SPECTRUM AND CHEMICAL COMPOSITION OF CRs ACCELERATED IN SNRs

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ABSTRACT
Spectrum and chemical composition of cosmic rays accelerated in supernova remnants are studied on a basis of kinetic approach. The cosmic ray transport equation with the Bohm diffusion coefficient has been numerically solved self-consistently with gas dynamic equations for the underlying flow. Comparison with observational results gives some indications that galactic cosmic rays are produced by supernovae shocks which expanded in the relatively low temperature partially ionized interstellar medium.

INTRODUCTION
Supernova remnants (SNRs) are considered as the main source of cosmic rays (CRs) in the Galaxy. Diffusive shock acceleration process is able to convert sufficient amount of the explosion energy into CRs and to produce CR spectrum with necessary shape and amplitude (Berezhko et al., 1996). At the same time there is no observational confirmation that the nuclear component of CRs is produced in SNRs. Investigation of CR chemical composition can give additional evidence whether SNRs are indeed the source of observed CRs (Berezhko et al., 1995; 1996; Ellison et al., 1997). The most pronounced aspect of the observed CR chemical composition is the increasing of relative abundance as function of atomic number $A$. Here we present the results to study under which conditions the theory fits the observed features of CR chemical composition.

METHOD
The description of SNR evolution and CR acceleration is based on the kinetic approach. It includes (Berezhko et al., 1996) the diffusive transport equation for the CR distribution function which is solved self-consistently together with the gas dynamic equations for the underlying flow. The model includes an assumption about injection of some fraction $\eta \ll 1$ of superthermal gas particles (ions) at the subshock into the acceleration regime. By definition gas particles becomes CRs when they reach some minimum velocity $v_{inj}$ during the thermalization. Therefore the momentum of injected particles

$$p_{Ainj} = Ap_{inj}$$ (1)

is proportional to the atomic number $A$. Here and hereafter variables without subscript $A$ corresponds to protons.

The expected chemical composition of accelerated CRs is sensitive to the dependence of the injection rate $\eta_A$ upon the atomic number. According to the hybrid plasma simulation of quasiparallel collisionless shock (Trattner and Scholer, 1993) the relative number of particles in the power-law tail of the spectrum is approximately the same for protons and $\alpha$-particles. Therefore we have to take

$$\eta_A = \eta.$$ (2)

We assume that supernovae (SN) shock expands into the uniform interstellar medium (ISM) with normal chemical composition. Therefore the relative number of accelerated nuclei $N_{Ainj}/N_{inj} = (\eta_A/\eta)(a_A/a) = a_A/a$ is determined by the solar system abundance $a_A$ of elements with the atomic number $A$. 
The shape of accelerated CR spectrum essentially depends upon the assumed CR diffusion coefficient. We use
\[ \kappa_A(p_A) = \frac{p_A c^2}{Q_A e}, \]
which at relativistic energy \((p_A \gg Amc)\) coincides with so called Bohm diffusion coefficient. Here \(c\) is the speed of light, \(m\) and \(e\) are the mass and charge of protons. The ion charge number \(Q_A\) is assumed to be a function of momentum \(p_A\). At the beginning of acceleration, that corresponds to small momenta \(p_A \sim p_{Ainj}\), \(Q_A\) coincides with the equilibrium ion charge state in background ISM \(Q_{Ai}\). At nonrelativistic energies the acceleration process is extremely fast because of the small value of the diffusion coefficient. Therefore we assume the constant ion charge number
\[ Q_A(p_A) = Q_{Ai} \quad \text{at} \quad p_A \leq Amc. \]
The acceleration process becomes progressively less rapid with increasing CR energy. Therefore at the sufficiently high energies \(p_A \gg Amc\) all kind of ions becomes completely ionized, that means
\[ Q_A = Z_A \quad \text{at} \quad p_A \gg Amc, \]
where \(Z_A\) is the nuclear charge number of elements with atomic number \(A\).

Due to the rigidity-dependent CR leakage from the Galaxy, the expected CR spectrum (flux) is connected with the spectrum \(J_A(p_A)\) produced in SNR (source spectrum) by the relation
\[ J_{Aobs}(p_A) \propto J_A(p_A) \tau(p_A/Z_A), \]
where we assume the power-low rigidity dependent mean CR residence time
\[ \tau(R) \propto R^{-\alpha}. \]

RESULTS AND DISCUSSION
In order to investigate the influence of nonlinear effects produced by the accelerated CR back-reaction and ISM parameters on the CR chemical composition we have performed calculations for high \((\eta = 10^{-3})\) and low \((\eta = 10^{-5})\) injection rates and for two typical phases of ISM: warm (with temperature \(T \simeq 10^4\)K) and hot \((T \simeq 10^6\)K). The initial ionic charge numbers \(Q_{Ai} = 1\) for all elements in warm ISM and \(Q_A\) slowly increases from \(Q_{Ai} = 1\) for \(H\) and \(Q_{Ai} = 2\) for \(He\) to \(Q_{Ai} = 9\) for \(Xe\) in the hot ISM (Kaplan and Pikelner, 1979). The value of the parameter \(\alpha\) (see eq.(7)) has been chosen to fit the observed proton’s CR spectrum.

Calculated hydrogen and helium spectra and CR abundance relative to solar system abundance versus atomic mass number (enhancement factor)
\[ e(A, \varepsilon_k) = \left[ J_{Aobs} \left( \frac{\varepsilon_A k}{A} \right) / J_{obs} \left( \varepsilon_k = \frac{\varepsilon_A k}{A} \right) \right] \left( \frac{a_A}{a} \right). \]

at kinetic energy per nucleon \(\varepsilon_k = \varepsilon_Ak/A = 3\)GeV are compared on Figure 1 with experimental data. The normalization of calculated spectra was made by fitting the observed hydrogen spectrum at kinetic energies \(\varepsilon_k = 10^2 \div 10^4\)GeV (the relative normalization of hydrogen to helium and other nuclei is fixed by the model). In the case of low temperature ISM our theory is applicable only for gas-phase ions only for which experimental data are presented on Figure 1b. We do not consider here the problem of acceleration of refractory elements, which locked in grains in the low temperature ISM (this interesting question was considered by Ellison et al., 1997).

One can see from Figure 1 that in the case of low injection, when nonlinear modification of the SN shock by the CR backreaction is negligible the theory in contrast to observation predicts
Fig. 1: CR spectra in kinetic energy per nucleon (a) and CR enhancement factor versus atomic mass number (b) for ISM temperature $T = 10^6$ and injection rate $\eta = 10^{-3}$ (dash-dotted lines), for $T = 10^4$ and $\eta = 10^{-5}$ (dashed lines), for $T = 10^4$ and $\eta = 10^{-3}$ (full lines).

much less efficient production of all kinds of species relative to protons. CR enrichment by heavy elements is not essential also for the high injection rate ($\eta = 10^{-3}$) in the case of hot ISM. Only in the low temperature ISM, with a low degree of ionization for all kind of species, the theory predicts essential CR enrichment by heavy elements if the injection rate is relatively high.

The shape of CR spectrum produced by the modified shock is essentially different at relativistic and nonrelativistic energies: $J(p) \propto p^{-\gamma_1}$ at $p \leq mc$ and $J(p) \propto p^{-\gamma_2}$ with $\gamma_2 < \gamma_1$ at $p \gg mc$ (Berezhko et al., 1996). The higher shock modification, the larger difference between $\gamma_1$ and $\gamma_2$. Taking into account the form (3) of the diffusion coefficient, for heavier species we have $J_A(p_A/A) \propto a_A(p_A/A)^{-\gamma_1}$ at $p_A \leq Q_{Ai}mc$ and $J_A(p_A/A) \propto a_A(p_A/A)^{-\gamma_2}$ at $p_A \gg Q_{Ai}mc$ that gives at relativistic energies the enhancement factor

$$e(A) = \left( \frac{A}{Q_{Ai}} \right)^{\gamma_1-\gamma_2} \left( \frac{A}{Z_A} \right)^{-\alpha}.$$  \hfill (9)

The ratio $A/Z_A$ is close to 2 for all elements except hydrogen and $\alpha$ is about 0.7 for three considered cases. Therefore for unmodified shock $\gamma_1 \simeq \gamma_2$ and we have $e < 1$ that means lower heavy element abundance relative to protons. The essential CR enrichment by heavy species ($e > 1$) is expected only under two conditions: i) in the case of low temperature ISM with low ionization state $Q_{Ai} \simeq 1$ and ii) at relatively high injection rate, which provide the efficient CR production and strong SN shock modification. It is important to note that according to the theory (Ellison et al., 1997; Trattner and Scholer, 1993; Malkov and Völk, 1995) and experiment in the solar wind (Trattner et al., 1994) the expected injection rate is not less than $\eta = 10^{-3}$.

Only under the above two conditions, as one can see from Figure 1b, the theory satisfactorily agrees with the data. At the same time, as it is seen from Figure 1a, in the case of high injection the theory predicts a much more harder hydrogen spectrum at highest energies $\varepsilon_k > 10^{13}$eV than observed.
Our CR spectra are also essentially harder compared with plane-wave kinetic model prediction (Ellison et al. 1997). The main reason of it is that in our case all phases of SNR evolution contribute to the overall CR spectrum (Berezhko et al. 1996). The highest energy CRs are produced at the end of free expansion phase, when the SN shock is especially strong and produces extremely hard CR spectrum. CRs with intermediate energies $\varepsilon_k = 10^{10} \div 10^{13}$ eV are mainly produced during the Sedov phase, when the SN shock is considerably weaker. As a result the overall CR spectrum is not of the pure power-law form but has a concave shape. In this sense the CR spectra presented by Ellison et al. (1997) correspond to the late Sedov phase, therefore they are essentially steeper than ours which include contribution of all phases of SNR evolution.

The possible explanation of the discrepancy between our theory and the experiment can be connected either with the acceleration or with the propagation of CRs in the Galaxy. In first case due to some underestimated physical factors SNR produces a more steeper CR spectrum than is predicted by our theory. The second possibility is that the actual escape of CRs from the Galaxy is more complicated than described by simple power-law Eq.(7).

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