Nuclear Cosmic Rays from Supernova Remnants

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Abstract

The nonlinear kinetic model of cosmic ray (CR) acceleration in supernova remnants (SNRs) is used to describe the properties of the young remnants of SN 1006, Tycho's Supernova, and Cassiopeia A in the Galaxy. The calculated expansion law and the radio-, X-ray and gamma-ray emissions produced by the accelerated CRs in these SNRs agree quite well with the observations, which in the case of Tycho's gamma-ray flux correspond to an upper limit. It is shown that the predicted pion-decay TeV gamma-rays from SN 1006, Cas A and Tycho dominate over the inverse Compton (IC) gamma-rays, generated by the CR electrons in the cosmic microwave background. It is also shown that the associated set of parameters is consistent with the idea that these SNRs are typical Galactic CR sources.

1. Introduction

Direct information about the high-energy CR population in SNRs can be obtained from observations of the nonthermal emission of SNRs. The electron CR component is very well visible in a wide wavelength range of radiation from radio to γ-ray emission, whereas the nuclear CR can only be detected in γ-rays. If this nuclear component is strongly enhanced inside SNRs then through inelastic nuclear collisions, leading to pion production and subsequent decay, γ-rays will be produced at the detectable level.

We briefly analyse the situation in young SNRs (SN 1006, Tycho and Cassiopeia A (Cas A)) on the basis of the nonlinear kinetic model [1] and conclude that all the observed characteristics of these young SNRs are consistent with the idea that the ensemble of Galactic SNRs constitutes the main source of the nuclear GCRs.

2. Results and discussion

The two main physical factors which influence the efficiency of the diffusive shock acceleration and its final significance are the injection rate and the effective

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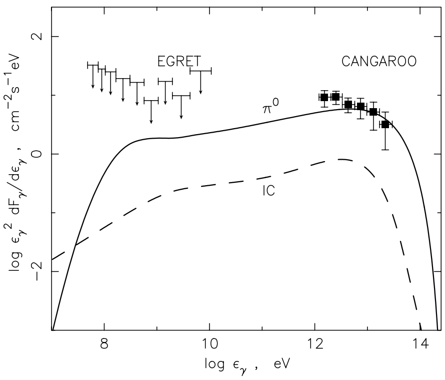

Fig. 1. Differential π^0-decay (solid line) and IC (dashed line) γ-ray fluxes of SN 1006 as a function of γ-ray energy [5]. High energy γ-ray flux data [6] and EGRET upper limits [7] are also shown.

magnetic field. The injection rate is the number of gas particles that are swept up by the shock and accelerated. It is described by a dimensionless injection parameter η which is a fixed fraction of the ISM particles entering the shock front. A sufficiently high injection rate $\eta = 10^{-4}$ to 10^{-3} which leads to efficient CR production occurs on the quasi-parallel portions of the shock surface. It is expected to be strongly suppressed at the quasi-perpendicular fractions of the shock surface. This lack of symmetry in the actual SNR can be approximately taken into account by a renormalization factor $f_{\rm re} = 0.15$ to 0.25 [2] which diminishes the nucleonic CR production efficiency as calculated in a spherically symmetric model.

The magnetic field strength plays a twofold role. First of all it determines the upper energy of CRs ϵ_{max} which can be achieved during the SNR evolution since $\epsilon_{max} \propto B$. To produce power-law spectrum at least up to the "knee" energy at 3×10^{15} eV, which we believe is a necessary condition for a GCR source, one needs a magnetic field strength that is several times larger than the typical ISM field [3]. Such a large effective field is expected to be the result of non-linear amplification near the SN shock by the CR acceleration process itself [4]. Secondly, the radio synchrotron emission of young SNRs, $S_\nu \propto \nu^{-\alpha}$, is characterized by spectral indexes $\alpha > 0.5$. Such steep spectra are produced by electrons accelerated at the shock modified by the nuclear CR backreaction if there exists a high magnetic field $B >> 10$ μG in the acceleration region. For such a strong magnetic fields in SNRs the electron spectrum has a lower maximum energy ϵ_{max} than the proton spectrum due to synchrotron losses. It gives a natural explanation for the fact that the value of ϵ_{max} extracted from the X-ray observations is so small, $\epsilon_{max} \sim 10$ TeV, that these SNRs could hardly be considered as sources of GCRs, if the proton spectrum was bounded by the same upper cutoff as expected for a low magnetic field.

The nonlinear kinetic model for CR acceleration in SNRs has been applied to SN 1006 in order to explain its observed properties [5]. The existing SNR data are very well approximated by a large downstream magnetic field value $B_d = 120$ μG, when an efficient nucleon injection rate $\eta = 2 \times 10^{-4}$ is assumed

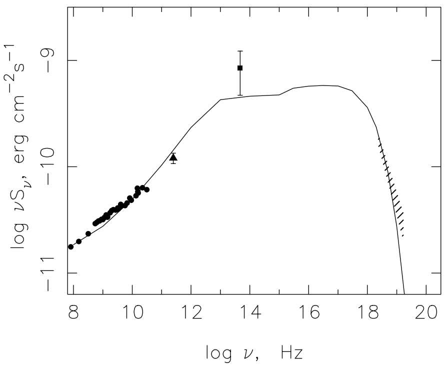

Fig. 2. Synchrotron spectral energy distribution of Cas A as a function of frequency at epoch 1970 [12]. The radio emission above 100 MHz [14], the data at 1.2 mm (triangle) [15] and 6 μm (square) [16], as well as the hard X-ray spectrum [17] are presented.

(these values are consistent with the observed radio spectral index $\alpha = 0.57$).

The π^0-decay γ-ray flux produced by the nuclear CR component exceeds the flux of IC γ-rays generated by the electronic CR component (Fig.1). The maximum energy of accelerated protons $\epsilon_{\rm max} = 3 \times 10^{14}$ eV and their total energy content $E_{\rm c} \approx 3 \times 10^{50}$ erg, reproduced in this case, are roughly consistent with the requirements for the Galactic CR sources.

The analysis of the radial distribution of the SNR surface brightness provides the additional strong evidence for efficient nuclear CR acceleration. The radial distribution of electrons with energy $\epsilon \approx 30$ TeV, which produce synchrotron radiation at keV-energies, is characterized by a sharp peak at the shock position with width $l \approx 0.03 R_s$ [5]. Taking into account that the current shock size is $R_s = 7$ pc we have $l \approx 0.2$ pc. The analysis of Chandra image of SN 1006 [8] , which results in an average value $l = 0.2$ pc in the X-ray energy range from 2 to 10 keV, gives excellent agreement with our model (see [9] for a details).

A very similar situation exists in Tycho's SNR [10]. A rather high downstream magnetic field strength $B_{\rm d} \sim 240$ μG and a proton injection rate $\eta = 3 \times 10^{-4}$ are needed to reproduce the observed steep and concave radio spectrum and to ensure a smooth cutoff of the synchrotron emission in the X-ray region. The resulting nonthermal electron to proton ratio turns out to be consistent with the observed ratio in interstellar space. The total γ-ray flux at 1 TeV (with the π^0-decay component exceeding the IC component) comes out to be slightly lower than the most restrictive observational upper limit from the HEGRA experiment [11].

In the case of Cas A [12] we adopted the specific model of Borkowski et al.[13] to describe the circumstellar medium. Accordingly, part of the slow red supergiant wind of the SN progenitor has been swept up into a dense shell by a fast stellar wind during the final blue supergiant (probably Wolf-Rayet) phase of the progenitor star. The spectral shape of shock-accelerated electrons with their dramatic synchrotron cooling in the downstream region is very well consistent with the observed synchrotron emission. The very steep radio spectrum $S_\nu \propto \nu^{-0.77}$ is reproduced as a result of a strongly modified shock. This shock modification can only be produced by accelerated protons. The significant synchrotron losses of

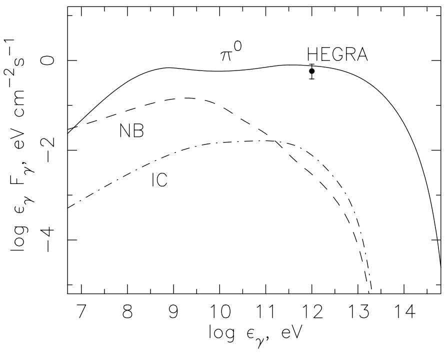

Fig. 3. Bremsstrahlung (dash-dotted), IC (dashed) and π^0-decay (solid) integral γ-ray energy fluxes of Cas A as a function of γ-ray energy [12]. The 1 TeV data point is from HEGRA [11].

electrons in the strong interior magnetic field $B_d \approx 1$ mG steepens their spectrum also at high energies $\epsilon_e > 10\,\mathrm{GeV}$, leading to a flat connection of the spectral energy distributions of the observed radio and X-ray synchrotron emissions (see Fig.2).

Our calculations show that at all energies above 1 GeV the γ-ray production is dominated by π^0-decay, consistent with the observed TeV γ-ray flux (see Fig.3). The leptonic emission is totally inadequate to explain the observed TeV γ-ray flux.

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3. References

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