Evidence of a Curved Cosmic-Ray Electron Spectrum in the Supernova Remnant SN 1006

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Abstract

We present the results of a joint spectral analysis of *Chandra* ACIS X-ray data, some radio data and the CANGAROO gamma-ray data for the eastern rim of the supernova remnant SN 1006. The results provide strong evidence that the shape of the GeV to TeV electron spectrum is curved as has been predicted. The best-fit values of the "maximum" energy of the electrons and the strength of the magnetic field are $\epsilon = 25^{+10}_{-7}$ TeV and $B = 10^{+8}_{-5}$ μG, respectively.

1. Introduction

At energies below 10–100 TeV, Galactic cosmic rays are thought to be accelerated primarily in the shocks of supernova remnants. If this hypothesis is true, then a significant fraction of the internal energy of a remnant (about 10% [7]) must be in the form of cosmic rays. That is, cosmic rays are dynamically important instead of being "test" particles. Ellison et al. [9] predict that a significant cosmic-ray pressure causes the cosmic-ray particle spectra to flatten with increasing particle energy. We present evidence for such a flattening in the GeV to TeV energy band of the electron spectrum of the supernova remnant SN 1006. This remnant is well suited for this study because the high-energy X-ray spectrum is dominated by synchrotron emission and the radio and X-ray spectra are well measured. In addition, the measurements of the gamma-ray spectrum of SN 1006 make it possible to independently determine the "maximum" energy of the electrons and the strength of the magnetic field.

2. Data and Analysis

The X-ray spectrum was produced by analyzing 68 ks of data obtained between 2000 July 10 and 2000 July 11 (UTC) using the Advanced CCD Imaging Spectrometer (ACIS) of the *Chandra X-ray Observatory*. The ACIS instrument is comprised of a 2×2 array (ACIS-I) and a 1×6 array (ACIS-S) of CCDs. Six of these ten detectors (ACIS-I2, -I3, -S1, -S2, -S3, and -S4) were used for SN 1006. The maximum on-axis effective area is about 720 cm^2 at 1.5 keV and is

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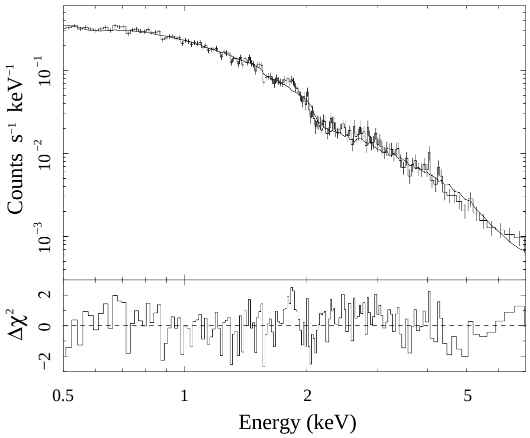

Fig. 1. A background-subtracted ACIS spectrum for a region of the bright eastern rim of SN 1006. The top panel shows the data (histogram with error bars) and the results of the best-fit model with curvature as a free parameter (solid curve). The bottom panel shows the differences between the data and the model divided by the uncertainties in the data.

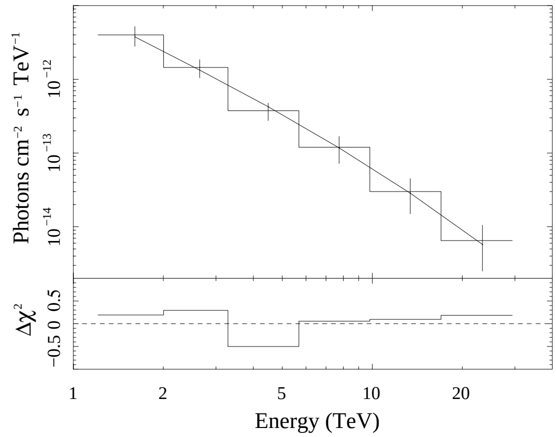

Fig. 2. The CANGAROO spectrum for the eastern rim of SN 1006 [11]. The top panel shows the data (histogram with error bars) and the results of the best-fit model (solid curve). The bottom panel shows the differences between the data and the model divided by the uncertainties in the data.

greater than 10% of this value for energies between about 0.3 and 7.3 keV. Over this energy band, the fractional energy resolution (FWHM/E) ranges from about 0.03 to 0.4. The results described here are based on an analysis of the ACIS-S3 data for a small ($49'' \times 49''$) region of the eastern rim where the X-ray flux is maximized [2]. The location of this region is more or less consistent with the location of peak flux at TeV energies [10]. The spectra of several other regions along the eastern rim were separately analyzed and the results of these analyses are consistent with the results presented here [2].

The sample of radio spectral data used here is the same as the compilation of data described by Allen et al. [3] for the entire remnant (not just the eastern rim). The radio spectral index of the entire remnant is assumed to be representative of the index of the eastern rim and the flux densities for the entire remnant are multiplied by a factor of 0.00175. This factor represents the fraction of the 843 MHz flux that is produced in the $49'' \times 49''$ region used for the X-ray analysis.

The gamma-ray data are the results of Tanimori et al. [11].

Since the X-ray spectrum is dominated by nonthermal emission (Fig. 1), these data (and the radio data) were fit with a model that includes only synchrotron emission. This model is derived from formulae in Baring et al. [5] and is based on the assumption that the electron density is uniform in the volume of

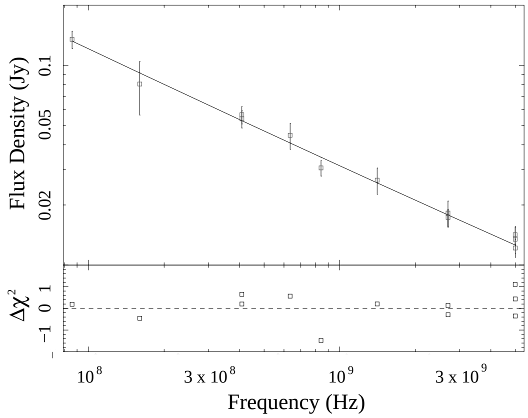

Fig. 3. The radio spectrum for the same region used for the X-ray analysis (see text). The top panel shows the data points with error bars and the results of the best-fit model. The bottom panel shows the differences between the data and the model divided by the uncertainties in the data.

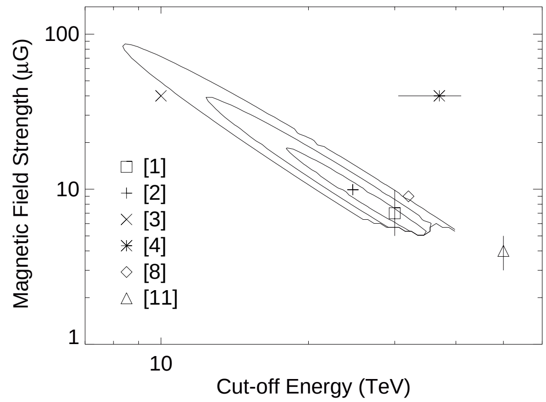

Fig. 4. The 1, 2, and 3 σ confidence contours in the parameter space defined by the exponential cut-off energy of the electron spectrum and the magnetic field strength. The contours are truncated at the high-energy end because the interstellar absorption column must be positive.

interest. The electron number-density spectrum

$$\frac{dn}{dpc} = A \left(\frac{pc}{\mathrm{GeV}} \right)^{-\Gamma + a \log\left(\frac{pc}{\mathrm{GeV}}\right)} e^{(\mathrm{GeV}-E)/\epsilon}, \qquad (1)$$

where n is the electron number density, $p = \gamma m v$, c is the speed of light, A is the number density at $p = 1$ GeV/c (in units of cm^{-3} GeV^{-1}), Γ is the differential spectral index at $p = 1$ GeV/c, a is the spectral "curvature," the logarithm is base ten, $E = \gamma m c^2$, and ϵ is the exponential cut-off (or "maximum") energy. The synchrotron model is also based on the assumptions that the magnetic field strength is a constant in the emitting region and that the angles between the electron momentum vectors and the magnetic field are uniformly distributed between 0 and π.

The gamma-ray data were fit with a model that includes only inverse-Compton scattering of the cosmic microwave background. This model is derived from the formulae of Blumenthal and Gould [6] using the electron spectrum of equation 1. The only additional fit parameter required for the gamma-ray data is a normalization constant.

3. Discussion and Conclusions

The results of the fit are presented in Figures 1–4 and Table 1. The models fit the data quite well. The best fit value for the spectral index at $p = 1$ GeV/c ($\Gamma = 2.20$) is determined by the slope of the radio data. This value is consistent with previously published results. Since the extrapolation of the radio spectrum

Table 1. Best-Fit Parameters

Parameter	Value	90% range
Γ	2.20	2.09–2.31
a	0.042	0.018–0.064
ϵ [TeV]	25	16–40
B [μG]	10	5–30
χ^2/dof	186/170	...

with this index to X-ray energies yields too little X-ray synchrotron emission, the results favor an electron spectrum that flattens with increasing energy ($a = 0.042$). That is, over the roughly 4.5 orders of magnitude in electron energy from the radio (GeV elections) to X-ray (30 TeV electrons) synchrotron regimes, the electron spectral index flattens from 2.2 to 2.0 ($2.2 - 0.042 \times 4.5$). This flattening is significant at the 2.8 sigma level and is qualitatively consistent with theoretical predictions [9]. Therefore, the results of our analysis support the idea that a significant fraction of the kinetic energy of the ejecta in SN 1006 has been transferred to cosmic rays. Since the total energy of the nonthermal electrons is only about 5×10^{46} erg, a tiny fraction of 10^{51} erg, the results suggest that cosmic-ray protons, which can have $\sim 10^2$ times more energy than electrons, must also be accelerated.

The best-fit values for the exponential cut-off (i.e. "maximum") energy of the electron spectrum ($\epsilon = 25^{+10}_{-7}$ TeV) and the strength of the magnetic field ($B = 10^{+8}_{-5}\ \mu$G) are determined by the shapes of the gamma-ray and X-ray spectra, respectively. The confidence contours for these two parameters are plotted in Figure 4. The centroid of these contours is somewhat sensitive to the value of the curvature parameter. If $a = 0$, then the center of the contours shifts to $\epsilon = 36$ TeV and $B = 7\ \mu$G.

4. References

1. Aharonian, F. A., Atoyan, A. M. 1999, A&Ap, 351, 330
2. Allen, G. E., Houck, J. C., Sturner, S. J. 2003, ApJ, in preparation
3. Allen, G. E., Petre, R., Gotthelf, E. V. 2001, ApJ, 558, 739
4. Bamba, A., et al. 2003, submitted
5. Baring, M. G., et al. 1999, ApJ, 513, 311
6. Blumenthal, G. R., Gould, R. J. 1970, Rev. Mod. Phys., 42, 237
7. Drury, L. O'C., Markiewicz, W. J., Völk, H. J. 1989, A&Ap, 225, 179
8. Dyer, K. K., et al. 2001, ApJ, 551, 439
9. Ellison, D. C., Berezhko, E. G., Baring, M. G. 2000, ApJ, 540, 292
10. Tanimori, T., et al. 1998, ApJ, 497, L25
11. Tanimori, T., et al. 2001, in Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 6, 2465