**ANTIPROTONS PRODUCED IN SUPERNOVA REMNANTS**

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**ABSTRACT**

We present the energy spectrum of an antiproton cosmic ray (CR) component calculated on the basis of the nonlinear kinetic model of CR production in supernova remnants (SNRs). The model includes the reacceleration of antiprotons already existing in the interstellar medium as well as the creation of antiprotons in nuclear collisions of accelerated protons with gas nuclei and their subsequent acceleration by SNR shocks. It is shown that the production of antiprotons in SNRs produces a considerable effect in their resultant energy spectrum, making it essentially flatter above 10 GeV so that the spectrum at TeV energies increases by a factor of 5. The calculated antiproton spectrum is consistent with the PAMELA data, which correspond to energies below 100 GeV. As a consistency check, we have also calculated within the same model the energy spectra of secondary nuclei and show that the measured boron-to-carbon ratio is consistent with the significant SNR contribution.

**Key words:** acceleration of particles – cosmic rays – ISM: supernova remnants

1. INTRODUCTION

There is great astrophysical interest in cosmic ray (CR) antiprotons. It is believed that most antiprotons originate in collisions of CR protons with interstellar medium (ISM) gas nuclei. Therefore, antiprotons represent a kind of so-called secondary CR component, opposite of the primary CRs, which originate in CR sources, presumably in supernova remnants (SNRs). The same is true for positrons, which are the other kind of secondary CR component.

The positron energy spectrum measured recently in the PAMELA, *Fermi*, and AMS-02 experiments at kinetic energy $\epsilon_k > 10$ GeV turned out to be much flatter than expected for positrons created in $p-p$ collisions in the interstellar medium (ISM). This stimulated many kinds of assumptions that a significant part of positrons originate from new astrophysical sources such as pulsars or the annihilation of dark matter particles (see Serpico 2012 for a review).

At the same time, SNRs are not only the most probable sources of primary CRs with energies below $10^{17}$ eV (e.g., Berezhko & Völk 2007), but also contribute significantly in the production of secondary CRs due to the reacceleration of CRs already existing in the ISM and due to nuclear collisions of primary CR particles with gas nuclei, leading to the creation of secondary particles that undergo subsequent acceleration by SNR shock. The detailed study of these processes for the case of secondary nuclei (Berezhko et al. 2003) based on the nonlinear kinetic theory of CR acceleration in SNRs (Berezhko et al. 1996) demonstrated that SNRs are expected to contribute significantly to secondary CR spectra at kinetic energies $\epsilon_k > 10$ GeV/nucleon, making it significantly flatter. Therefore, it is natural to suggest that the observed flattening of the positron energy spectrum at $\epsilon_k > 10$ GeV can be partly or even predominantly due to SNR contribution. A simple estimate (Blasi 2009) and a detailed study (Berezhko & Ksenofontov 2013) have indeed confirmed that the observed flat high-energy positron spectrum is consistent with the expected SNR contribution. (Note that both these studies were performed in the leaky box framework, which is a poor approximation for electrons and positrons. More detailed consideration, based on the diffusive model for CR propagation in the ISM (Ahlers et al. 2009; Mertsch & Sarkar 2014) confirmed such a conclusion. One can therefore expect that SNRs also contribute significantly to the antiproton spectrum at high energies.

Here we calculate the energy spectrum of antiprotons produced in SNRs to compare it with the existing data and make the prediction at higher energies $\epsilon_k > 100$ GeV where experimental data do not yet exist. As a consistency check (see also Mertsch & Sarkar 2009 for a similar point), we have also calculated within the same model the energy spectra of secondary nuclei and show that the measured boron-to-carbon ratio measured is consistent with considerable SNR contribution.

2. PRODUCTION OF SECONDARY CRs IN SNRs

The acceleration of CRs in SNRs starts at some relatively low energy when some kind of suprathermal particles begin to cross the SNR shock front. Any mechanism that supplies suprathermal particles into the shock acceleration is called injection.

A small fraction of the postshock thermal particle population is able to recross the shock, which indicates the beginning of its shock acceleration. This is the most general and the most intense injection mechanism. It occurs for all kinds of ions and electrons existing in the ISM and therefore it is relevant for primary CRs only. The corresponding injection rate is determined by the number of particles involved in the acceleration from each medium volume that crossed the shock and can be represented in the form (Berezhko et al. 1996):

$$N_{\text{inj}} = \eta N_{\text{g1}}, \quad p_{\text{inj}} = \lambda mc_{\text{s1}}^2,$$

where $N_{\text{g}} = \rho/m_p$ is the gas number density, $c_s$ is the sound speed, and the subscripts 1 (2) refer to the point just ahead (behind) the shock. Typical values of the dimensionless injection parameters which provide CR production with required efficiency are $\eta = 3 \times 10^{-4}$ and $\lambda = 4$. Secondary CRs like secondary nuclei Li, Be, B, or positrons and antiprotons by definition are not presented in the ISM and therefore they cannot be produced due to such an injection.

Kinetic energy of all kinds of Galactic cosmic ray (GCR) particles is considerably larger than the energy of gas particles injected from the postshock thermal pool. Therefore, all GCRs that meet the expanding SNR shock are naturally involved in...
the diffusive shock acceleration. CR acceleration due to this second relevant injection mechanism, which is usually called “reacceleration.” This term is used to distinguish the process of a further increase in energy of already energetic particles due to interactions with SNR shocks during their propagation in the ISM. In this regard, it is similar to the stochastic acceleration (also called reacceleration) of GCRs due to their interactions with background MHD turbulence. Since GCR energy spectra are relatively steep and have a peak at kinetic energy \( \epsilon_k = \epsilon_{\text{GCR}} \approx 1 \text{ GeV} \), their injection can be represented in the form

\[
N_{\text{inj}} = N_{\text{GCR}}, \quad p_{\text{inj}} = p_{\text{GCR}}, \tag{2}
\]

where \( N_{\text{GCR}} \) is the total number of GCR species per unit volume and \( p_{\text{GCR}} \) is their mean momentum, which corresponds to \( \epsilon_{\text{GCR}} \).

During their acceleration inside SNRs, primary nuclei produce secondary nuclei in nuclear collisions with the background gas like GCRs do in the Galactic disk. An essential fraction of these already energetic particles has the possibility of being involved in further shock acceleration. This is the third mechanism of secondary CR production inside SNRs. It was studied for the first time to describe the formation of the secondary CR nuclei spectra (Berezhko et al. 2003).

The production rate of secondary CR particles due to the nuclear collisions of primary CRs with the gas nuclei within SNR can be described by the source term

\[
q_s(r, p, t) = 4\pi c N_s \int_0^\infty dp' p'^2 \sigma_{ps}(p, p') f_p(r, p', t), \tag{3}
\]

in the transport equation for the distribution function of secondary CRs \( f_s(r, p', t) \). Here \( \sigma_{ps}(p, p') \) is an inelastic cross section of secondary CR production with momentum \( p \) in the collision of primary (parent) nuclei of momentum \( p' \) with the gas nuclei, \( t \) is the time interval since the supernova explosion, and \( r \) is the radial distance from the presupernova star. In the case of secondary nuclei (Li, Be, B), the parent nuclei are heavier (C, N, O), whereas in the case of antiprotons, all kinds of nuclei accelerated in SNRs (predominantly protons) play the role of parent nuclei. Reacceleration and the acceleration of nuclei created in SNRs in nuclear collisions are of prime importance for secondary CRs even though a relatively small amount of primary CRs are also produced during these processes.

The source term \( q_s \) describes the creation of secondaries throughout the remnant, everywhere downstream and upstream of the SNR shock up to distances \( d \sim l_p(p') \) of the order of the diffusive length \( l_p(p') \) of their parent primary CRs. An essential part of these particles is naturally involved in the acceleration at an SNR shock. It includes all the particles created upstream and particles created downstream at distances less than their diffusive length \( l_p(p) \) from the shock front. The number of these particles is an increasing function of their momentum because \( l \propto \kappa(p) \propto p \) for the Bohm-type diffusion coefficient \( \kappa(p) \) which is realized during efficient CR acceleration in SNRs (e.g., Berezhko 2008). This makes the secondary particle spectra

\[
N_s(p, t) = 16\pi^2 p^3 \int_0^\infty dr r^2 f_s(r, p, t), \tag{4}
\]

produced in SNRs harder compared with the spectra of primaries \( N_p(p, t) \).

The SNR efficiently accelerates CRs up to some maximal age \( T_{SN} \) when SNRs release all previously accelerated CRs, primaries, and secondaries, with the spectra \( N_p(\epsilon_k) = v^{-1}N_p(p, T_{SN}) \) and \( N_s(\epsilon_k) = v^{-1}N_s(p, T_{SN}) \), respectively, into the surrounding ISM. Here \( \epsilon_k \) and \( v \) are the kinetic energy and particle speed with momentum \( p \).

The number of secondary CRs involved in the reacceleration at the SNR evolutionary epoch \( t \) is proportional to the SNR volume \( V(t) \), therefore \( N_s(p, t) \sim V(t) \). This is not so for primary CRs because the progressively increasing number of injected CRs \( N_{\text{inj}}V \) is accompanied by the decrease of their momentum \( p_{\text{inj}} \propto V_s \) due to the shock deceleration. As a result, the number of primary relativistic CRs \( N_p(p, t) \) remains nearly constant at late Sedov evolutionary phases (e.g., Berezhko et al. 1996). As a consequence, the number of secondary CRs created in nuclear collisions \( N_s(p, t) \propto tN_p(p, t) \) increases at late evolutionary phases in proportion to SNR age \( t \). Due to the above factors, secondary CRs are mainly produced on the late SNR evolutionary phases \( t \sim T_{SN} \).

These CRs released from SNRs together with secondary CRs produced in the ISM form the total secondary \( N_s(\epsilon_k) \) and primary \( N_p(\epsilon_k) \) CR populations. At sufficiently high energies the \( s/p \) ratio of the nuclear component within a simple leaky box model is given by the expression (Berezhko et al. 2003)

\[
\frac{n_s}{n_p} = \frac{n_s'}{n_p} + \frac{N_s}{N_p}, \tag{5}
\]

where \( n_s'(\epsilon_k) \) represents the spectrum of secondaries produced in nuclear collisions of primary CRs within the Galactic disk. Within the leaky box model, it is approximately given by the expression (Berezhko et al. 2003)

\[
n_s'/n_p = \sigma x / m_p, \quad x = \rho \tau_{esc} / \epsilon_k \text{ is the escape length which is the mean matter thickness traversed by GCRs in the course of their random walk in the Galaxy, } \rho \text{ is the ISM gas density, } \tau_{esc} \text{ is the CR escape time from the Galaxy, and } m_p \text{ is the proton mass,}
\]

\[
\sigma = \int_0^\infty d\epsilon_k \sigma_{ps}(\epsilon_k, \epsilon_k') n_p(\epsilon_k') / \int_0^\infty d\epsilon_k n_p(\epsilon_k'). \tag{6}
\]

Note that at sufficiently high energies, the \( s/p \) ratio \( n_s'/n_p \approx N_s'/N_p \) is determined by the \( s/p \) ratio \( N_s'/N_p \) produced in the SNRs independently in the propagation model, which influences the ratio \( n_s'/n_p \).

3 RESULTS AND DISCUSSION

We have calculated the overall energy spectra of all relevant CR species accelerated in SNRs, within a kinetic nonlinear model. The model is based on a fully time-dependent self-consistent solution of the CR transport equation together with the gas dynamic equations in spherical symmetry. It includes the most relevant physical factors, which are essential for the evolution and CR acceleration in an SNR, and it is able to make quantitative predictions of the expected properties of CRs produced in SNRs and their nonthermal radiation. The application of the theory to individual SNRs has demonstrated its capability of explaining the observed SNR nonthermal emission properties (Berezhko 2008). The theory is able to explain major characteristics of the observed CR spectrum up to an energy of \( \sim 10^{17} \text{ eV} \) (see Berezhko et al. 1996; Berezhko 2008 for details). A similar approach was recently developed by other authors (Ptuskin et al. 2010; Kang 2010).

We restrict ourselves to the most simple case of Type Ia SN in uniform ISM with corresponding SN parameter values: explosion energy \( E_{SN} = 10^{51} \text{ erg} \) and ejecta mass \( M_{ej} = 1.4 M_\odot \).
We use typical values of the dimensionless parameters $\eta = 3 \times 10^{-4}$ and $\lambda = 4$, which describe the injection of gas particles into the shock acceleration (Völk et al. 2003). We consider the typical ISM with hydrogen number density $N_H = 1.5 \text{ cm}^{-3}$, temperature $T_0 = 10^4 \text{ K}$, and magnetic field values $5 \mu \text{G}$, which roughly correspond to the average ISM within the Galactic disk. We adopt a time-independent upstream magnetic field value $B_0$ and ignore the magnetic field amplification effect because the secondaries are mainly produced at the late evolutionary phases (Berezhko et al. 2003) when this effect becomes irrelevant.

We perform a self-consistent calculation up to the SNR age $t_{SN}$ when SNRs release all previously accelerated CRs into the surrounding ISM. We adopt the value $t_{SN} = 10^5 \text{ yr}$ appropriate for the considered range of ISM density (Berezhko et al. 2003).

The calculated antiproton-to-proton ratio $\tilde{p}/\tilde{p} = n_{\tilde{p}}(\epsilon_k)/n_p(\epsilon_k)$ as a function of energy together with PAMELA data are shown in Figure 1. We use the cross section $\sigma(\epsilon, \epsilon') = 1.6 \sigma_{pp}(\epsilon, \epsilon')$, the parameterization of Shibata et al. (2008) for the cross section of antiproton production in $p-p$ collisions $\sigma_{pp}(\epsilon, \epsilon')$, and the correction factor 1.6 which describes the contribution of heavier nuclei. Since the observed antiproton spectrum has a peak at $\epsilon_k \approx 2 \text{ GeV}$, we use $N_{n_{\tilde{p}}} = 10^{-14} \text{ cm}^{-3}$ and the value of $p_{n_{\tilde{p}}}$, which corresponds to the kinetic energy $\epsilon_{\tilde{p}} = 2 \text{ GeV}$. For the spectrum of antiprotons produced in the ISM, we use the results of calculations performed in Donato et al. (2001). It is very close to what was used by Blasi & Serpico (2009) in their similar consideration. It is seen that antiprotons at energies $\epsilon_{\tilde{p}} < 10 \text{ GeV}$ are produced in SNRs equally effectively by both mechanisms, whereas at $\epsilon_{\tilde{p}} > 10 \text{ GeV}$, the creation of antiprotons in $p-p$ collisions and their subsequent acceleration becomes dominant. In total, the antiproton production in SNRs makes the energy dependence of $\tilde{p}/\tilde{p}$ considerably flatter so that at $\epsilon_{\tilde{p}} \sim 10^3 \text{ GeV}$ the ratio becomes larger by a factor of about 5. Within the energy range $30 \text{ GeV} < \epsilon_{\tilde{p}} < 3000 \text{ GeV}$, the energy dependence of the ratio $\tilde{p}/\tilde{p} \propto \epsilon_{\tilde{p}}^{-0.25}$ is expected to be very flat.

PAMELA data, which agrees well with our calculation, within the energy range $10 \text{ GeV} < \epsilon_{\tilde{p}} < 100 \text{ GeV}$, provide evidence that the actual ratio $\tilde{p}/\tilde{p}$ is indeed flatter than is expected if antiprotons are created in ISM only.

The production of antiprotons in SNRs estimated by Blasi & Serpico (2009) is considerably larger (by a factor of 4 at $\epsilon_{\tilde{p}} = 10^3 \text{ GeV}$) compared with our calculation even though these authors have neglected the reacceleration process entirely. It is due to a number of simplifications made by these authors. For example, in the actual situation the overlap between the radial profile of protons $f(r, p)$ with the gas density profile $\rho(r)$ which has a peak value $\rho \approx 4 \rho_{\text{ISM}}$ at the shock ($r = R_s$), progressively decreases with the increase of energy at high energies $\epsilon_{\tilde{p}} > 100 \text{ GeV}$, because the radial profile of protons becomes progressively broader. Here $\rho_{\text{ISM}}$ is the gas density of the ISM. This leads to a decrease of the effective gas density from the value $\rho(r = R_s) \approx 4 \rho_{\text{ISM}}$ to $\rho(r > R_s) \approx \rho_{\text{ISM}}$ that follows the decrease of the antiproton production. This factor was neglected by Blasi & Serpico (2009), which is one of the reasons that lead them to an overestimation of antiproton production.

In order to check the consistency of other types of secondary CR production, we have calculated the boron-to-carbon (B/C) ratio within the same model and compare it with the existing experimental data in Figure 2.

The boron nuclei represent the example of secondary nuclei. To calculate boron spectrum, we use the overall number density of boron nuclei in the ISM $N_{\text{B}} = 7.9 \times 10^{-14} \text{ cm}^{-3}$ injected at a kinetic energy $\epsilon_{\text{inj}} = 0.6 \text{ GeV}/n$ which corresponds to the mean GCR energy for these elements. Compared with the previous study (Berezhko et al. 2003), except C, N, and O nuclei as parent species following Mertsch & Sarkar (2009) and Tomassetti & Donato (2013), we also included heavier primaries up to Si, which contributes about 10% of the boron production.

Due to boron production in SNRs, the expected B/C ratio undergoes considerable flattering which starts at an energy $\epsilon_{\tilde{b}} \approx 100 \text{ GeV}/\text{nucleon}$. As one can see in Figure 2, this is consistent with the measurements recently performed in balloon (Derbina et al. 2005) and AMS-02 space (Aguilar 2013) experiments, even though for a more strict conclusion one needs measurements with higher statistics at energies above 1 TeV/n.
The calculated SNR contribution into the secondary CR spectra represents a component that is unavoidably expected if SNRs are the main source of GCRs. Comparing with the existing data leads to the conclusion that the observed high energy excess of secondary nuclei can be produced in Galactic SNRs. This enables us to expect similar excess in the antiproton energy spectrum. The data expected very soon from the AMS-02 experiment will make it clear whether the actual ratio $\bar{p}/p$ is indeed not less flat than we predict at energies $\epsilon_k > 10$ GeV.

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