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Gamma ray production in SNR's — contribution from photomeson process

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Abstract. We estimate the integral γ-ray fluxes above 10 MeV photon energy, likely to result from neutral pion decay, following photomeson interactions between ultra-high energy protons accelerated in Supernova Remnants (SNR) and the background non-thermal X-ray photon field. Taking SN1006 as a test case, we find that the integral fluxes in the TeV range are significantly lower than the experimentally reported values, indicating the ineffectiveness of the photo-meson interaction as a source of the reported TeV γ-ray signal from SNR.

1. Introduction

Supernova remnants (SNR) are believed to be a major source of galactic cosmic-rays with energies $\leq 10^{15}$ eV (Drury, 1983). This hypothesis is supported by the COS-B detection of $\geq$ 100MeV γ-rays from Loop-I SNR (Bhat et al., 1985), EGRET detection of $\leq 10GeV$ photons from 10 nearby SNR (Esposito et al., 1996) and of non-thermal X-ray emission (in the keV range) from several SNR, including Cas-A, SN1006, IC 443 and RXJ 1713.7-3946 (Koyama et al., 1995 and references therein). Evidence for the acceleration of particles to $\geq$ 100 TeV energies in SNR is also provided by the recent detection of VHE ($> 10^{11}$ eV) γ-rays from SN1006 (Tanimori et al., 1998) and the Vela SNR (Bhat, 1997). In principle, TeV γ-rays can result from the decay of neutral pions generated in the interactions of the UHE protons, either with the background matter (beam-dumping process) or with background photon fields (photo-meson process). More commonly, TeV photons are also produced by inverse Compton interactions of UHE electrons with the background photons fields, e.g., 2.7K microwave background. While some estimates of the gamma-ray spectra resulting from the beam-dumping and the inverse Compton process in SNR have been made in the recent past (Drury et al., 1994; Naito and Takahara, 1994; Pohl, 1996), we focus our attention here on the photomeson process, taking SN1006 as a test case. The estimated integral TeV photon fluxes, resulting from this process, are found to be significantly lower than the experimentally reported values for SN1006, indicating that the photo-meson process may not be important as far as TeV γ-ray generation in SNR is concerned.

2. Photomeson interaction

We follow the kinematics of the basic photomeson interaction, considering only the single-pion production, viz, $p + \gamma \rightarrow p + \pi^0$, as discussed in detail by Hayakawa and Yamamoto (1963). The $p - \gamma$ interaction is considered in three frames of reference : (i) the observer's frame, (ii) the proton rest-frame and (iii) the centre of mass frame (CMF). Here, the unprimed variables refer to the observer's frame, primed variables to the proton rest frame and the barred variables to the CMF.

In the proton rest frame, photons are confined to the mean opening angle given by tan $\theta' = \frac{1}{\gamma p}$ and have energies

$$\in' = \in \gamma_p (1 + \beta_p \cos \theta) \tag{1}$$

where $\in$ is the background photon energy and γ_p, β_p are the Lorentz factor and the velocity of the proton respectively in observer's frame (for c = 1). The threshold condition for single pion production is

$$\in'_{th} = M_\pi (1 + \frac{M_\pi}{2M_p}) \approx 145\ MeV \tag{2}$$

where M_p and M_π are the proton and pion rest masses respectively.

If $\rho_p(E_p)$ and $n_\gamma(\in)$ represent the densities of protons and non-thermal X-ray photons per unit energy, while E_p (E_π) represents the proton (pion) energies in the SNR envelope, the pion spectrum is given by

$$\rho_\pi(E_\pi)\ dE_\pi = 2\pi \int_{E_{min}}^{E_{max}} d\in \int_{E_p^{min}}^{E_p^{max}} dE_p \int_0^\pi d(\cos\ \theta) F(E_\pi) \sigma(\in') \rho_p(E_p) \frac{n(\in')}{4\pi} (1 + \cos\ \theta) \tag{3}$$

where the energy distribution function is given by

$$F(E_\pi) = \int d\Omega f(E_\pi, \theta) = \frac{2\pi}{\gamma \bar{P}_\pi}\ g(\cos\ \bar{\theta}) \tag{4}$$

$\bar{P}_\pi$ being the pion momentum. From the available experimental data, $g(\cos\ \bar{\theta})$ is given by

$$g(\cos\ \bar{\theta}) = \frac{1}{\sigma(\in')}\ [A(\in') + B(\in') \cos\ \bar{\theta} + C(\in') \cos^2 \bar{\theta}] \tag{5}$$

where $\sigma(\in') = 4\pi(A(\in') + \frac{C(\in')}{3})$ is the total cross section for the $p + \gamma \rightarrow p + \pi^0$ process. $A(\in')$, $B(\in')$, $C(\in')$ are the energy dependent fitting parameters required to fit the experimental data (Berkelman and Waggoner, 1960).

If E_0 is the total energy in cosmic-ray protons in the supernova remnant, taken here as a spherical shell of radius R and thickness D, it follows from Naito and Takahara (1994).

$$\rho_p(E_p) = 4.30 \times 10^3 \frac{4\pi}{c} \frac{1}{S(\alpha,E_p^{max})} E^{-\alpha}(\frac{E_0}{10^{50}erg}) (\frac{10pc}{R})^2 (\frac{1pc}{D}) (cm^3GeV)^{-1} \tag{6}$$

where α is the differential index of source protons and

$$S(\alpha,E_p^{max}) = \frac{1}{2-\alpha}\left[\frac{1}{(E_p^{max})^{\alpha-2}} - \frac{1}{(M_p)^{\alpha-2}}\right] \quad for \quad \alpha > 2.0$$

$$= \log (\frac{E_p^{max}}{M_p}) \; for \; \alpha{=}2.0 \tag{7}$$

The limits of integration over E_p in Equation (4) are given by

$$E_p^{max/min} = \frac{2M_p(M_p + 2\epsilon')E\pi}{2M_p\epsilon' + M_\pi^2 \pm \sqrt{(2M_p\epsilon' - M_\pi^2)^2 - 4M_\pi^2 M_p^2}} \tag{8}$$

In order to obtain $n(\epsilon')$ used in Eqn. (4), we make use of the power-law spectral form of the observed X-ray background from the SNR, viz., $n(\epsilon) = n_0\epsilon^{-\delta}(cm^3keV)^{-1}$, where δ is observationally known and n_0 is derived from the observed X-ray luminosity L_x ($\approx 10^{35}$ erg s^{-1}) in the energy interval, $E_{min} = 0.5$ keV to $E_{max} = 10$ keV. The decay $\pi^o \rightarrow \gamma + \gamma$ leads to the γ-ray integral spectrum as discussed by Stecker (1968),

$$\rho_\gamma(E_\gamma)\, dE_\gamma{=}2dE_\gamma \int_{E_\gamma}^{\infty} dE\pi \; \frac{\rho\pi(E_\pi)}{E_\pi} \tag{9}$$

The integral in Eqn. (9) has been computed for the case $E_p^{max} = 10^{15}$ eV, $E_{min} = 0.5$ keV and $E_{max} = 10$ keV. With these values, we find that the resonance region on the photomeson interaction is predominantly contributing to pion spectrum in Eqn. (4) and as such we have parameterized the distribution in Eqn. (6) over this resonance energy region, to obtain $A(\epsilon')$, $B(\epsilon')$ and $C(\epsilon')$.

In the present study, we have used a reasonable upper limit of $E_0 = 10^{50}$ ergs for the total energy in relativistic protons (~ 10 % of the energy released in the SN explosion), R = 100pc, D=1pc, observer-to-source distance $d{=}1.0kpc$, $\delta{=}1.8$ (typical values for SN 1006), and have used three different values of the proton spectral index, viz., α = 2.0, 2.2, 2.5. Fig. 1 shows the derived integral γ-ray spectrum.

3. Results and discussions

As seen from Fig. 1, the estimated integral TeV flux resulting from the photo-meson process in SN1006 is significantly lower than the value ~ $(3.0 \pm 0.54) \times 10^{-12}$ photons cm^{-2} s^{-1} above 3.0 TeV., reported by Koyama et al., (1995), based on observations with the CANGAROO imaging Cerenkov telescope. This implies that the major contribution for the observed TeV γ -ray flux in case of SN1006 and other SNR has to come from either the beam-dumping

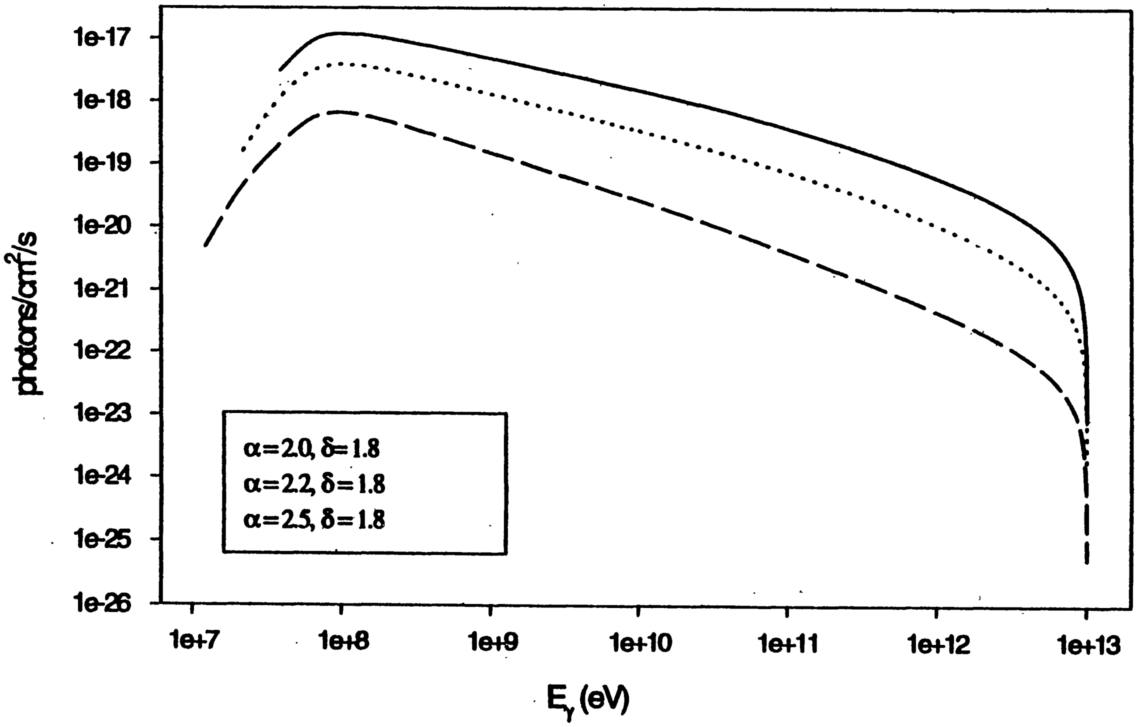

Figure 1. Integral γ-ray spectrum above 10 MeV photon energy for three different values of the differential proton spectral index. The estimated integral flux at ~ 1 TeV is ~ 6 order of magnitude lower than the reported flux for SN1006.

mechanism or the inverse Compton process. Recent measurements with the Whipple and HEGRA Cerenkov imaging systems on possible TeV γ-ray emission from 6 nearby SNR, including γ-Cygni and IC 443 (Bhat, 1997) have yielded upper limits on the TeV photon fluxes which fall below the model predictions based on the conventional beam-dumping process. Taken together with the above-referred result on SN1006, the observations clearly indicate that the scenario whereby energetic protons interact either with background material target or radiation fields to generate TeV γ-rays may not be favoured in actual practice. On the contrary, the recent work of Pohl (1996) suggests that the observed TeV photon flux from SN1006 can be adequately explained in terms of the inverse Compton upscattering of 2.7 K microwave background radiation by UHE electrons. It follows that, while we have now sufficient proof for leptonic acceleration to UHE in galactic SNR, the direct evidence for hadronic acceleration to UHE regime is yet to be obtained.

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