Cosmic ray production in the supernova remnants with account of reacceleration: secondary to primary ratio

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Abstract

Cosmic ray (CR) spectra produced in supernova remnants are calculated on the basis of the nonlinear kinetic model. This includes reacceleration of background galactic cosmic rays (GCRs) and spallation of CR nuclei due to collisions with the gas nuclei, together with the injection and subsequent acceleration of suprathermal particles from the postshock thermal pool. It is shown that GCR reacceleration and CR spallation produce a measurable effect especially in the secondary to primary ratio, making its energy dependence considerably flatter at high energies compared with the predictions of the standard model.

1. Introduction

It is a widely accepted hypothesis that supernova remnants (SNRs) are the main sources of cosmic rays (CRs) in the Galaxy. Released from SNRs, the primary relativistic nuclei interact with the interstellar gas and produce lighter secondary relativistic nuclei as a result of nuclear spallation. The boron-to-carbon (B/C) ratio is an example of the secondary-to-primary (s/p) ratio in CRs.

In the course of their propagation in the Galaxy GCRs have a finite chance to meet again some SN shock and to undergo reacceleration. At high energies a flattening of the s/p ratio is expected due to such reacceleration [1-3]. Whereas previous considerations were based on a simplified plane wave approach, we have applied the nonlinear kinetic model for CR production in SNRs [4] in order to calculate the CR spectrum with the inclusion of reacceleration of ambient GCRs and of nuclear spallation *inside* the sources, and to study the effect on the secondary to primary ratio.

2. Results and discussion

For estimates we use here the simple leaky box model in order to describe the transport and nuclear fragmentation of comic rays in the Galaxy. Since boron

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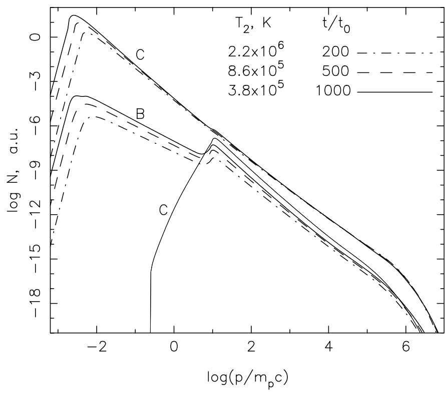

Fig. 1. The momentum spectra of B and C nuclei produced during SNR evolution in a warm ISM up to three different time moments ($t_0 = 367$ yr).

is mainly produced due to spallation of carbon and oxygen, the B/C ratio can be written in the form

$$\frac{n_B}{n_C} = \frac{x(\sigma_{CB} + \sigma_{OB} n_O/n_C)}{m_p + \sigma_B x} + \frac{N_B}{N_C}\frac{(m_p + \sigma_C x)}{(m_p + \sigma_B x)}, \tag{1}$$

where $x = m_p N_g v \tau_c$ is the escape length, i.e. the mean matter thickness traversed by GCRs in course of their random walk in the Galaxy, $n(\epsilon_k)$ is their differential number density as a function of their kinetic energy per nucleon, τ_c is the mean residence time in the Galaxy, σ is the spallation cross section, $N(\epsilon_k)$ is the total differential number of CRs created during the entire evolution of a single SNR (overall CR spectrum), v is the particle speed, $N_g = \rho_0/m_p$ is the ISM number density, ρ_0 is the ISM density, and m_p is the proton mass.

The overall CR spectra $N(\epsilon_k)$ are produced due to injection of some fraction η of the postshock thermal particle distribution [1] and reacceleration of already existing GCR particles whose energy is high enough $\epsilon_k \gtrsim 100$ MeV/n so that all of them participate in the acceleration. The CR secondary elements have a very steep energy spectrum with a quit sharp peak at $\epsilon_{GCR} \approx 600$ MeV/n. Therefore, in the case of reacceleration, it is assumed that the existing GCR population is advected into the SN shock front with the single energy $\epsilon_k = \epsilon_{GCR}$. Also included is the secondary GCR production inside SNRs.

In detail we consider the evolution of a typical type Ia SNR in three essentially different phases of the ISM: a diluted hot ISM with hydrogen number density $N_H = 0.003$ cm^{-3} and temperature $T_0 = 10^6$ K, a warm ISM with $N_H = 0.3$ cm^{-3} and $T_0 = 10^4$ K, and an ISM with the $N_H = 1$ cm^{-3} and $T_0 = 10^4$ K. Numerical results corresponding to the so-called warm ISM with $N_H = 0.3$ cm^{-3} are presented in Fig.1, where the boron and carbon momentum spectra $N(p,t)$ are shown that include all particles accelerated during the SNR evolution up to three different moments of time t. One can see that reacceleration of GCRs provides quite a small contribution to the overall C-spectrum. In the B-spectra two different component are clearly seen. The first one is peaked at momentum $p = p_{GCR} \approx Am_pc$ of injected GCRs. Since p_{GCR} does not depend on time, the efficiency of their acceleration (reacceleration) progressively increases with time, roughly proportional to the total number of particles involved in the acceleration. This number is proportional to the shock volume V_{SN}. Since in this case the late SN evolutionary phases, when the SN shock is already weaker than in the early Sedov phase, are so important for secondary CR production, their overall spectrum is essentially steeper than the spectrum of primary nuclei (see Fig.1). The second B-component is due to the spallation of energetic carbon and oxygen nuclei. Its spectrum is significantly harder than that of the first one, because it is directly related with the the spectra of primaries. Therefore it contributes importantly only at very high momenta $p \gtrsim 10^4 m_p c$ and also dominates at very low momenta $p < p_{GCR}$, where boron production due to reacceleration is negligible.

As a result the ratio $r_s = N_B/N_C$ becomes steeper and increases with time. Therefore the effect of GCR reacceleration on the B/C ratio depends strongly on the confinement time T_{SN} which is that SNR age at which previously accelerated CRs are released into the Galactic volume. There are two factors which determines the confinement time T_{SN}. The first one is the decrease of the shock Mach number during the SNR evolution. When it becomes so low at some stage $t = t_4$ that the shock compression ratio drops below 4, the acceleration of freshly injected particles becomes inefficient. The acceleration process may also stop at some stage $t = t_6$, when the postshock temperature drops below 10^6 K so that radiative SNR cooling sets in. We adopt here $T_{SN} = min\{t_4, t_6\}$. In the case of a warm ISM the postshock gas temperature $T_2 = 1.3 \times 10^6$ K at $t = 300t_0$. Therefore the confinement time is $T_{SN} = t_6 \approx 10^5$ yr ($t_0 = 367$ yr in this case).

According to the standard leaky box model the value of the escape length $x_g \approx 14$ g/cm^2 at GeV energies, with energy dependence $x_g \propto \epsilon_k^{-0.6}$ for $\epsilon_k >$ 5 GeV/n, fits the existing B/C data [5]. Here x_g is the escape length in the case when CR sources do not produce secondary CRs. The galactic model with distributed stochastic reacceleration predicts a weaker decrease of the B/C ratio at high energies $\epsilon_k > 30$ GeV/n $x_g \propto \epsilon_k^{-0.3}$ [6]. Since the source contribution leads to a decrease of the actual escape length, we assume a simple relation $x = \delta x_g$. The B/C ratio calculated with these two functions $x_g(\epsilon_k)$ are shown in Fig.2 by the dotted lines. At low ISM density the production of B nuclei in SNRs is completely due to their reacceleration, whereas at larger ISM densities the spallation of C and O nuclei becomes more important.

Since the actual ISM density where SN explosions take place is not known, we present in Fig.2 the expected range of the B/C ratio which corresponds to ISM hydrogen number densities from $N_H = 0.003$ cm^{-3} to 1 cm^{-3}. To fit the existing data one needs $\delta = 0.3$, 0.7 and 0.9 for $N_H = 0.003$ cm^{-3}, 0.3 cm^{-3} and 1 cm^{-3}, respectively. The escape length x substantially decreases only if all SNRs explode into a diluted ISM with $N_H = 0.003$ cm^{-3}. In this case the influence of reacceleration becomes strong already for $\epsilon_k \sim 10$ GeV/n. This is in contradiction

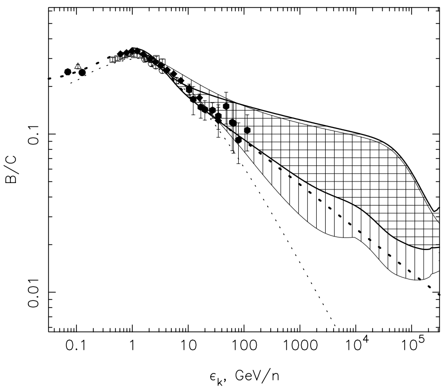

Fig. 2. B/C ratio as a function of kinetic energy per nucleus. The dotted area between the two solid lines represents the expected B/C ratio for the circumstellar hydrogen number density range $N_H = 0.003$ to $1\ \mathrm{cm}^{-3}$. Thick (thin) lines correspond to the leaky box model with (without) distributed stochastic reacceleration.

with the existing data. In the two other cases the relative decrease of x is not so significant. It is much lower than the Wandel estimates [3], because the active period of SNR evolution stops much earlier than he suggested.

Nevertheless, our consideration performed within the nonlinear kinetic model confirm that the boron production in SNRs leads to much higher values of the B/C ratio at energies $\epsilon_k > 100$ GeV/n. Depending on the mean gas density at the SNRs sites the expected B/C ratio is between 0.02 and 0.06 at energies $\epsilon_k \gtrsim 1$ TeV/n. A detection of such a flat energy dependence of the ratio would be a consistency test for GCR production in SNRs.

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