A&A manuscript no. (will be inserted by hand later)

Your thesaurus codes are: 02.01.1; 09.03.2; 09.19.2; 13.07.3

ASTRONOMY AND ASTROPHYSICS 3.10.2018

Leptonic origin of TeV gamma-rays from Supernova Remnants

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received: ?; accepted: ?

Abstract. The lineless power-law emission observed by ASCA from the northeastern rim of the supernova remnant SN1006 has recently been interpreted as synchrotron radiation of electrons with energies around 100 TeV. In this letter we calculate the flux of inverse Compton emission at TeV photon energies that is a natural consequence of the existence of such high energy electrons and the cosmic microwave background. We find that the predicted flux is near the present sensitivity limit of the southern Čerenkov telescope CANGAROO, and should be detectable with the next performance improvements. The spectrum of SN1006 at a few TeV will be very soft.

The existence of such highest energy electrons in SN1006 may not be a unique to this remnant. We can therefore conclude that the detection of TeV γ -ray emission in any supernova remnant does not necessarily provide evidence for a large number of cosmic ray nucleons in these objects, and thus is no simple test of cosmic ray origin as far as nucleons are concerned.

Key words: γ -rays – supernova remnants: SN1006 – cosmic rays

1. Introduction

In a recent paper Koyama et al. (1995) claimed evidence for shock accelerated electrons with energies around 100 TeV in the supernova remnant SN1006. ASCA X-ray observations of the northeastern rim show a lineless X-ray continuum with a power-law spectrum up to 8 keV, in contrast to the spectrum of the interior of the remnant which is dominated by emission lines characteristic of highly ionized material. This power-law emission is interpreted as synchrotron radiation of high-energy electrons in the ambient magnetic fields. For a field strength of 10 μ G the required electron energy would be of order 100 TeV. The synchrotron origin is supported by a correlation between X-ray and radio surface brightness along the northeastern rim. Adding the southwestern counterpart the rims provide 75% of the integrated flux above 1 keV.

The energy spectral index of the power-law emission is $\alpha = 1.95 \pm 0.2$, similar to the integrated spectrum seen by GINGA (Ozaki et al. 1994), but steeper than the $\alpha \simeq 1.2$ from earliest

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observations (Becker et al. 1980). The old spectral index value was very attractive as it allowed modelling of the radio-to-Xray spectrum as synchrotron emission of electrons which are accelerated in a shock wave against losses due to adiabatic expansion and synchrotron radiation (Reynolds and Chevalier 1981; Ammosov et al. 1994). An energy spectral index around 2 at X-ray energies will require more complicated models, for example a cut-off in the electron spectrum which is smoothed out in the synchrotron emission by variations of the magnetic field strength.

One may be attracted to attribute the observed X-ray spectrum to inverse Compton emission. Given the obvious spectral differences between the radio and X-ray emission and the lack of target photons with energies of less than a few $10^{-5} \,\mathrm{eV}$ the only reasonable scenario would involve scattering of NIR and optical photons by electrons with Lorentz factors between 10 and 100. To match the observed luminosities at X-rays and radio frequencies the electron spectrum would have to be extremely soft below a critical Lorentz factor of $\gamma_c = 1000$. If not invoking a new population of electrons the only reasonable model for this would be acceleration against strong Coulomb and ionization losses which leads to an additional factor $\exp(\gamma_c/\gamma)$ in the electron number density and a soft synchrotron spectrum with power-law character. However, Coulomb and ionization losses at $\gamma_c = 1000$ on a time scale of much less than the age of SN1006 imply a density of $n \gg 3 \cdot 10^4 \text{ cm}^{-3}$ which appears excluded by HI data and the lack of free-free absorption.

In this letter we propose a test for the hypothesis that electrons are frequently accelerated to energies around 100 TeV in the shells of supernova remnants. Electrons of this energy will upscatter photons of the microwave background to energies of a few TeV, well in the energy range of Čerenkov telescopes. The flux in γ -rays of energy around 10 TeV is independent of the spectral index since we see particles of similar energy in X-rays and TeV γ -rays. The only unknown variable is the magnetic field strength which controls the synchrotron emissivity. In the next section we will calculate the flux of TeV γ -rays for two values of the X-ray spectral index to estimate also the effect of a slow turn-over in the electron spectrum. The result will be discussed in comparison to the sensitivity of the Čerenkov telescope CANGAROO in section 3.

2. Emission from high-energy electrons

2.1. Synchrotron radiation at X-rays

We have estimated the integral X-ray emission from SN1006 from the results of GINGA (Ozaki et al. 1994) and TENMA (Koyama et al. 1987). Attributing 40% of this to the north-eastern rim we obtain for its flux

$$I_x = 10^{-3} \left(\frac{E}{3 \text{ keV}}\right)^{-3} \text{ ph./cm}^2/\text{sec/keV}$$
(1)

We have performed the calculations also for a photon spectral index of 2.5 to account for the spectral uncertainties and possible spectral variations. With

$$N = C\gamma^{-r} = C(mc^2)^{(r-1)}E^{-r}$$
(2)

as the total number spectrum of relativistic electrons we can calculate the synchrotron flux at X-ray energies for a randomly oriented magnetic field (Rybicki and Lightman 1979)

$$I(E) \simeq \frac{\sqrt{3}e^2 C h^{s-2}}{12 s D^2 c} \Gamma\left(\frac{3s+8}{6}\right) \Gamma\left(\frac{3s-2}{6}\right) \left(\frac{3eB}{8mcE}\right)^s$$
ph./cm²/sec/erg (3)

where s = (r + 1)/2 is the photon spectral index, D is the distance, and h is Planck's constant. To match the observed photon flux the number of electrons is required to be

$$\frac{C}{D^2} \simeq \begin{cases} 6 \cdot 10^{31} \ B_{-5}^{-3} & \text{for } s=3\\ 5 \cdot 10^{23} \ B_{-5}^{-2.5} & \text{for } s=2.5 \end{cases}$$
(4)

where B_{-5} is the magnetic field strength in units of 10 μG .

2.2. Inverse Compton emission at TeV energies

Due to the Klein-Nishina cut-off only scattering of microwave background photons is important. The differential cross section for the up-scattering of a photon with incident energy ϵ to energy E_{γ} by elastic collision with an electron of energy E is given by (Blumenthal and Gould 1970)

$$\sigma(E_{\gamma}, \epsilon, E) = \frac{3 \sigma_T (mc^2)^2}{4 \epsilon E^2} \times \left[2q \ln q + (1+2q)(1-q) + 0.5 \frac{(\Gamma_e q)^2 (1-q)}{1+\Gamma_e q} \right]$$
(5)

where

$$q = \frac{E_{\gamma}}{\Gamma_e(E - E_{\gamma})}$$
 and $\Gamma_e = \frac{4 \epsilon E}{m^2 c^4}$



Fig. 1. The γ -ray spectrum of SN1006 due to inverse Compton scattering of microwave photons. The solid line is calculated for a photon spectral index of s=3 (in the X-rays) while the dotted line is appropriate for a photon spectral index of s=2.5. The total flux at ~10 TeV, where the curves cross, depends only on the magnetic field strength which in this plot is taken to be 20 μ G. The dark bar indicates the present sensitivity of the CANGAROO observatory.

Since in our case $\Gamma_e \approx 1$ the Thomson limit is not valid. The γ -ray flux at TeV energies is then calculated as

$$I_{\gamma} = \frac{c C(mc^2)^{r-1}}{4\pi D^2} \int_{E_{min}} dE \int d\epsilon \ n(\epsilon) E^{-r} \sigma(E_{\gamma}, \epsilon, E) \tag{6}$$

where

$$n(\epsilon) = \frac{1}{\pi^2 (\hbar c)^3} \frac{\epsilon^2}{\exp\left(\frac{\epsilon}{kT}\right) - 1}$$
(7)

is the blackbody spectrum of the microwave background. The resulting $\nu F(\nu)$ flux from SN1006 is given is Fig.1 for the two photon spectral indices 2.5 and 3. At lower energies the inverse Compton spectrum has the same power-law behaviour as the synchrotron emission while above a few TeV it suffers a smooth steepening due to the Klein-Nishina cut-off. At around 10 TeV, where both curves cross, the flux scales only with the observed synchrotron flux in X-rays and with the magnetic field strength which in this plot is taken to be 20 μG according to an estimate on the basis of the minimum energy assumption. This is in contrast to corresponding predictions for the γ -ray emission of nucleonic origin, in which both an unknown efficiency factor for the kinetic energy transfer from the supernova to cosmic rays and an unknown quantity of ambient gas enters the calculation (Drury et al. 1994; Aharonian et al. 1994).

3. Discussion

The predicted flux can be compared the present sensitivity of TeV γ -ray telescope on the southern hemisphere. Air shower arrays like JANZOS have an energy threshold of around 100

TeV which is beyond the Klein-Nishina cut-off in the inverse Compton spectra, and hence are inadequate instruments to detect this emission. However, the current upper limit for SN1006 ($\leq 1.7 \cdot 10^{-13}$ ph./cm²/sec) may still place constraints on the nucleonic component of cosmic rays in this object (Allen et al. 1995).

The Čerenkov telescope CANGAROO on the other hand has an energy threshold of around a TeV which appears advantageous also in view of the particle spectrum in the remnant of SN1006. We have estimated the current sensitivity of CAN-GAROO from the upper limit on another supernova remnant (Mori et al. 1995). The sensitivity is indicated by the dark bar in Fig.1. Obviously, the predicted TeV flux for a photon spectral index of 3 and a mean magnetic field strength of $20 \,\mu G$ nearly meets the sensitivity limit of CANGAROO. If the spectrum is harder, or if it is gradually rolling over, the predicted flux is within a factor of 3 of the observing capabilities of CAN-GAROO. It is obvious that there must be a roll-over to a flatter spectrum somewhere between 10 GeV and 10 TeV to harmonize with the EGRET data for which we derive an upper limit of $2 \cdot 10^{-7}$ ph./cm²/sec integrated above 100 MeV corresponding to a $\nu \hat{F}(\nu) = 2 \cdot 10^{-11} \text{ TeV/cm}^2/\text{sec}$ for a photon spectral index of 2.

The predicted integrated photon flux above 1 TeV is

I(> 1 TeV) =

$$\begin{cases} 1.3 \cdot 10^{-12} \left(\frac{B}{20\mu G}\right) & \text{cm}^{-2} \text{sec}^{-1} & \text{for } \text{s}{=}3 \\ 5 \cdot 10^{-13} \left(\frac{B}{20\mu G}\right)^{-2.5} & \text{cm}^{-2} \text{sec}^{-1} & \text{for } \text{s}{=}2.5 \end{cases}$$
(8)

The energy loss time scale of an electron with 100 TeV energy in a magnetic field of strength 20 μG is around 200 years, short enough to influence the spectrum considerably. A first estimate of the particle energy at which synchrotron losses start to alter the spectrum can be derived by equating the loss time scale and the age of SN1006. The resulting 20 TeV electron energy correspond to synchrotron radiation at 200 eV and to inverse Compton emission at 1 TeV. It may also be that at 100 TeV the electron spectrum is not yet in a steady-state. So if the steep synchrotron spectrum reflects a smooth cut-off in the electron spectrum due to synchrotron losses counterbalancing the acceleration or also incomplete acceleration, the expected γ -ray luminosity spectrum would be constant at a few times 10^{-12} TeV/cm²/sec below 1 TeV, more or less follow the dotted line in Fig.1 up to a few TeV, and then follow the solid line.

4. Conclusions

In this letter we have calculated the flux of TeV γ -rays from the remnant of SN1006 which is expected from inverse Compton scattering of microwave background photons, if the synchrotron interpretation of the lineless power-law emission in X-rays is correct. It is shown that for a reasonable magnetic field strength $(20 \,\mu G)$ the predicted flux is of the same order as the present sensitivity limit of the Čerenkov telescope CAN-GAROO. The TeV γ -ray emission is a natural consequence of the synchrotron nature of the X-ray emission and can therefore be used as a test for the latter interpretation.

The following conclusions can be drawn:

– With a slight improvement in sensitivity or a lower energy threshold the CANGAROO telescope should be able to observe inverse Compton scattered microwave photons from the remnant of SN1006, if the power-law emission at X-rays is really synchrotron radiation. The predicted spectrum is rather steep with a photon spectral index of around 3.

– If supernova remnants other than SN1006 can be detected by Čerenkov telescopes, this will not provide evidence of shock accelerated protons, as was proposed by Drury et al. (1994), since substantial emission of highest energy electrons may not only play a role in SN1006 but also in other supernova remnants.

– We strongly encourage high-resolution X-ray spectroscopy observations of the supernova remnants Cas A and IC443 which both appear to have power-law emission spectra above 4 keV (Holt et al. 1994; Wang et al. 1992).

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