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

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Abstract

A joint spectral analysis of *Chandra* ACIS X-ray data and *MOST* radio data was performed for thirteen small regions along the bright northeastern rim of the supernova remnant SN 1006. These data were fitted with a synchrotron radiation model. The nonthermal electron spectrum used to compute the photon emission spectra is the traditional exponentially cut-off power law with one notable difference. The power-law index is not a constant. It is a linear function of the logarithm of the momentum. This functional form enables us to show, for the first time, that the electron spectrum of SN 1006 seems to flatten with increasing energy. At 1 GeV (i.e. radio–synchrotron-emitting momenta), the power-law index is about 2.2. At 10 TeV (i.e. X-ray–synchrotron-emitting momenta), the index is about 2.0. This result is qualitatively consistent with theoretical models of the amount of curvature in the proton spectrum of the remnant and implies that cosmic rays are dynamically important instead of being "test" particles.

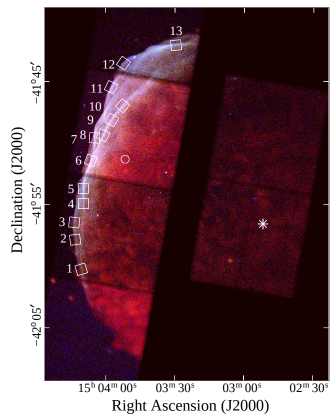

Figure 1. A color-coded ACIS image of the northeastern rim of SN 1006. The red, green and blue colors correspond to the energy bands 0.4–1, 1–2 and 2–7 keV, respectively. Most of the emission at energies greater than 1 keV is concentrated in the (white-colored) filaments along the rim. The edges of the six, square CCDs used to observe the remnant are evident. The relatively high brightness of the CCD with the circle on it and the CCD in the lower left-hand corner is due to an enhanced low-energy sensitivity for these two devices. The circle at $\alpha_{2000} = 15^h3^m51^s.56$ and $\delta_{2000} = -41°51'18''.8$ indicates the location of the nominal aim point of the telescope. The asterisk at $\alpha_{2000} = 15^h2^m51^s.7$ and $\delta_{2000} = -41°56'33''.0$ is the location of the center of the supernova remnant (Winkler & Long 1997).

Assumptions

- The differential electron spectrum is described by a function of the form

$$\frac{dn}{dp} = A\left(\frac{p}{p_0}\right)^{-\Gamma + a\log\left(\frac{p}{p_0}\right)} e^{(p_0-p)/p_{\rm m}}, \quad (1)$$

  where n is the electron number density, $p = \gamma m v$, A is the number density at $p = p_0$, $p_0 = 1$ GeV/c, Γ is the differential spectral index at $p = p_0$, a is the spectral "curvature," the logarithm is base ten and $p_{\rm m}$ is the exponential cut-off (or "maximum") momentum.
- The shape of the radio spectrum in each region is the same as the shape of the radio spectrum of the entire remnant.
- The shape of the synchrotron spectrum is uniform inside each of the regions.
- The estimates of the radio flux densities for each region are accurate.

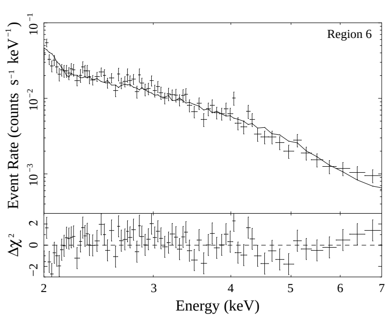

Figure 2. The ACIS spectrum for region 6 of the bright northeastern rim of SN 1006. The top panel shows the sum of the source and background spectra (data points) and the sum of the best-fit model and background spectrum (curve). The model displayed here includes spectral curvature as a free parameter. The bottom panel shows the differences between the data points and the curve divided by the uncertainties in the data points.

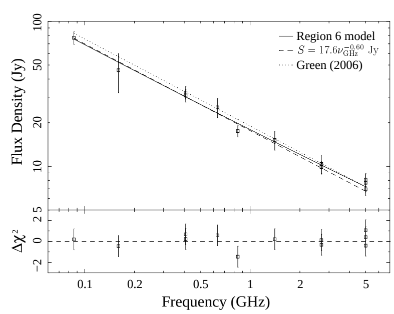

Figure 3. The radio spectrum for the entire supernova remnant SN 1006. The top panel shows the data points and three models. The dashed line is the best-fit power law: $S(\nu) = 17.6^{+6.3}_{-4.8}\,(\nu/1\ \mathrm{GHz})^{-\alpha}$ Jy, where $\alpha = 0.60^{+0.08}_{-0.09}$. The dotted line is a power law using Green's (2006) spectral parameters ($S(\nu) = 19\,(\nu/1\ \mathrm{GHz})^{-0.6}$ Jy). The solid curve is the best-fit curved synchrotron model for region 6 scaled by the factor 571. The bottom panel shows the differences between the data points and the solid curve divided by the uncertainties in the data points.

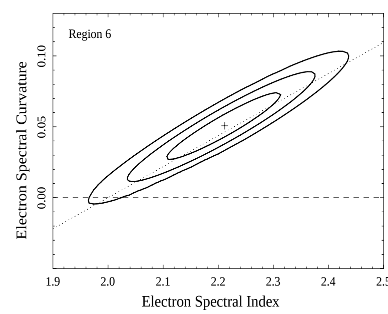

Figure 4. The 1, 2 and 3 σ confidence contours for region 6 in the parameter space defined by the electron spectral index Γ and electron spectral curvature a. The plus symbol indicates the best-fit values of the index and curvature. A positive curvature (i.e. a result above the dashed line) is favored at the 3 σ confidence level for this region. The diagonal dotted line is the expected slope of the linear relationship between the index and curvature parameters.

Table 1. Best-Fit Parameters[a]

Region	RA[b] (h m s)	Dec.[b] (° ′ ″)	Γ[c]	a[d]	$\nu_{\rm m}$[e] (10^{16} Hz)	χ^2/dof
1	15 04 10.7	−42 00 15	$2.24^{+0.16}_{-0.16}$	$0.050^{+0.070}_{-0.059}$	$2.0^{+6.4}_{-1.3}$	8.4/18
2	15 04 13.3	−41 57 51	$2.27^{+0.13}_{-0.15}$	$0.071^{+0.051}_{-0.047}$	$1.8^{+2.8}_{-1.0}$	12.9/22
3	15 04 13.7	−41 56 27	$2.27^{+0.13}_{-0.13}$	$0.080^{+0.039}_{-0.039}$	$2.1^{+2.1}_{-1.0}$	11.0/27
4	15 04 09.7	−41 54 54	$2.22^{+0.12}_{-0.12}$	$0.051^{+0.030}_{-0.031}$	$3.1^{+2.1}_{-1.2}$	50.2/46
5	15 04 09.7	−41 53 41	$2.23^{+0.11}_{-0.12}$	$0.060^{+0.026}_{-0.027}$	$4.3^{+2.1}_{-1.3}$	71.4/63
6	15 04 06.5	−41 51 25	$2.21^{+0.11}_{-0.11}$	$0.051^{+0.025}_{-0.026}$	$5.8^{+2.6}_{-1.6}$	91.5/84
7	15 04 04.8	−41 49 35	$2.19^{+0.11}_{-0.11}$	$0.036^{+0.027}_{-0.027}$	$8.9^{+6.9}_{-3.5}$	69.2/60
8	15 04 01.1	−41 49 22	$2.20^{+0.11}_{-0.11}$	$0.042^{+0.026}_{-0.027}$	$6.1^{+3.6}_{-2.0}$	69.4/71
9	15 03 57.3	−41 48 08	$2.20^{+0.11}_{-0.11}$	$0.042^{+0.026}_{-0.027}$	$6.0^{+3.3}_{-1.9}$	73.0/72
10	15 03 52.6	−41 46 58	$2.20^{+0.11}_{-0.12}$	$0.042^{+0.026}_{-0.027}$	$6.5^{+3.7}_{-2.2}$	71.4/69
11	15 03 57.7	−41 45 28	$2.20^{+0.11}_{-0.11}$	$0.057^{+0.028}_{-0.028}$	$10.8^{+10.3}_{-4.6}$	65.3/61
12	15 03 52.3	−41 43 31	$2.21^{+0.11}_{-0.11}$	$0.060^{+0.032}_{-0.032}$	$8.2^{+10.9}_{-4.1}$	32.2/37
13	15 03 29.5	−41 42 03	$2.25^{+0.11}_{-0.12}$	$0.070^{+0.031}_{-0.031}$	$3.3^{+2.5}_{-1.2}$	35.5/42
Mean[f]	…	…	2.221 ± 0.013	0.054 ± 0.006	…	…

[a] The uncertainties are reported at the 90% confidence level and include only the statistical contributions.
[b] The right ascension and declination coordinates of the centers of each extraction region.
[c] The differential spectral index of the electron spectrum at $p = 1$ GeV/c.
[d] The curvature parameter of the electron spectrum.
[e] The critical frequency associated with the highest-energy electrons.
[f] The 90% uncertainties were used as weights to compute the means.

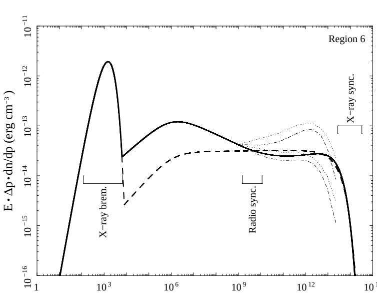

Figure 5. The best-fit electron number-density spectra for region 6. The solid and dashed curves are the spectra for the models with and without spectral curvature, respectively. The upper set of dotted and dot-dashed curves are the models for the proton (not electron) spectrum of SN 1006 presented by Ellison et al. (2000). These curves are plotted only for momenta $p > mc$ (i.e. the range of momenta to which our fits are sensitive) and are normalized to the solid curve at a kinetic energy of 0.9 GeV. The lower set of dotted and dot-dashed curves are the same pair of models multiplied by $(E/0.9\ \mathrm{GeV})^{-0.2}$ to compensate for the difference between the index used by Ellison et al. (2000) and our best-fit index. The amount of spectral curvature in the solid curve is consistent with the amount of curvature in the lower set of dotted and dot-dashed curves. From left to right, the three bracketed energy bands are primarily responsible for the observed thermal bremsstrahlung, radio synchrotron and X-ray synchrotron emission, respectively.

Conclusions

- We performed a joint spectral analysis of *Chandra* ACIS X-ray and *MOST* radio data for thirteen small regions along the bright northeastern filaments of the supernova remnant SN 1006. The data are well fitted by a curved synchrotron model.
- The mean amount of curvature (0.054 ± 0.006) in the electron spectrum is qualitatively consistent with predictions of the amount of curvature in the proton spectrum of SN 1006 (Ellison et al. 2000).
- The best-fit power-law index at 1 GeV (i.e. at radio-synchrotron–emitting momenta) is 2.221 ± 0.013. Including the effect of curvature, the effective spectral index at 10 TeV (i.e. at X-ray–synchrotron—emitting momenta) is 2.005 ± 0.027 (90% confidence level uncertainties). This effective index is consistent with the predictions of Berezhko et al. (2002).
- The evidence of a curved electron spectrum suggests that cosmic rays are not "test" particles. The cosmic-ray pressure at the shock is large enough to modify the structure of the shock. Since nonthermal electrons contain only about 0.1% (i.e. 10^{48} ergs) or less of the total internal energy, the results provide indirect evidence of a much more energetic population of cosmic-ray protons.

References

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