Astrophysical Journal Letters, in press

DISCOVERY OF TEV GAMMA RAYS FROM SN1006: FURTHER EVIDENCE FOR THE SNR ORIGIN OF COSMIC RAYS

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ABSTRACT

This paper reports the first discovery of TeV gamma-ray emission from a supernova remnant made with the CANGAROO 3.8 m Telescope. TeV

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gamma rays were detected at the sky position and extension coincident with the north-east (NE) rim of shell-type Supernova remnant (SNR) SN1006 (Type Ia). SN1006 has been a most likely candidate for an extended TeV Gamma-ray source, since the clear synchrotron X-ray emission from the rims was recently observed by ASCA (Koyama et al. 1995), which is a strong evidence of the existence of very high energy electrons up to hundreds of TeV in the SNR. The observed TeV gamma-ray flux was $(2.4 \pm 0.5(statistical) \pm 0.7(systematic)) \times 10^{-12}$ cm^{-2} s^{-1} ($\geq 3.0 \pm 0.9$ TeV) and $(4.6 \pm 0.6 \pm 1.4) \times 10^{-12}$ cm^{-2} s^{-1} ($\geq 1.7 \pm 0.5$ TeV) from the 1996 and 1997 observations, respectively. Also we set an upper limit on the TeV gamma-ray emission from the SW rim, estimated to be 1.1×10^{-12} cm^{-2} s^{-1} ($\geq 1.7 \pm 0.5$ TeV, 95% CL) in the 1997 data.

The TeV gamma rays can be attributed to the 2.7 K cosmic background photons up-scattered by electrons of energies up to about 10^{14} eV by the inverse Compton (IC) process. The observed flux of the TeV gamma rays, together with that of the non-thermal X-rays, gives firm constraints on the acceleration process in the SNR shell; a magnetic field of 6.5 ± 2 μG is inferred from both the synchrotron X-rays and inverse Compton TeV gamma-rays, which gives entirely consistent mechanisms that electrons of energies up to 10^{14} eV are produced via the shock acceleration in SN1006.

Subject headings: gamma rays:observations – ISM:individual (SN1006) – supernova remnant

1. Introduction

On the other hand, intense non-thermal X-ray emission from the rims of Type Ia SNR SN1006 (G327.6+14.6) has been observed by ASCA (Koyama et al. 1995), and ROSAT (Willingale et al. 1996), which is considered, by attributing the emission to synchrotron radiation, to be strong evidence of an existence of high energy electrons up to ∼100 TeV. SN1006 is a typical shell-type SNR which has no apparent central engine for high energy particles such as a neutron star or a black hole. Nevertheless, the existence of very high energy particles in a type Ia SNR is widely accepted from shock acceleration theory (Blandford & Eichler 1987; Jones & Ellison 1991). If so, TeV gamma rays would also be expected from inverse Compton scattering (IC) of low energy photons (mostly attributable to the 2.7 K cosmic background photons) by these electrons. By assuming a value for the magnetic field strength (B) in the emission region of the SNR, several theorists (Pohl 1996; Mastichiadis 1996; Mastichiadis & de Jager 1996; Yoshida & Yanagita 1997) calculated the expected spectra of TeV gamma rays using the observed radio/X-ray spectra. An observation of TeV gamma rays would thus provide not only further direct evidence of the existence of very high energy electrons but also other important information such as the strength of the magnetic field and the diffusion coefficient of the shock acceleration.

With this motivation, SN1006 was observed by the CANGAROO imaging air Čerenkov telescope in March and June 1996, and March and April 1997.

2. Observations

The observations were made with the 3.8m diameter Čerenkov imaging telescope of the CANGAROO Collaboration (Patterson & Kifune 1992; Hara et al. 1993) near Woomera, South Australia (136°47' E and31°06' S). The 3.8 m alt-azimuth mounted telescope had a ∼3 TeV threshold for detecting gamma rays near 70° elevation in the 1996 observations. The 3.8m mirror was recoated in 1996 October, and its reflectivity improved from 45% to more than 80%, decreasing the threshold energy by about a factor of two. A multi-pixel camera consisting of 256 square photomultiplier tubes, arranged in an array of 0°.18 steps, has a total field of view (FOV) of about 3° (Hara et al. 1993).

SN1006 was observed for 28 hours (on-source) and 18 hours (off-source) in April and June 1996. Both of the North East (NE) and the South West (SW) rims were located within the FOV. By monitoring the single counting rate in each phototube, we were able to track the passage of the star (magnitude 3.13) within the FOV, and the pointing of the telescope was monitored to an accuracy of 0°.02 using the trajectory of this star. In March and April 1997, in an effort to confirm the 1996 result, we made additional observations of 34 hours (on source) and 29 hours (off-source) with the same tracking as in June 1996.

3. Analysis and Results

The imaging analysis of the data is based on the usual parameterization of the elongated shape of the Čerenkov light image as: "width","length", "distance" (location), "conc" (shape), and the image orientation angle α (Hillas 1985; Weekes et al. 1989). In the α distribution of the events selected by the imaging analysis, the peak appearing around the origin ($\alpha \leq 15^\circ$) in the on-source data is attributed to γ-rays from the target position, and the number of background events under the peak was estimated from the flat region of the α distribution (30°–90°) in the on-source data. Here off-source data were used to verify the non-existence of any peculiar structure in the α plot around the origin not due to gamma-ray events. The application of this technique to data recorded with the CANGAROO telescope has, to date, resulted in the detection of TeV gamma rays from PSR1706-44 (Kifune et al. 1995) and the nebula surrounding the Crab (Tanimori et al. 1994; Tanimori et al. 1998). From the results on the previously observed objects, the position of a gamma-ray point source can be determined to an accuracy of 0.1°. The point spread function (PSF) of the CANGAROO telescope is estimated to have a standard deviation of $0^\circ.18$ when fitted with a Gaussian function.

The hard X-ray profile of the NE rim observed by ASCA suggests that the TeV gamma rays may emanate from an extended area over a few times the PSF of the CANGAROO telescope (several tenths of a degree in extent). In order to search the emission region of TeV gamma rays in SN1006, significances of peaked events with $\alpha \leq 15^\circ$ were calculated at all grid-points in $0^\circ.09$ steps in the FOV which is half of the standard deviation of the PSF. The source point in the NE rim giving the most significant α peak ($\alpha \leq 15^\circ$) was found at the maximum flux point in the 2–10 keV band of the ASCA data. The α plot of the selected gamma-ray-like events at the X-ray maximum flux point is shown in Fig.1a. Clear peaks due to an excess of gamma-ray events are seen at $\alpha \sim 0^\circ$ for the on-source data of April and June but not for the off-source data. At this X-ray flux maximum point, the statistical significances of these peaks are estimated to be 3.0σ in April, 4.7σ in June, and 5.3σ in total, using the definition mentioned above. The resulting contour map of significances is shown in Fig.2a, in which the contours of the hard X-ray flux and the maximum flux point in the 2–10 keV band of the ASCA data also are overlaid as solid bold-lines and marked by a cross, respectively. The region showing significant TeV gamma-ray emission extends along the ridge of the NE rim over the PSF of the telescope, and matches the X-ray image fairly well.

In March and April 1997, in order to confirm the 1996 result, we made additional observations. Figure 1b shows the α distribution of gamma-ray like events selected by the same procedure as used for the 1996 data. A clear peak ($\alpha \leq 15^\circ$) was observed again with the significance of 7.7σ at the maximum hard X-ray flux point of ASCA. The improvement of the detection significance was due to the twice increase of the reflectivity of the mirror. Thus the TeV gamma-ray emission from the NE rim of SN1006 has been confirmed (Tanimori et al. 1997). Figure 2b shows the contour map of significances. The TeV gamma-ray emission region also looks elongated along the ridge of the NE rim, although the profile of 1997 data is not as extend as that from the 1996 data. In order to verify whether the emission region is extended or not, the profiles of the NE rim in 1996 and 1997 data were fit using a superposition of two PSFs located along the ridge of the NE rim and also using a single PSF. Although the 1996 result favours the fit using a superposition of two PSFs against a single PSF, the 1997 data, with better statistics, does not show significant improvement for a superposition of two PSFs. From these significance maps we therefore can not claim the extent of the TeV gamma-ray emission region quantitatively. Further study is required.

The threshold energy for the observed gamma rays was determined from Monte Carlo simulations, as the maximum of the product of the differential flux times the effective collecting area; the latter is a function of gamma-ray energy. Compared the 1997 result to the 1996 result, the threshold energy was decreased about a factor of two, and the number of the detected gamma-like events was increased twice. This indicates a differential photon spectral index $d\log N(h\nu)/d\log(h\nu)$ of –2 around a few TeV ($N(h\nu)$ in photons cm^{-2}s^{-1}TeV^{-1}). Also the α peak due to gamma-ray like events can be seen even in about ten times higher energy region than the threshold energy in the 1997 data, which means that there exists little effect of the spectral cut-off in the observed energy region. Therefore the differential spectral index was simply assumed to be -2 in calculating the integral fluxes of our data. Results of the Monte Carlo simulation give a threshold gamma-ray energy of 3$\pm$0.9 TeV and an effective area of approximately 6.6$\times$ 10^8 cm^2 for the 1996 observation of SN1006. Approximating the emission as coming from a single point source at the maximum flux point in the NE rim, the integral gamma-ray flux for the 1996 observations was calculated to be $(2.4 \pm 0.5 \pm 0.7) \times 10^{-12}$ cm^{-2} s^{-1} ($\geq 3.0 \pm 0.9$ TeV). The threshold energy for the 1997 observations was also estimated to be 1.7 ± 0.5 TeV. Using similar approximations to those above, the gamma-ray integral flux for the 1997 observation was calculated to be $(4.6 \pm 0.6 \pm 1.4) \times 10^{-12}$ cm^{-2} s^{-1} ($\geq 1.7 \pm 0.5$ TeV). In those fluxes the first and second errors are statistical and systematic respectively. The systematic error mainly arises from the uncertainty of the absolute threshold energy. A larger flux would be obtained if the emission extends wider than the PSF of our detection. Also the systematic error due to the assumed differential spectrum was evaluated: considering the uncertainties in shock acceleration models such as nonlinear effects and energy cut off in the electron spectrum (Jones & Ellison 1991), we varied the spectral index from –1.2 to –4.0. In this range, the integral flux changes by about –2% (–1.2) to +20% (–4.0), which is relatively smaller than that due to the uncertainty of the absolute threshold energy.

No significant excess is evident in Fig. 2a near the position of the maximum X-ray flux from the SW rim. The X-ray observation by ASCA indicates that the integral flux of hard X-rays (≥ 2 keV) in the NE rim occupies ∼60% of the whole hard X-ray flux emitted from SN1006 (Ozaki 1997). The current analysis method of using the α distribution has difficulty in separating two emission regions as close as $0^{\circ}.6$ of the NE and SW rims. The weaker emission might be hindered by the stronger one from the NE rim. Thus, we set an upper limit on the TeV gamma-ray emission from the SW rim, estimated to be 1.1×10^{-12} cm^{-2} s^{-1} ($\geq 1.7 \pm 0.5$ TeV, 95% CL) from the α distribution in the 1997 data at the position of the maximum ASCA flux in the SW rim.

4. Discussion

This detection of TeV gamma rays from SN1006 presents a convincing confirmation of the shock acceleration mechanism for very high energy particles up to ∼100 TeV in a SNR. The TeV gamma ray emission region is observed to likely extend over ∼30 arcmin along the ridge of the NE rim.

From the non-thermal X-ray observation, the detected TeV gamma rays are readily presumed to be generated by IC scattering of very high energy electrons on 2.7K cosmic background photons. All of the calculated fluxes of TeV gamma rays based on those assumptions are consistent with the TeV gamma-ray fluxes obtained by assuming that the magnetic field strength (B) in the emission region of the SNR is around 10μG. One model (Yoshida & Yanagita 1997) calculates the expected TeV gamma-ray spectrum as a function of the strength of the magnetic field assuming a power law with exponential cutoff energy spectrum for electrons where the value of necessary parameters are determined by fitting the observed radio and X-ray synchrotron emissions. The observed fluxes of TeV gamma-rays (≥ 1.7 TeV and ≥ 3 TeV) fit well if we take $B = 6.5 \pm 2\mu$G in the model as shown in Fig.3.

The other candidate of the production mechanism of TeV gamma-ray emission is a decay of neutral pions induced by high energy protons accelerated in the SNR. However, we can neglect the flux from the π^0 decay due to following arguments. Since SN1006 (G327.6+14.6) is located above the galactic plane, the matter density at the shock is low (∼0.4 cm^{-3}: Willingale et al. 1996) so that the expected flux will be about a factor of ten less than the observed flux. The upper limit for GeV gamma-ray emission from the EGRET archive data is also consistent with the IC model. Thus, the detected gamma-rays are likely to be explained by IC radiation from electrons, and our result testifies to the existence of the very high energy electrons of more than several times 10 TeV in SN1006. The highest energy of non-thermal electrons can be estimated from the turning point in the synchrotron spectrum and the resultant magnetic fields. Although the turning energy of SN1006 is not yet precisely determined in recent observations, a 1 keV photon from synchrotron radiation corresponds to an electron energy of $\sim$ 60 TeV for $B = 6.5\mu$G. These values of highest energy and field strength, and 1000 years of life time for SN1006 are almost consistent with shock acceleration theory. Observations of some other bands and evolutional theories of the SNR are required to confirm the highest accelerated energy more precisely (Sturner et al. 1997; Gaisser, Protheroe, and Stanev 1997).

The observed concentration of hard X-rays and gamma-rays emissions into the rims in SN1006 also suggests the possibility that the relation between the direction of the magnetic field and the shock front may determine the efficiency of particle acceleration. Reynolds (Reynolds 1996) pointed out that the magnetic field in the upstream of the shock of the rims in SN1006 is likely to be parallel to the shock front, which may show the predominance of highly oblique shocks, where the efficiency of shock acceleration is improved (Jokipii 1987; Naito & Takahara 1995).

Searches for TeV gamma-ray emission from six SNRs in the northern hemisphere have been carried out using a large imaging air Čerenkov telescope by the Whipple group (Buckley et al. 1998), and turned out unsuccessfully. SN1006 is so far the only SNR in which the existence of very high energy electrons up to $\sim$ 100 TeV is suspected from X-ray data. Recently non-thermal hard X-ray emissions from several SNRs have been observed (Koyama et al. 1997; Keohane et al. 1997; Allen et al. 1997), implying the existence of electrons up to a few tens of TeV. It is clear that more efforts for detecting TeV gamma rays from SNRs are necessary to understand the shock acceleration mechanism in more detail and therefore the origin of cosmic rays.

We thank Prof. K. Koyama, Prof. J. Nishimura, Dr. M. Ozaki, and Dr. O. de Jager for their fruitful discussions. This work is supported by a Grant-in-Aid in Scientific Research of the Japan Ministry of Education, Science, Sports and Culture, the Australian Research Council and International Science and Technology Program and the Sumitomo Foundation. The receipt of JSPS Research Fellowships (P.G.E., T.N., M.D.R., K.S., G.J.T. and T. Yoshikoshi) is also acknowledged.

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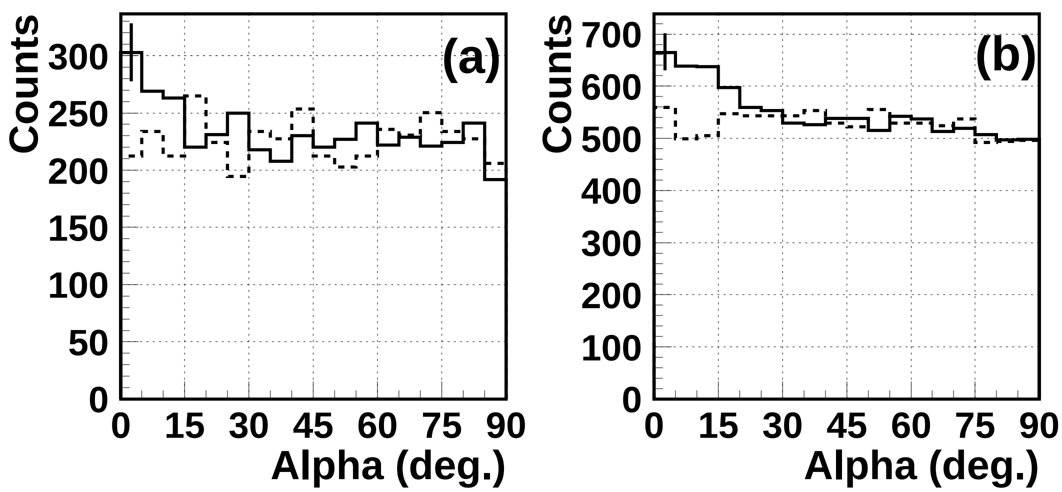


Fig. 1.— (a) The number of observed events as a function of the orientation angle α for the 1996 data at the maximum flux point of hard X-rays where on- and off-source data are indicated by the solid and dotted lines, respectively. (b) The same α plot for 1997 data, where the on- and off-source data are indicated by the solid and dotted lines, respectively. Plots of all off-source data are normalized to those of on-source data by the exposure times.

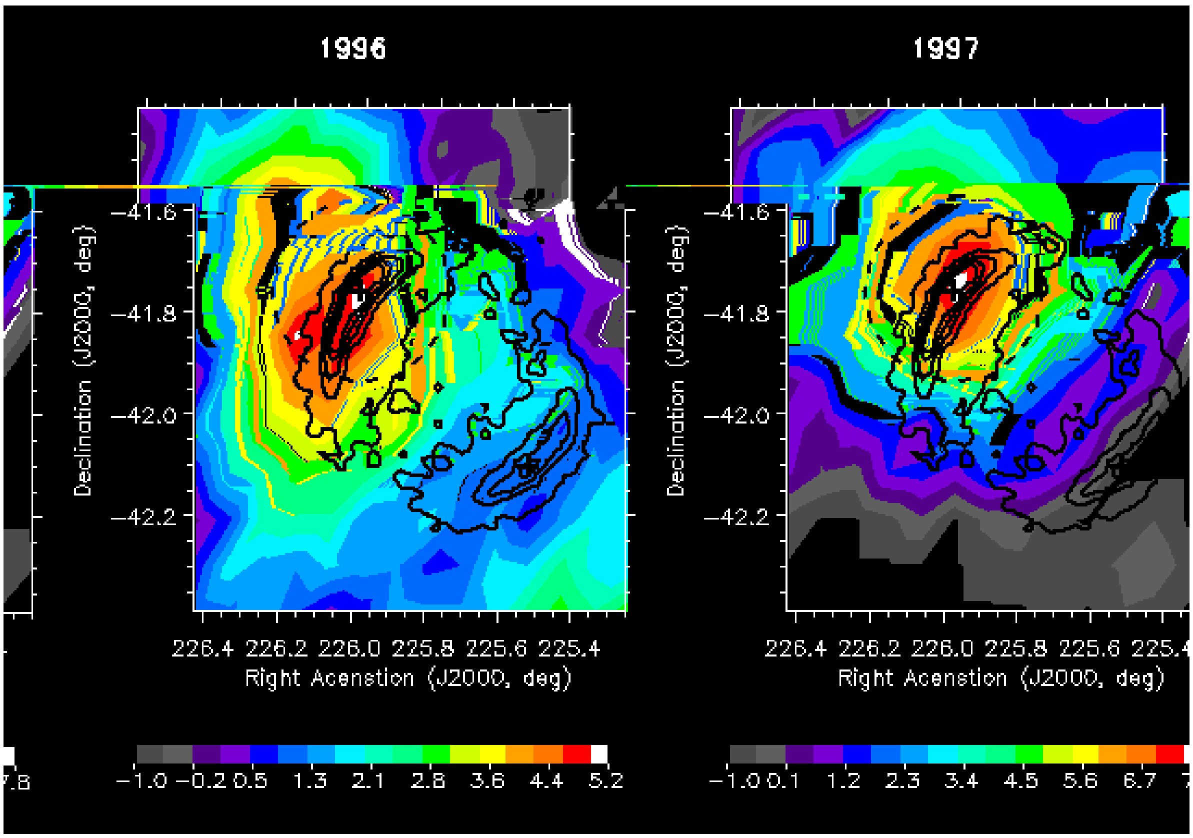
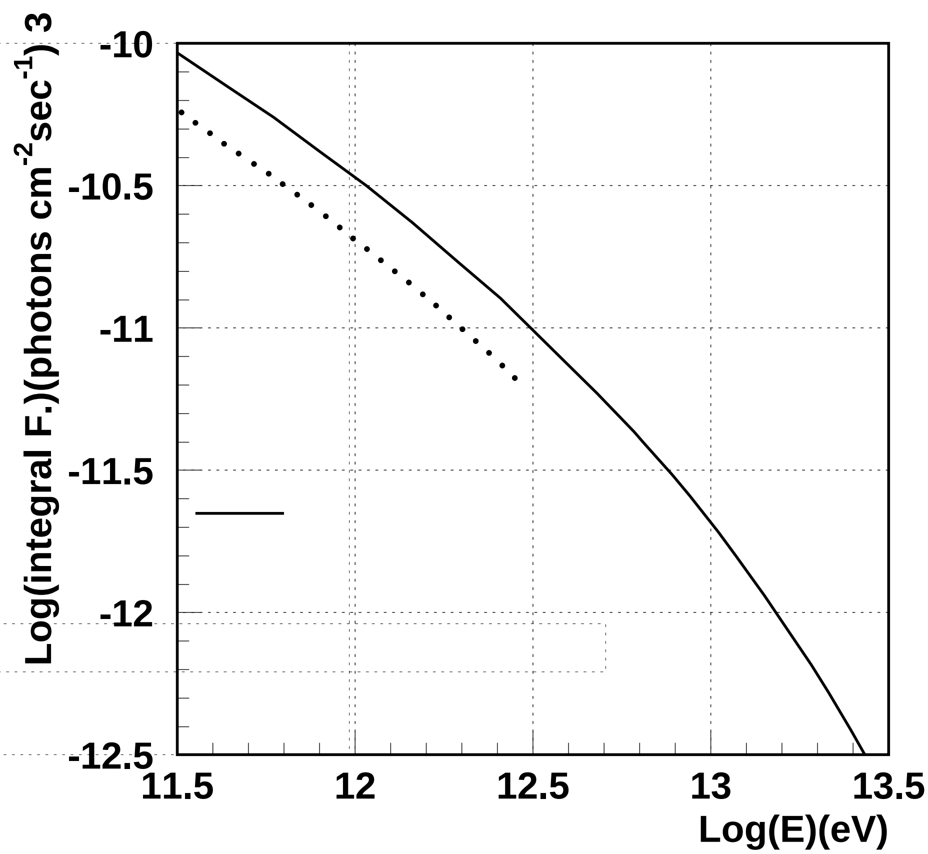


Fig. 2.— (a) The contour map of statistical significance for various positions in the sky around SN1006. Also the maximum flux point in the 2–10 keV band of the ASCA data is marked by a cross. The dashed circle is the area of the point spread function of the CANGAROO telescope within which the significance is larger than half the maximum value. (b) The same contour map obtained from the 1997 data.


Log(integral F.)(photons cm^{-2}sec^{-1}) 3
-10
-10.5
-11
-11.5
-12
-12.5
11.5
12
12.5
13
13.5
Log(E)(eV)