Inverse Compton Gamma-ray Background due to Supernova Remnants

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Abstract

We study the contribution of the source cosmic rays (SCRs), confined in supernova remnants (SNRs), to the diffuse high energy gamma-ray emission above 1 GeV from the Galactic disk. Gamma-rays produced by the SCRs have a much harder spectrum compared with those generated by the Galactic cosmic rays (GCRs) which uniformly occupy a much larger residence volume. The contribution of the SCRs becomes dominant at gamma-ray energies above 10 GeV and at TeV energies it exceeds the flux due to nuclear GCRs by more than one order of magnitude. Accurate measurements of the diffuse Galactic gamma-ray emission at TeV-energies can provide an important test for the CR origin from such sources.

1. Introduction

According to the results obtained with the Energetic Gamma Ray Experiment Telescope (EGRET) [1] above 1 GeV, the observed average diffuse γ-ray intensity in the inner Galaxy, exceeds the model prediction significantly. It was also shown [2] that CRs, accelerated and confined in SNRs, give an important contribution to the high-energy γ-ray emission from the Galactic disk. Since the CR energy spectrum inside SNRs is much harder than on average in the Galaxy, this relative SNR contribution increases with energy and becomes in fact dominant at γ-ray energies $\epsilon_\gamma > 100$ GeV. Compared with that earlier study [2] we take here into account that a considerable fraction of those SNRs, which correspond to type II and Ib supernovae, expands into the nonuniform circumstellar medium strongly modified by the presupernova wind, and we also consider in more detail the contribution of the CR electrons due to inverse Compton (IC) scattering on the background photon field. As demonstrated below, they lead to an order of magnitude increase of the Galactic γ-ray emission at TeV-energies.

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2. Results and discussion

The majority of the GCRs is presumably accelerated in SNRs. The total number of SNRs $N_{SN} = \nu_{SN} T_{SN}$ is an increasing function of their assumed life time T_{SN}, i.e. the time until which they can confine the accelerated particles; here ν_{SN} is the Galactic SN rate. Therefore the oldest SNRs dominate the total γ-ray luminosity [2]. Then the CRs in the Galaxy are represented by two basically different populations. The first one consists of the ordinary GCRs and presumably occupies a large Galactic residence volume quasi-uniformly. The second CR population, which we call Source Cosmic Rays (SCRs), is represented by shock accelerated CRs that are still confined in the localized SNRs. During the initial, active period of SNR evolution of about $t \leq 10^5$ yr when the SN shock is relatively strong, the volume occupied by the accelerated CRs practically coincides with the shock volume. In later stages the shock becomes weak and CRs begin to leave the SNR acceleration region. After some period of time T_{SN} the escaping SCRs become very well mixed into the "sea" of GCRs.

The total γ-ray spectrum measured from an arbitrary Galactic disk volume is expected to be [2]

$$dF_\gamma/d\epsilon_\gamma = (dF_\gamma^{GCR}/d\epsilon_\gamma)[1.4 + R(\epsilon_\gamma)], \tag{1}$$

where $dF_\gamma^{GCR}/d\epsilon_\gamma$ is the π^0-decay γ-ray energy spectrum due to GCRs. For the ratio $R = Q_\gamma^{SCR}/Q_\gamma^{GCR}$ of the γ-ray production rates due to SCRs and GCRs, we have

$$R(\epsilon_\gamma) = 0.07\zeta(T_p/10^5 \text{ yr})(\epsilon_\gamma/1 \text{ GeV})^{0.6}(1 + R_{ep}), \tag{2}$$

where $\zeta = N_g^{SCR}/N_g^{GCR}$, N_g^{GCR} and N_g^{SCR} are the gas number density in the Galactic disk and inside SNRs respectively, $R_{ep} = Q_\gamma^{IC}/Q_\gamma^{pp}$ is the ratio of the IC to π^0-decay γ-ray production rates due to the SCRs.

The proton SCR confinement time which is also the confinement time $T_e = T_p$ of the electron component, if synchrotron losses are not more restrictive for electrons (see below), is given by the expression

$$T_p = \min\{T_{SN}, 10^3(\epsilon/\epsilon_{max})^{-5} \text{ yr}\}\text{ , or } T_p = \min\{3 \times 10^4, 300(\epsilon/\epsilon_{max})^{-5}\} \text{ yr} \tag{3}$$

for the case of SNRs expanding into a uniform ISM and into the bubble created by the presupernova star wind, respectively; $\epsilon_{max} = 10^5$ GeV, and $\epsilon_\gamma = 0.1\epsilon$, which is roughly valid for the hadronic γ-ray production process.

In the energy range considered, the γ-ray luminosity of a single SNR due to IC electron scattering on the background photons can be described in the Thompson limit. Performing then the integration over all possible SNR ages we find the luminosity ratio:

$$R_{ep} = 73.6K_{ep}(N_{ph}/N_g^{SCR})(4\epsilon_\gamma\epsilon_{ph}/3m_e^2c^4)^{(\gamma-1)/2} \tag{4}$$

for γ-ray energies $\epsilon_\gamma < \epsilon_\gamma^*$, and

$$R_{ep} = 73.6K_{ep}\left(\frac{N_{ph}T_e}{N_g^{SCR}T_p}\right)\left(\frac{4\epsilon_\gamma\epsilon_{ph}}{3m_e^2c^4}\right)^{(\gamma-1)/2}\left(\frac{\epsilon_\gamma}{\epsilon_\gamma^*}\right)^{-1/2}\left(1+\ln\sqrt{\frac{\epsilon_\gamma}{\epsilon_\gamma^*}}\right) \quad (5)$$

for $\epsilon_\gamma > \epsilon_\gamma^*$, where $\epsilon_\gamma^* = 8(\epsilon_{ph}/1\ \mathrm{eV})(10^5\ \mathrm{yr}/T_e)^2(B/10\ \mu\mathrm{G})^{-4}$ TeV is the energy of γ-rays which are emitted by electrons with synchrotron loss time equal to T_e, N_{ph} and ϵ_{ph} are the number density and the energy of the background photons, K_{ep} is electron to proton SCR ratio. We take into account the cosmic microwave and the far infrared radiation fields. The maximum energy of SCR electrons is also restricted by their synchrotron losses $\epsilon_{max}^e = 24(V_s/10^3\ \mathrm{km/s})(B/10\ \mu\mathrm{G})^{-1/2}$ TeV. Here V_s is the shock speed at a given SNR evolutionary phase. At the beginning of the Sedov phase ($t \sim 10^3$ yr) the shock speed is about $V_s \approx 4\times10^3$ km/s. Later on it decreases as $V_s \propto t^{-3/5}$, and therefore the electron confinement time can be written in the form $T_e = \min\{T_p, 10^3(\epsilon_e/\epsilon_{max}^e)^{-5/3}\ \mathrm{yr}\}$.

In Fig.1 we present a calculated γ-ray spectrum, expected from the central part of the Galaxy, and based on the above expressions with $T_{SN} = 10^5$ yr, $K_{ep} = 10^{-2}$, and $N_g^{SCR} = N_g^{GCR}$. A SCR power law index $\gamma = 2.15$ and average efficiency of SCR production in SNRs, which are required for GCRs, were used. The Tibet upper limit data [3], shown in Fig.1, are multiplied by a factor of 3 since we present the expected γ-ray flux from the region $|b| \le 2^\circ$ whereas the original data correspond to $|b| \le 5^\circ$. It was assumed [4] that 32% of SNe are type II and Ib SNe which have a massive progenitor star whose winds strongly modify the circumstellar medium. In this case CRs are mainly produced when the SN shock reaches the swept-up thin shell with a gas number density $N_g^{SCR} = 10$ cm³ and a radius $R_{sh} = 30$ pc. The contribution of these SNRs to the background radiation, essential at $\epsilon_\gamma < 300$ GeV, satisfactorily fits the EGRET data [1] (see Fig.1). The SCR contribution becomes dominant already at $\epsilon_\gamma > 10$ GeV. At TeV energies the predicted flux, which is mainly due to SCR electron component, exceeds the lowest HEGRA upper limit [5] almost by a factor of two. Even if T_{SN} is as short as 2×10^4 yr the expected SCR contribution at TeV energies is only by a factor of two lower and is still more than an order of magnitude in excess of the GCR contribution. The restriction for the electron confinement time T_e due to their synchrotron losses becomes essential at γ-ray energies $\epsilon_\gamma > 1$ TeV, which leads to a steepening of the γ-ray spectrum (see Fig.1a).

The only physical element which strongly influences the IC γ-ray production rate is the SNR magnetic field. In Fig.1b we present the same calculations as in Fig.1a, but with a mean SNR magnetic field value $B = 30\ \mu$G. Such a large value can be attributed to its amplification at the shock front due to the nonlinear CR backreaction. Compared with the previous case IC γ-rays are decreased by a factor of about ten, and therefore the flux is dominated by π^0-decay γ-rays. One can see that in this case the expected γ-ray flux is below the HEGRA upper limit

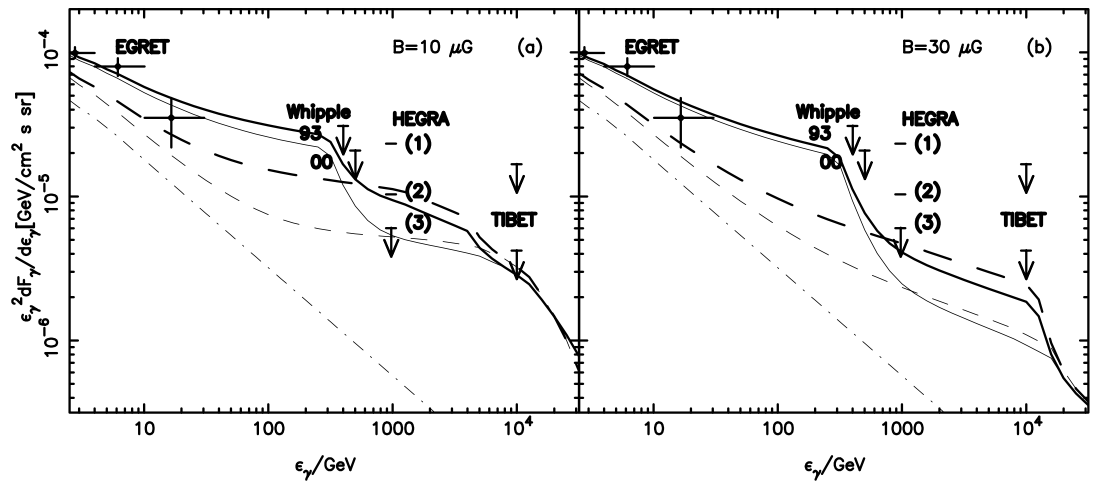

Fig. 1. The average diffuse γ-ray spectrum of the inner Galaxy ($38^\circ < l < 43^\circ$, $|b| \leq 2^\circ$). The dash-dotted line represents GCR contribution. Thick and thin lines correspond to $T_{SN} = 10^5$ yr and $T_{SN} = 2 \times 10^4$ yr. Dashed lines correspond to a uniform ISM, full lines correspond to the case when 32% of the SN energy is released into wind bubbles. SNR magnetic fields $B = 10$ μG (a) and 30 μG (b) were assumed, respectively. EGRET [1], Whipple [6,7], HEGRA [5] and TIBET [3] data are shown.

already at the SCR confinement time $T_{SN} = 10^5$ yr and considerably below the Tibet upper limit.

We conclude that the expected γ-ray flux at TeV-energies is consistent with the existing upper limits if either the SNR life time is as short as 2×10^4 yr or if the magnetic field in SNRs is substantially amplified relative to the typical ISM field. It is much harder and almost an order of magnitude higher than the GCR contribution. The detection of such a hard and high γ-ray background could be considered as a consistency test for the GCR origin in SNRs.

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3. References

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