the detector including the atmosphere, respectively. The functions $A(E)$ and $P(E;E')$ were estimated using Monte Carlo simulations. The equation (1) has to be deconvolved to obtain $f(E)$. However, it is not easy if the functions being convolved are not simple. Instead of doing a deconvolution, we directly fit the function (1) to the observed rate histogram using numerical techniques and taking the binning effect into account. Figure 1 shows the results of power-law fits for the 1994 to 1995 and 1997 data sets. These two spectra are consistent with each other within their error regions. Fitting a power-law function to the both data together between 1 TeV and 100 TeV gives a best-fit spectrum of $f(E) = (2.6 \pm 0.6) \times 10^{-12}(E/2\ \mathrm{TeV})^{-2.4\pm0.2}$ photons cm^{-2} s^{-1} TeV^{-1} with $\chi^2 = 7.2$ for 8 degrees of freedom, where the errors are statistical only.

As a method to estimate the systematic error of the spectrum, we tried to reconstruct a rate spectrum of cosmic-ray protons using the same technique. The result is shown in Figure 2. The rate spectrum calculated using a proton spectrum directly measured by a balloon experiment [14] is slightly higher than the observed rate since the observed rate also includes the heavier components of cosmic rays. However, the contribution of the heavier components to the total rate is smaller than that of protons [15]. Therefore, even if we conservatively understand this result, the systematic error of the spectrum must be smaller than a factor of 2.

The Durham group recently reported an upper limit to the unpulsed emission from the Vela pulsar with the threshold energy of 300 GeV [16]. If we compare it with our spectrum although their result is not for the position of our TeV source, the upper limit is very close to the extrapolation of our spectrum, but does not conflict taking the error region into account.

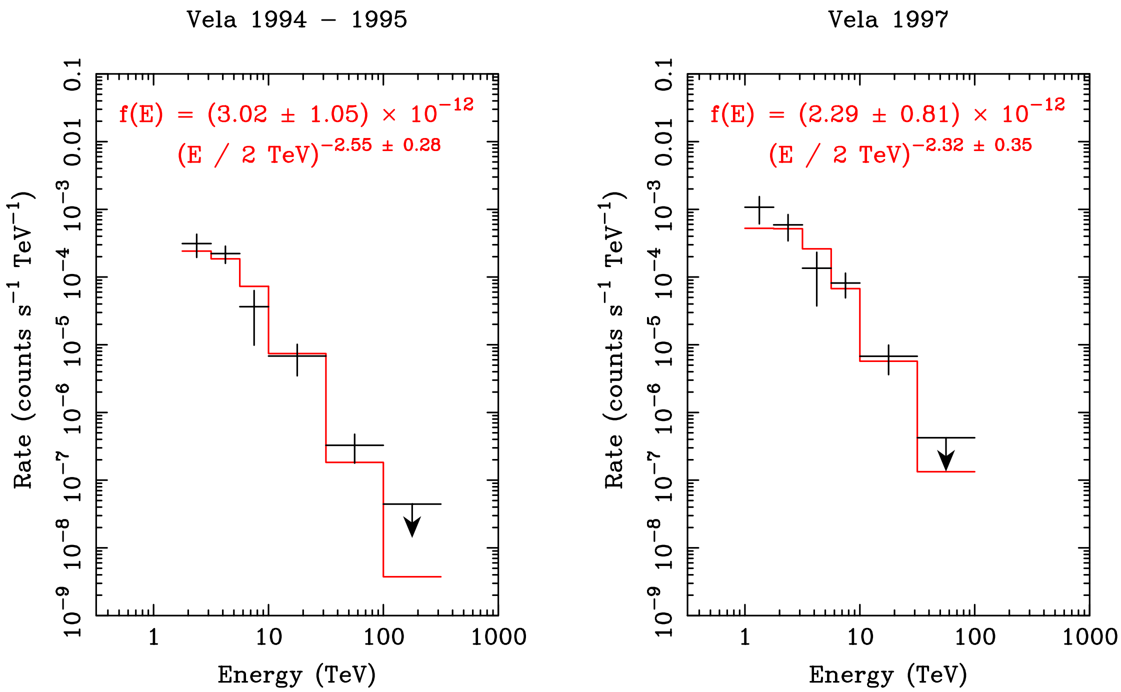

FIGURE 1. Rate spectra of the Vela pulsar region with the best-fit power-law spectra. The left and right graphs are for the 1994 to 1995 data and for the 1997 data, respectively.

CONCLUSIONS

We observed RX J1713.7–3946 and the X-ray binaries Cen X-3 and Vela X-1 in 1998 using the 3.8 m telescope. The preliminary analysis shows some evidence of TeV emission from RX J1713.7–3946. On the other hand, no signal was found from either of the X-ray binaries. We also estimated a spectrum of the Vela pulsar region using the 1994 to 1997 data taken by the 3.8 m telescope. The best-fit spectrum has the form of $(2.6 \pm 0.6) \times 10^{-12} (E/2\ \mathrm{TeV})^{-2.4 \pm 0.2}$ photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{TeV}^{-1}$ and the systematic error of the spectrum is smaller than a factor of 2.

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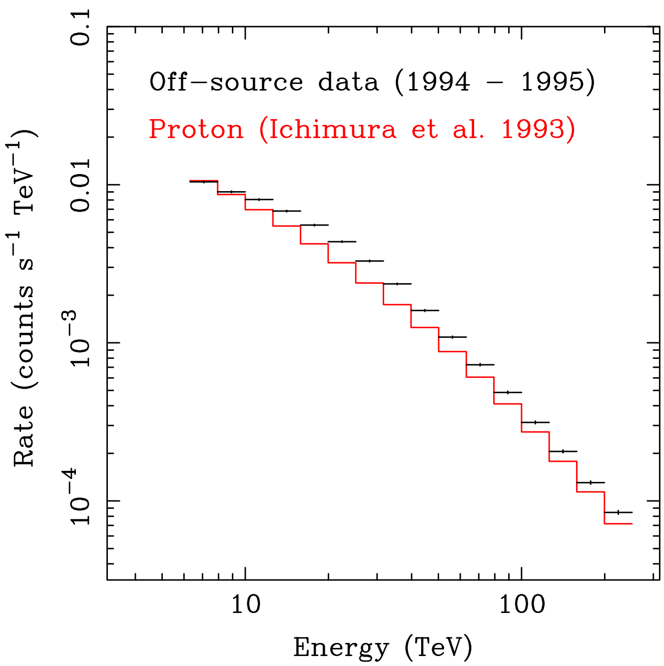

FIGURE 2. Rate spectra of cosmic-ray protons. The lower spectrum was calculated using a directly measured primary proton spectrum [14] and the upper spectrum is the observed off-source data, which includes not only protons but also helium and other components of cosmic rays.

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