DISCOVERY OF TeV GAMMA RAYS FROM SN 1006: FURTHER EVIDENCE FOR THE SUPERNova REMNANT ORIGIN OF COSMIC RAYS

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ABSTRACT

In this Letter we report the discovery of TeV gamma-ray emission from a supernova remnant made with the CANGAROO 3.8 m telescope. TeV gamma rays were detected at the sky position and extension coincident with the northeast rim of shell-type supernova remnant (SNR) SN 1006 (Type Ia). SN 1006 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.), which is strong evidence for the existence of very high energy (up to hundreds of TeV) electrons in the SNR. The observed TeV gamma-ray flux was $(2.4 \pm 0.5 \text{[statistical]} \pm 0.7 \text{[systematic]}) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} (\geq 3.0 \pm 0.9 \text{TeV})$ and $(4.6 \pm 0.6 \pm 1.4) \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} (\geq 1.7 \pm 0.5 \text{TeV})$ from the 1996 and 1997 observations, respectively. Also, we set an upper limit on the TeV gamma-ray emission from the southwest rim, which is estimated to be $1.1 \times 10^{-12} \text{cm}^{-2} \text{s}^{-1} (\geq 1.7 \pm 0.5 \text{TeV}, 95\% \text{confidence level})$ in the 1997 data. The TeV gamma rays can be attributed to the 2.7 K cosmic background photons upscattered by electrons of energies up to about $10^{14} \text{eV}$ by the inverse Compton process. The observed flux of the TeV gamma rays, together with that of the nonthermal 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 the inverse Compton TeV gamma rays, which provides entirely consistent evidence that electrons of energies up to $10^{16} \text{eV}$ are produced via shock acceleration in SN 1006.

Subject headings: gamma rays: observations — ISM: individual (SN 1006) — supernova remnants

1. INTRODUCTION

The origin of high-energy cosmic rays remains unclear in spite of the long history of cosmic-ray study. While supernova remnants (SNRs) are the favored site for the origin of cosmic rays up to $10^{16} \text{eV}$, since they satisfy the required energy input rate into the galaxy and have a size comparable to the Larmor radius of the highest energy particles, direct supporting evidence is sparse. Recently, detections of GeV gamma rays from the regions near several SNRs have been reported by EGRET (Esposito et al. 1996). Those results might be evidence of the assumed SNR origin of cosmic rays. However, recent observations by the Whipple group of six SNRs, including three detections of EGRET sources, have given upper limits at the hundreds of GeV energy region (Buckley et al. 1998), which are below the expected flux from shock acceleration theory (Drury, Aharonian, & Völk 1994; Naito & Takahara 1994), unless cutoffs in the particle spectrum occur (Sturmer et al. 1997; Gaisser, Protheroe, & Stanev 1998).

On the other hand, intense nonthermal X-ray emission from the rims of Type Ia SNR SN 1006 (G327.6+0.3) has been observed by ASCA (Koyama et al. 1995) and ROSAT (Willingale et al. 1996), which, by attributing the emission to synchrotron radiation, is considered to be strong evidence of the existence of high-energy electrons up to ~100 TeV. Remnant SN 1006 is a typical shell-type SNR that 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 (Blanford & Eichler 1987; Jones & Ellison 1991). If this is the case, TeV gamma rays would also be expected from inverse Compton (IC) scattering 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
Fig. 1.—(a) Number of observed events as a function of the orientation angle $\alpha$ for the 1996 data at the maximum flux point of hard X-rays, where the on- and off-source data are indicated by the solid and dotted lines, respectively. (b) The same $\alpha$-plot for the 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 the on-source data by the exposure times.

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, SN 1006 was observed by the CANGAROO$^{16}$ imaging air Cerenkov telescope in 1996 March and June and 1997 March and April.

2. OBSERVATIONS

The observations were made with the 3.8 m Cerenkov imaging telescope of the CANGAROO Collaboration (Patterson & Kifune 1992; Hara et al. 1993) near Woomera, South Australia (136°47’ E, 31°06’ S). The 3.8 m altitude-azimuth mounted telescope had a $\sim$3 TeV threshold for detecting gamma rays near 70° elevation in the 1996 observations. The 3.8 m mirror was recoated in 1996 October, and its reflectivity improved from 45% to more than 80%, decreasing the threshold energy by a factor of about 2. A multipixel 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).

SN 1006 was observed for 28 hr (on-source) and 18 hr (off-source) in 1996 April and June. Both the northeast (NE) and southwest (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 1997 March and April, in an effort to confirm the 1996 result, we made additional observations of 34 hr (on-source) and 29 hr (off-source) with the same tracking as in 1996 June.

3. ANALYSIS AND RESULTS

The imaging analysis of the data is based on the usual parameterization of the elongated shape of the Cerenkov light image as “width,” “length,” “distance” (location), “concentration” (shape), and the image orientation angle $\alpha$ (Hillas 1985; Weeke et al. 1989). In the $\alpha$-distribution of the events selected by the imaging analysis, the peak appearing around the origin ($\alpha \leq 15°$) in the on-source data is attributed to gamma rays from the target position, and the number of background events below the peak was estimated from the flat region of the $\alpha$-distribution ($30°$–$90°$) in the on-source data. Here off-source data were used to verify the nonexistence of any peculiar structure in the $\alpha$-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 PSR 1706–44 (Kifune et al. 1995) and the nebula surrounding the Crab (Tanimori et al. 1994, 1997, 1998). From the results of 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°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 SN 1006, significances of peaked events with $\alpha \leq 15°$ were calculated at all grid points in 0°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 $\alpha$-peak ($\alpha \leq 15°$) was found at the maximum flux point in the 2–10 keV band of the ASCA data. The $\alpha$-plot of the selected gamma-ray–like events at the X-ray maximum flux point is shown in Figure 1a. Clear peaks due to an excess of gamma-ray events are seen at $\alpha \sim 0°$ for the on-source data of April and June but not for the off-source data. At this X-ray maximum flux point, the statistical significances of these peaks are estimated to be 3.0 $\sigma$ in April, 4.7 $\sigma$ in June, and 5.3 $\sigma$ in total, using the definition mentioned above. The resulting contour map of significances is shown in Figure 2a (Plate L2), 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 thick 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 1997 March and April, we made additional observations in order to confirm the 1996 result. Figure 1b shows the $\alpha$-distribution of gamma-ray–like events selected by the same procedure that was used for the 1996 data. A clear peak ($\alpha \leq 15°$) was observed again, with the significance of 7.7 $\sigma$ 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 SN 1006 has been confirmed (Tanimori et al. 1997). Figure 2b shows the contour map of the significances. The TeV gamma-ray emission region also looks elongated along the ridge of the NE rim, although the profile of the 1997 data is not as extended 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 the 1996 and 1997 data were fitted using a superposition of two PSFs located along the ridge of the NE rim and also using a single PSF. Although the 1996 result favors 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. Therefore, from these significance maps, we cannot establish 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. A compar-
The first and second errors are statistical and systematic errors.

The comparison of the 1997 result with the 1996 result shows that the number of the detected gamma-ray-like events was increased by a factor of about 2 in the 1997 data compared with the observed TeV gamma ray fluxes from the 1996 and 1997 observation of SN 1006. Approximating the emission as coming from a single point source at the maximum flux point in the NE rim, the integral gamma-ray flux in the 1996 observations was calculated to be $(2.4 \pm 0.5 \pm 0.7) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$. The threshold energy for the 1997 observations was also estimated to be $1.7 \pm 0.5$ TeV. Using approximations similar to those above, the gamma-ray integral flux for the 1996 observation was calculated to be $(4.6 \pm 0.6 \pm 1.4) \times 10^{-12}$ cm$^{-2}$ s$^{-1}$ (1.7 $\pm$ 0.5 TeV). In those fluxes, the first and second errors are statistical and systematic errors, respectively. The systematic error arises mainly from the uncertainty of the absolute threshold energy. A larger flux would be obtained if the emission extended wider than the PSF of our detection. Also, the systematic error due to the assumed differential spectrum was evaluated: considering the uncertainties, such as nonlinear effects and energy cutoff, in shock acceleration models 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 Figure 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 ($\geq$2 keV) in the NE rim occupies $\sim$60% of the whole hard X-ray flux emitted from SN 1006 (M. Ozaki 1997, private communication). The current analysis method of using the $\alpha$-distribution has difficulty 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 SW rim. Thus, we set an upper limit on the TeV gamma-ray emission from the SW rim, which is estimated to be $1.1 \times 10^{-11}$ cm$^{-2}$ s$^{-1}$ (1.7 $\pm$ 0.5 TeV, 95% confidence level) from the $\alpha$-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 SN 1006 presents convincing confirmation of the shock acceleration mechanism for very high energy particles up to $\sim$100 TeV in an SNR. The TeV gamma-ray emission region is observed to extend probably over $\sim0^\circ 1$ along the ridge of the NE rim.

From the nonthermal X-ray observation, the detected TeV gamma rays are readily presumed to be generated by IC scattering of very high energy electrons on 2.7 K 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 10 $\mu$G. 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 an exponential cutoff energy spectrum for electrons, where the values of the necessary parameters are determined by fitting the observed radio and X-ray synchrotron emissions. The observed fluxes of TeV gamma rays ($\geq$1.7 and $\geq$3 TeV) fit well if we take $B = 6.5 \pm 2 \mu$G in the model as shown in Figure 3.

The other candidate for 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 p$^+$ decay by considering the following arguments. Since SN 1006 (G327.6+14.6) is located above the Galactic plane, the matter density at the shock is low ($\sim$0.4 cm$^{-3}$; Willingale et al. 1996), so that the expected flux will be about a factor of 10 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 tens 10 TeV in SN 1006. The highest energy of nonthermal electrons can be estimated from the turning point in the synchrotron spectrum and the resultant magnetic fields. Although the turning energy of SN 1006 is not yet precisely determined in recent observations, a 1 keV photon energy 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 a lifetime of 1000 yr for SN 1006, are almost consistent with shock acceleration theory. Observations of some other bands and evolitional theories of the SNR are required to confirm more precisely the highest accelerated energy (Sturmer et al. 1997; Gaisser et al. 1998).

The observed concentration of hard X-ray and gamma-ray emissions in the rims of SN 1006 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 (1996) pointed out that the magnetic field that is upstream from the shock of the rims in SN 1006 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 Cerenkov telescope by the Whipple group (Buckley et al. 1998) and have turned out to be unsuccessful. So far, SN 1006 is the only SNR in which the existence of very high energy electrons up to \( \sim 100 \text{ TeV} \) is suspected from X-ray data. Recently, nonthermal 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 additional 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.

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Fig. 2.—(a) Contour map of statistical significance for various positions in the sky around SN 1006. 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 PSF 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.

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