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Study of the TeV gamma-ray spectrum of SN 1006 around the NE Rim

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Abstract. The differential spectrum of TeV gamma rays between 1.5 TeV and 20 TeV from the north-east rim of SN1006 was obtained from the data observed in 1996 and 1997 using the 3.8m CANGAROO Čerenkov telescope. This spectrum matches the model calculated using the Inverse Compton (IC) process with 2.7k Cosmic Microwave Background (CMB). This enables us to estimate the absolute strength of the magnetic field around the shock and the maximum energy of accelerated electrons with the considerable accuracy: the obtained field strength and maximum electron energy are 4 ± 1 μG and 50 TeV respectively.

Also we have detected again the TeV gamma-ray emission from the same position using the 10m CANGAROO-II telescope in 2000, and the preliminary spectrum around 1 TeV region is presented in this conference. The two spectra agree well in the overlapped energy region.

1 Introduction

Recent observations in both X rays and TeV gamma rays dramatically revealed the existence of non-thermal particles in the Supernova Remnants (SNR), which are accelerated up to $\sim$ 100 TeV presumably by the shock acceleration process. First set of such observations is the intense non-thermal X-ray emission from the rims of Type Ia SNR SN1006 (G327.6 +14.6) by ASCA (Koyama et al. 1995) and ROSAT (Willingale et al. 1996), and the subsequent detection of TeV gamma-ray emission from the Norh East (NE) rim by CANGAROO (Tanimori et al. 1998). The detected integral fluxes above TeV were consistent with predictions based on the Inverse Compton scattering (IC) of high energy electrons with low energy photons of 2.7 K cosmic background (Mastichiadis and de Jager 1996; Yoshida and Yanagita 1997). Following this success, other two SNRs have been detected in the same two energy bands; strong synchrotron X-ray emission and TeV gamma rays from RXJ1713.7−3946 (G347.3−0.5) were detected by ASCA in 1997 (Koyama et al., 1997) and by CANGAROO in 2001 (Muraishi et al., 2001) respectively, and also those from Cassiopeia A were detected by Beppo SAX (Allen et al., 1997) and HEGRA (Pühlhofer et al., 1999).

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At present, SNRs are generally favored as the site for the generation of galactic cosmic rays (mainly protons). High energy gamma rays detected from SNRs could be considered to emanate from π° decays induced by collisions between swept-up matter and accelerated protons in SNRs. On the other hand, gamma-rays detected from SN1006 are likely to be explained by IC radiation by very high energy electrons (Tanimori et al. 1998), because the matter density around the shock front in SN 1006 is too tenuous ($\sim$0.4 cm^{-3}: Willingale et al. 1996) to generate the observed TeV gamma-ray flux from π°s decays. The model based on the synchrotron-IC process can fit all the data of radio, X-ray and TeV gamma rays. This model, in addition, predicts a flatter power law spectrum ($E^s dE$) with an index of $s =\sim -1.6$ below the TeV band with a turnover to a steeper spectra around the TeV region. In this scheme, this steepening can be explained by a high energy limit of parent electrons, as an energy flux peak of the synchrotron emission appears in the soft X-ray region.

At present there still remains the possibility that an additional component of gamma rays from π° decays with the index of $s \sim -2.2$ would gradually dominate instead of IC radiation in the sub-TeV energy region. Detailed study of the spectral shape is quite important to answer this question.

In April 2000, the new 10m CANGAROO-II telescope was completed (Tanimori, et al., 2001 and Kawachi et al., 2001). Both RXJ1713.7$-$3946 and SN1006 have been detected again with high statistics by this new telescope, and their results are presented in this conference (Enomoto et al, 2001; Hara et al., 2001). Thus we have firmly established the TeV gamma-ray emission from SNRs.

Here we report on a further analysis of the same data set used in the previous paper (Tanimori et al., 1998) in order to extract spectral information for the reasons mentioned above.

2 Analysis and Results

Observations were done with the 3.8m Čerenkov imaging telescope of the CANGAROO Collaboration (Patterson & Kifune 1992; Hara et al. 1993) near Woomera, South Australia (136°47' E and 31°06'S) in 1996 and 1997.

An imaging analysis using the conventional parameterization was applied for the data, where the parameter cuts were varied as a function of the energy of the shower. These variations of parameter cuts were estimated from the simulation study. Here we add the additional analysis to enhance the gamma-ray signals using the fine timing information of each hit photomultiplier (about 1 ns time resolution). An image obtained from a single telescope gives only one angle: the projection of the direction on a plane normal to the mirror axis. Stereo observations are required to obtain the two angles necessary to determine the direction of a gamma-ray in the sky. For a single telescope, the unknown angle of the shower direction lies on the extended long axis of the elliptic image. However if we know both the the arrival times and the height of the emitting point of Čerenkov light, the shower direction can be reconstructed. In other words, the arrival timings of Čerenkov photons emitted from a shower can be calculated if both the height and the direction of a shower are known. Therefore, by assuming the height of shower generation ($\sim$ $10,000\mathrm{m}$ is used here), the unknown angle can be calculated using the observed arrival timings of Čerenkov photons. The simulation indicated that the obtained angle is quite insensitive to the assumption of the shower height. We actually obtained this angle event by event, and used it only to estimate the direction of the shower development along the long axis of the image. By selecting the shower images for events from the target direction, gamma-ray events should be enhanced, and indeed α peaks in both the 1996 and 1997 data became more significant. The result of the 1997 data is presented in Figs. 1a and b and the significance of the α peaks was increased from 7.5 σ to 8.8 σ by this method. After this cut, about 70% of background events that survived through imaging selections can be further removed, while about 75%

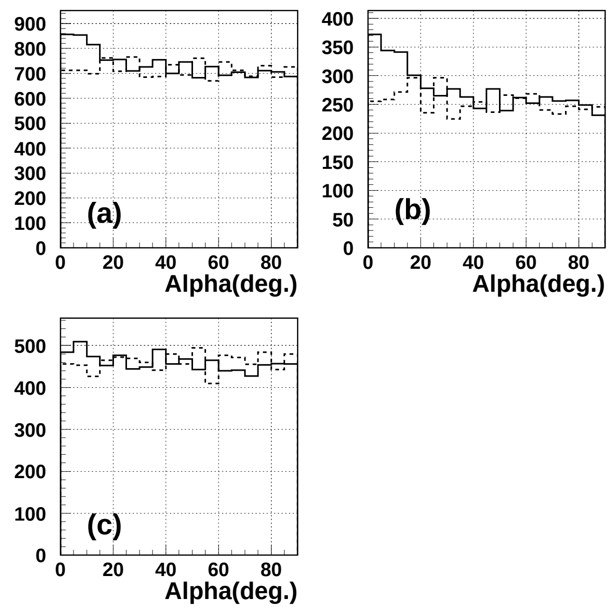

Fig. 1. (a) Plot of the event distribution as a function of the α for the 1997 data. (b) is the similar plot after applying the timing selection, and (c) is also the similar plot for rejected events of (a) by this cut.

of the gamma-ray events remained.

In order to obtain the differential energy spectrum, several α plots were made by varying the minimum and maximum numbers of detected Čerenkov photons. The collecting area, trigger efficiency and threshold energy corresponding to each α plot were independently estimated from simulations, where events were generated between 1 TeV and 30 TeV using an initial power-law index of ~ -2.2. This initial index was estimated from two observed integral fluxes 1996 (threshold energy $\geq$ 3.5 TeV) and 1997 (threshold energy $\geq$ 1.7 TeV). At first the spectrum was calculated using this index. Using the new index obtained from this spectrum, the above simulations and calculations were iterated in a similar way until the spectral index converged. Other initial values of the index were tried, but the resultant index converged to the similar value.

The resultant differential spectrum, *J(E)*, between 1.5 TeV and 20 TeV is plotted in Fig.2 in which only statistical errors are shown. It can be written as:

$$J(E) = (1.1{\pm}0.4){\times}10^{-11}(\frac{E}{1TeV})^{-2.3\pm0.2}\ \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1},(1)$$

where errors quoted are statistical. Systematic errors are estimated to be ~30%. Differential fluxes of 1996 and 1997 data were also individually calculated, and those fluxes were consistent within one sigma errors. Furthermore the differential flux without applying the timing reconstruction method was obtained to be quite similar to this flux.

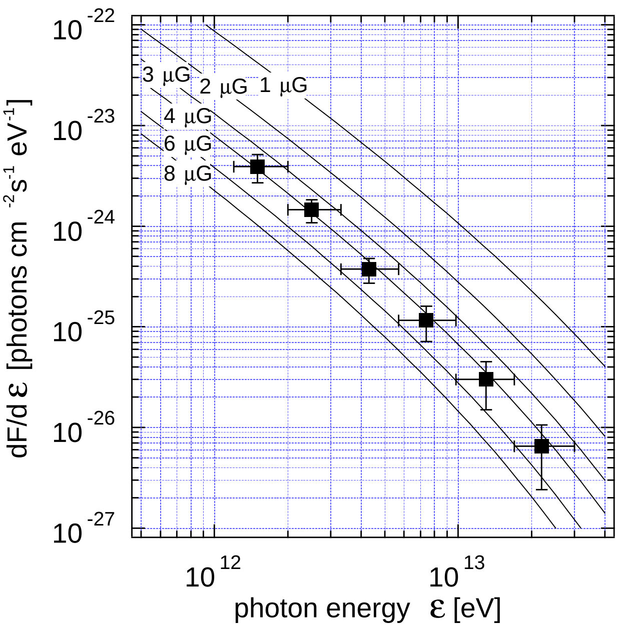

Fig. 2. Observed differential spectrum from the NE rim, where only statistical errors are shown. In addition, spectra of TeV gamma rays for several magnetic field strengths *B* calculated by the IC model are presented.

3 Discussion

The resultant differential spectrum shows a spectral index of -2.3 between 1.5 TeV and 20 TeV. The profile of the observed differential spectrum may resolve which IC or π° decay mechanism dominates this TeV emission. The model used here originated in Yoshida and Yanagita (1997), similar to the previous paper, while we improved the treatment of the approximation for the synchrotron flux (Naito et al., 1999): a simple δ function centered on the characteristic frequency was changed to the full function describing synchrotron emission (Rybicki and Lightman 1979 and references therein). The electron spectrum was assumed to be as

$$\frac{dN_e}{dE} = N_0 \left(\frac{E}{m_e c^2} \right)^s \exp\left(-\frac{E}{E_{\max}} \right) \quad . \tag{2}$$

In addition, the latest data of both radio (Reynolds and Ellison 1992) and X-rays from ROSAT and ASCA (Willingale et al. 1996; Ozaki 1998) were used in fitting the synchrotron flux. In particular, we used the partial fluxes emitted from the NE rim for all data: for the ASCA data the partial flux has been directly obtained by Ozaki (1998), and for the radio and the ROSAT data the partial fluxes were estimated using the morphological distributions of radio (Winkler and Long 1997) and ROSAT (Willingale et al. 1996) data. Comparing the calculated synchrotron flux to the observational data, we obtain $s = -2.2$ and $(E_{\max}/TeV)\sqrt{(B/\mu\mathrm{G})} = 101$. In Fig.2 several expected IC spectra are plotted by varying the strength of the ambient magnetic field, where $B = 4 \pm 1\mu$G is most probable, and this model matches successfully in the convex shape. The resultant field strength means the $E_{max} \sim 51$ TeV from the above formula.

Figure 3 shows the wide band energy spectrum from the radio to TeV regions at the north rim of SN1006 and also the above fitting (Naito et al., 1999). All data are fitted very well all over the wide band. Here an allowable spectrum due to π° decays generated by high energy proton is also plotted taking into account the upper limit of GeV gamma-ray fluxes, which obviously conflicts with the observed TeV gamma-ray flux. Those upper limits in the GeV region of this figure were calculated from the EGRET archive data using a maximum likelihood method (Mattox et al., 1996). These results seems very reasonable consequence considering the tenuous shell of ($\leq\sim$0.4 cm^{-3}; Willingale et al. 1996).

Thus the identification of the parent particles of the TeV gamma-rays (electron or proton) will be possible by observing the wide spectrum from sub- to multi-TeV region as shown in Fig.3. A Gamma-ray spectrum flatter than -2.0 in this region is surely due to the I.C. process, while that due to π° decay generated by collision between ISM and high energy proton is expected to be steeper than -2.0.

From this fitting, the energy flux of TeV gamma rays due to the IC process at 300 GeV is estimated to be $\sim$ 4 eV cm^{-2}s^{-1}, which is lower than the upper limit (8 eV cm^{-2}s^{-1} at 300GeV) reported in Chadwick et al. (2000). Also we have observed again TeV gamma rays from the NE rim of SN1006 observed by the 10m telescope as presented in this conference (Hara et al., 2001). Although the new data is still very preliminary, the spectra are consistent in the overlapping energy region.

In this conference, we present the interesting spectrum of TeV gamma rays of PSR1706$-$44 showing an obvious break of the spectrum around 1 TeV (Kushida et al., 2001). This breaking can be fit by the IC model quite well similar to the case of SN1006. These two results indicate the major role of IC process for the production of high energy gamma rays in the universe.

However, our result showing the IC process dominance for the production of TeV gamma rays in SN1006 does not imply the nonexistence of the plenty of high energy protons accelerated by a diffusive shock. Conventional diffusive shock theories naturally predict efficient acceleration of protons in SNRs. In SN1006, a deficiency of target protons surrounding the SNR may conceal accelerated protons from being revealed.

RXJ1713.7$-$3946 is the second SNR emitting both synchrotron X-rays and TeV gamma rays. However, the environment of RXJ1713.7$-$3946 is obviously different from SN1006; for example, association of RXJ1713.7$-$3946 with a molecular cloud is reported from the CO observation (Slane et al., 1999). Our new result on RXJ1713.7$-$3946 indicates a more intense flux below 1 TeV, while the flux above 1 TeV of it is similar to that of SN1006 (Enomoto et al., 2001). Those features looks inconsistent with the scenario of the IC model. Future analyses of SN1006 and RXJ1713.7$-$3946 will soon provide both the differential spectra between $\sim$ 300 GeV and $\sim$ 10 TeV and the image of TeV gamma ray emission respec-

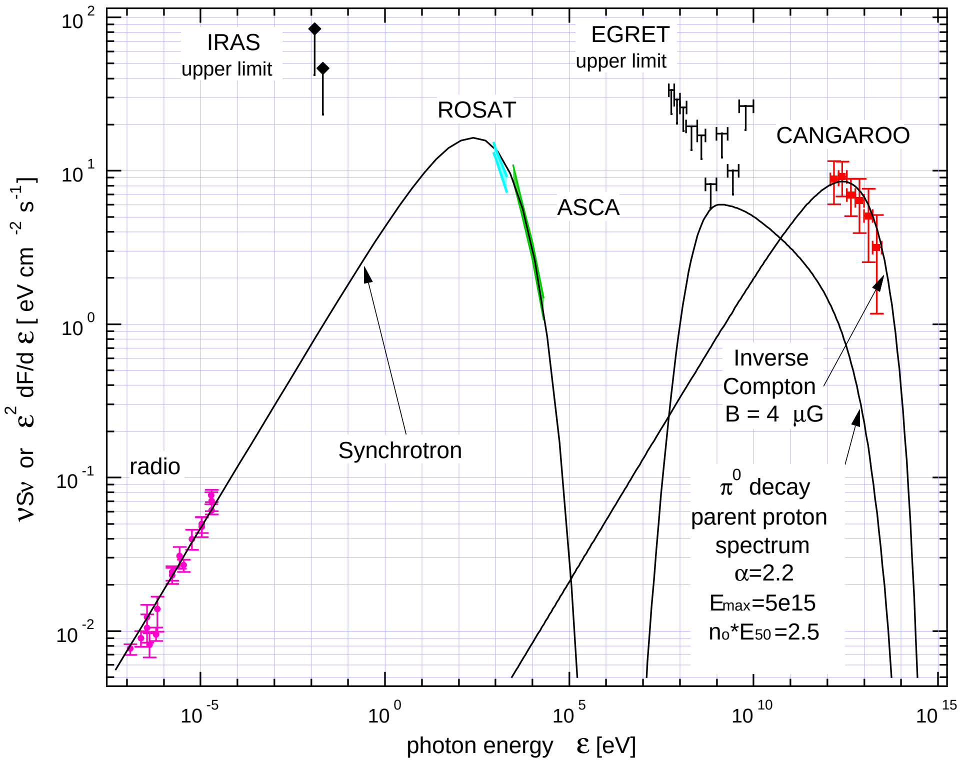

Fig. 3. Multi-band spectrum of energy fluxes observed from the NE rim, where observed fluxes or upper limits of radio (Reynolds 1998), infrared, soft X-ray (estimated from Willingale et al. 1996), hard X-ray (Ozaki 1998), GeV gamma rays (calculated from the EGRET archive data), and TeV gamma rays are presented. Solid lines are the fits based on the model of IC model and neutral pion decay.

tively, which will tell us what kind of particle is accelerated and generates TeV gamma rays in each SNR.

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