

Origin of Galactic Cosmic Rays from Supernova Remnants

E.G. Berezhko

Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, 31 Lenin Ave., 677891 Yakutsk, Russia

Abstract

We analyze the results of recent measurements of Galactic cosmic ray (GCRs) energy spectra and the spectra of nonthermal emission from supernova remnants (SNRs) in order to determine their consistency with GCR origin in SNRs. It is shown that the measured primary and secondary CR nuclei energy spectra as well as the observed positron-to-electron ratio are consistent with the origin of GCRs up to the energy 10^{17} eV in SNRs. Existing SNR emission data provide evidences for efficient CR production in SNRs accompanied by significant magnetic field amplification. In some cases the nature of the detected γ -ray emission is difficult to determine because key SNR parameters are not known or poorly constrained.

Keywords: acceleration of particles, cosmic rays, ISM: supernova remnants

1. Introduction

Supernova remnants (SNRs) are considered as a main cosmic ray (CR) source. They are able to support a constant density of the Galactic cosmic ray (GCR) population against loss by escape, nuclear interactions and ionization energy loss. The mechanical energy input to the Galaxy from each supernova (SN) is about 10^{51} erg so that with a rate of about one every 30 years the total mechanical power input from supernovae is of the order 10^{42} erg/s (e.g. [1, 2]). Thus supernovae have enough power to drive the GCR acceleration if there exists a mechanism for channeling about 10% of the mechanical energy into relativistic particles.

An appropriate acceleration mechanism is known since 1977 [3]. This is so called regular or diffusive shock acceleration process. The strong shock produced by high velocity ejecta expanding into the ambient medium pick up a few particles from the plasma flowing into the shock fronts and accelerate them to high energies.

The theory of particle acceleration by the strong shocks associated with SNRs at present is sufficiently well developed and specific to allow quantitative model calculations (e.g. see [4, 5, 6, 7, 8] for reviews). Theoretically progress has been due to the development of the kinetic nonlinear theory of diffusive shock acceleration [9, 10, 11, 12, 13]. The theory consistently includes the most relevant physical factors, essential for SNR evolution and CR acceleration, and it is able to make quantitative predictions of the expected properties of CRs produced in SNRs and their nonthermal radiation.

There are also strong theoretical and observational reasons, that argue for a significant amplification of the magnetic field as a result of the pressure gradient of the accelerating CRs, exciting instabilities in the precursor of the SNR shock. The most important consequence of magnetic field amplification in SNRs is the substantial increase of the maximal energy of CRs, accelerated by SN shocks, that presumably provides the formation of GCR spectrum inside SNRs up to the energy 10^{17} eV.

Considerable progress have been achieved during the last years in experimental determination of GCR spectra

Email address: berezhko@ikfia.ysn.ru (E.G. Berezhko)

and spectra of nonthermal emission of SNRs. To empirically confirm that the main part of GCRs indeed originates in SNRs one has to check the consistency of the theoretical expectations with the observed properties of GCRs and nonthermal emission of SNRs.

Here we analyze the existing data especially those obtained in recent experiments PAMELA, Fermi and AMS-02 together with observational results of nonthermal emission of SNRs in order to check their consistency with GCR origin in SNRs.

2. Production of CRs in SNRs

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 which supply suprathermal particles into the shock acceleration is called injection.

Some small fraction of the postshock thermal gas particle population are able to recross the shock that means the beginning of their shock acceleration. This is the most general and the most intense injection mechanism. It occurs for all kind of ions and electrons existing in the interstellar medium (ISM) and therefore it is relevant for primary CRs only. The corresponding injection rate is determined by the number of particles involved into the acceleration from each medium volume crossed the shock and by the momentum of these particles [9]:

$$N_{\text{inj}} = \eta N_{\text{e1}}, \quad p_{\text{inj}} = \lambda m c_s^2. \quad (1)$$

Here N_{e} is the number density of considered elements in ISM, c_s is the sound speed, 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 $\lambda = 4$. Since positrons, antiprotons and nuclei Li, Be, B are not represented in the ISM secondary CRs can not be produced due to such an injection.

Kinetic energy of all kind of GCR particles is considerably larger than the energy of gas particles injected from the postshock thermal pool. Therefore all GCRs which meet the expanding SNR shock are naturally involved into the diffusive shock acceleration. CR acceleration due to this second relevant injection mechanism is usually called "reacceleration".

Since GCR energy spectra are relatively steep and have a peak at kinetic energy $\epsilon_k = \epsilon_{\text{GCR}} \sim 1$ GeV their injection parameters can be represented in the form

$$N_{\text{inj}} = N_{\text{GCR}}, \quad p_{\text{inj}} = p_{\text{GCR}}, \quad (2)$$

where N_{GCR} is the total number of GCR species per unit volume and p_{GCR} is their mean momentum, that corresponds to ϵ_{GCR} .

Primary nuclei during their acceleration inside SNRs produce secondary nuclei in nuclear collisions with the background gas like GCRs do it in the Galactic disk. Essential fraction of these already energetic particles has possibility to be involved in further shock acceleration. This is the third mechanism of CR production inside SNRs. For the first time it was studied to describe the formation of secondary CR nuclei spectra [14].

Secondaries with momentum p are created throughout the remnant, everywhere downstream and upstream of SNR shock up to the distances $d \sim l_p(p')$ of the order of the diffusive length $l_p(p')$ of their parent primary CRs with momentum $p' > p$. Essential part of these particles are naturally involving in the acceleration at SNR shock. It includes all the particles created upstream and the particles created downstream at distances less than their diffusive length $l_s(p)$ from the shock front. Since diffusive length $l \propto \kappa(p) \propto p$ is increasing function of momentum for the Bohm type diffusion coefficient $\kappa(p)$ which is realized during efficient CR acceleration in SNRs the spectrum of secondary CRs for the first time intersecting the shock front is very hard $N_{\text{inj}}(p) \propto p^{-1}$ within wide range of their momenta p . This makes the secondary particle spectra $N_s(p, t)$, produced in SNR, harder compared with the spectra of primaries $N_p(p, t)$.

The SNR efficiently accelerates CRs up to some maximal age $T_{\text{SN}} \sim 10^5$ yr when SNR release all previously accelerated CRs, primaries and secondaries, with the energy spectra $N_p(\epsilon_k, T_{\text{SN}})$ and $N_s(\epsilon_k, T_{\text{SN}})$ respectively, into surrounding ISM. Here ϵ_k is the particle kinetic energy. These CRs released from SNRs together with secondary CRs produced in 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 nuclear component within simple leaky box model is given by the expression [14]

$$\frac{n_s}{n_p} = \frac{n'_s}{n_p} + \frac{N_s}{N_p}, \quad (3)$$

where $n'_s(\epsilon_k)$ represents the spectrum of secondaries produced in nuclear collisions of primary CRs within the Galactic disk. It is approximately given by the expression [14] $n'_s/n_p = \sigma x/m_p$, where $x = \rho v \tau_{\text{esc}}$ is the escape length which is the mean matter thickness traversed by GCRs in the course of their random walk in the Galaxy, ρ is the ISM gas density, $\tau_{\text{esc}}(\epsilon_k)$ is the CR escape time from the Galaxy, m_p is the proton mass, σ is the cross-section of secondary CRs production.

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