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Cosmic ray production in supernova remnants including reacceleration: the secondary to primary ratio

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Abstract. We study the production of cosmic rays (CRs) in supernova remnants (SNRs), including the reacceleration of background galactic cosmic rays (GCRs) — thus refining the early considerations by Blandford & Ostriker (1980) and Wandel et al. (1987) — and the effects of the nuclear spallation inside the sources (the SNRs). This combines for the first time nuclear spallation inside CR sources and in the diffuse interstellar medium, as well as reacceleration, with the injection and subsequent acceleration of suprathermal particles from the postshock thermal pool. Selfconsistent CR spectra are calculated on the basis of the nonlinear kinetic model. It is shown that GCR reacceleration and CR spallation produce a measurable effect at high energies, especially in the secondary to primary (s/p) ratio, making its energy-dependence substantially flatter than predicted by the standard model. Quantitatively, the effect depends strongly upon the density of the surrounding circumstellar matter. GCR reacceleration dominates secondary CR production for a low circumstellar density. It increases the expected s/p ratio substantially and flattens its spectrum to an almost energy-independent form for energies larger than 100 GeV/n if the supernovae explode on average into a hot dilute medium with hydrogen number density $N_{\rm H} = 0.003$ cm^{-3}. The contribution of CR spallation inside SNRs to the s/p ratio increases with increasing circumstellar density and becomes dominant for $N_{\rm H} \gtrsim 1$ cm^{-3}, leading at high energies to a flat s/p ratio which is only by a factor of three lower than in the case of the hot medium. Measurements of the boron to carbon ratio at energies above 100 GeV/n could be used in comparison with the values predicted here as a consistency test for the supernova origin of the GCRs.

Key words. theory – cosmic rays – shock acceleration – supernova remnants – reacceleration – secondary to primary ratio

1. Introduction

It is a widely accepted hypothesis that supernova remnants (SNRs) are the main sources of cosmic rays (CRs) in the Galaxy. Supernovae occur randomly in the Galaxy (although with some correlation in space) and have a complicated time evolution. The selfconsistent nonlinear kinetic theory of diffusive shock acceleration nevertheless gives rather definite predictions on the shape, the amplitude and the time evolution of the spectra of CRs accelerated at the shock during the different phases of SNR evolution (Berezhko et al. 1996; Berezhko and Völk 1997; Berezhko and Ksenofontov 1999).

Released from SNRs, CRs experience energy-dependent diffusion and, possibly, large scale convective transport in the interstellar medium (ISM). During their propagation in the Galaxy, the primary relativistic nuclei interact with interstellar gas nuclei and produce lighter secondary relativistic nuclei as a result of nuclear spallation. The secondary nuclei have approximately the same energy per nucleon as the parent primaries.

Boron nuclei represent an example of pure secondaries and the Boron-to-Carbon (B/C) ratio is an example of the secondary-to-primary (s/p) ratio in CRs. The abundance

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of secondary nuclei, measured over a wide energy range, yields important information on the process of CR transport in the Galaxy (e.g. Berezinskii et al. 1990). Up to approximately 100 GeV/n the measured power law spectrum of secondary nuclei is steeper than the spectrum of primary nuclei. This leads to the conclusion that primary GCRs are mainly produced in compact sources (SNRs for example) and that their spectrum $n(\epsilon_\mathrm{k}) \propto \epsilon_\mathrm{k}^{-\gamma_\mathrm{g}}$, for kinetic energies $\epsilon_\mathrm{k} \gg 1$ GeV/n, is steeper than the spectrum, $N(\epsilon_\mathrm{k}) \propto \epsilon_\mathrm{k}^{-\gamma_\mathrm{s}}$ of the particles produced in the sources, the so-called source cosmic rays (SCRs): the GCR power law index $\gamma_\mathrm{g} = \gamma_\mathrm{s} + \mu$ is considerably larger than the SCR power law index γ_s with a value μ r anging between $\mu = 0.3$ and 0.7.

The diffusion of relativistic particles in the Galaxy, after they have left the compact sources (assumed here to be SNRs), may be accompanied by an additional distributed reacceleration in the turbulent ISM. This reacceleration can not be strong for particles with energies 1 GeV/n $\lesssim \epsilon_\mathrm{k} \lesssim 100$ GeV/n as evident from the observed energy-dependent decrease of the abundance of secondaries in this energy range (Hayakawa 1969). Some weak reacceleration is possible and may in fact explain the observed energy dependence of the s/p ratios with a characteristic peak at about 1 GeV/n (see Jones et al. 2001, and references therein). In the "minimal" model, the stochastic reacceleration is produced by the same randomly moving inhomogeneities which are assumed to be responsible for the spatial diffusion of CRs in the galactic magnetic field. The velocity of these inhomogeneities is close to the Alfvén velocity $c_\mathrm{a} \sim 30$ km/s. The characteristic time of distributed reacceleration is approximately equal to the escape time from the Galaxy for particles with magnetic rigidities of about 1 GV (the magnetic rigidity is $R = pc/Ze$, where p is the particle momentum, Ze denotes the particle charge, and c is the speed of light). Escape dominates over reacceleration at high rigidities $R >> 1$ GV, so that the effect of distributed reacceleration in the interstellar turbulence is weak at high energies. In detail the importance of distributed reacceleration for the formation of the GCR spectrum remains unclear. It may well be that the peaks in the s/p ratios are caused by a specific dependence of the CR diffusion on energy or by the effect of large scale convection on the transport of low energy CRs (Jones et al. 2001). It should be stressed however that the distributed reacceleration through interstellar Alfvénic turbulence is negligible at energies $\epsilon_\mathrm{k} \gtrsim 20$ GeV/n in all versions of the galactic CR propagation.

The scenario described is valid for the major part of the GCRs which left the source regions and do no more interact with SNR shocks propagating in the ISM. However, a wandering energetic particle has a finite probability to again meet a SNR shock which efficiently accelerates CRs, and therefore to undergo strong reacceleration. The background primary and secondary CR nuclei experience strong reacceleration and significant transformation of their energy spectra after interaction with high velocity shocks. Strongly reaccelerated primaries and secondaries at the shock have flat spectra typical of the source spectrum. These particles are mixed with and diluted by a large amount of background GCRs after their release from their parent SNR. In principle they may become recognizable above some energy as a flat component of galactic secondary nuclei.

The effect described above was studied by Wandel et al. (1987) (see also the original paper by Blandford & Ostriker 1980) who found that a flattening of the s/p ratio can be expected at high energies due to reacceleration by strong SNR shocks. At the same time, applied to an actual galactic ISM, this model leads to the conclusion (Wandel 1988) that one has to expect a reacceleration effect mainly due to old and weak SNR shocks of Mach numbers $M < 2$ which also essentially influence the CR spectra at GeV energies and make the CR mean escape length from the Galaxy as small as 3 to 5 g cm^{-2}. These conclusions were based on a simplified plane wave approach. All the SN shocks were considered to be of the same strength and the final predictions depend substantially on this suggested strength.

We note also that it is hard to believe that such weak shocks are even able to accelerate relativistic particles in the same manner as a plane shock. Indeed, to be efficiently accelerated by a spherical shock of size R_s and speed V_s, particles should have a sufficiently small diffusion coefficient (e.g. Berezhko 1996)

$$\kappa \lesssim 0.1 R_\mathrm{s} V_\mathrm{s}. \tag{1}$$

Shocks of size $R_\mathrm{s} \approx 30$ pc and speed $V_\mathrm{s} \approx 300$ km/s (Wandel 1988) give the restriction $\kappa \lesssim 3\times 10^{26}$ cm^2/s. Such a small value can only be produced near the shock front by selfexcited Alfvén waves, because the CR diffusion coefficient due to interstellar turbulence exceeds this value even at GeV energies (e.g. Berezinskii et al. 1990). On the other hand the spectrum of particles accelerated by such weak shocks is so steep, $n \propto p^{-\gamma}$ with $\gamma \approx 4$, that, even if extended into the relativistic energy range $p > mc$, it contains too small an amount of energy to substantially amplify the ISM turbulence. This means that efficient acceleration of relativistic particles in SNRs stops earlier, at higher Mach numbers $M \approx 4$, when the shock compression ratio drops significantly below the asymptotic non-relativistic value $\sigma = 4$, and freshly accelerated particles become unable to provide a high level of turbulence near the shock front. Therefore it is assumed that at this age $t = T_\mathrm{SN}$, SNRs release all previously accelerated CRs into the surrounding ISM.

The energy increase of relativistic CRs upon encountering the SNR of age $t > T_\mathrm{SN}$ is negligible because their relatively large diffusive length $l = \kappa/V_\mathrm{s} > 0.1 R_\mathrm{s}$ reduces their energy gain at the shock front almost to the adiabatic energy loss in the expanding downstream region. Therefore we neglect the acceleration and/or reacceleration of CRs by these old SNRs.

Since according to the above physical arguments the maximum age and the corresponding number of SNRs which effectively accelerate CRs is presumably much smaller than assumed by Wandel (1988), the effect of reacceleration of GCRs is also much smaller. Nevertheless it is still important, especially at high energies for the case of a low-density ISM.

In this paper we shall in addition take the effect of nuclear spallation inside the sources into account. The energy spectrum of these source secondaries is harder than that of reaccelerated secondaries. Therefore it plays dominant role at high energies for a high-density ISM.

Note that the CR source spectrum $N(\epsilon_k)$ which is the resultant overall spectrum of CRs accelerated during the whole active period of SNR evolution depends on the GCR spectrum $n(\epsilon_k)$ since not only the injection of suprathermal particles leads to the formation of $N(\epsilon_k)$ but the reacceleration of existing background GCRs contributes as well. These spectra $N(\epsilon_k)$ should therefore be determined through a selfconsistent solution of the equations which describe the GCR propagation in the Galactic confinement volume with all accompanying effects, together with the equations which describe the SNR evolution and the CR acceleration. Fortunately this rather complicated problem can be simplified without loss of accuracy. Indeed, due to the steep GCR spectrum at relativistic energies $\epsilon_k \gg 1$ GeV/n only the injection of GCRs with energies $\epsilon_k \lesssim 1$ GeV/n plays a role for the formation of $N(\epsilon_k)$. Since the GCR spectra $n(\epsilon_k)$ at these subrelativistic energies are known from experiment, we use them as an physical input quantities, like other ISM parameters, in our selfconsistent nonlinear kinetic model for CR acceleration in SNR, so that $N(\epsilon_k)$ can be considered as consistently determined together with the GCR spectra $n(\epsilon_k)$.

We also want to emphasize that the shape of the overall CR spectrum $N(\epsilon_k,t)$ differs at each stage of SNR evolution significantly from the spectrum of freshly accelerated CRs $n(\epsilon_k,t)$, especially during the late Sedov phase. In this late phase, when the shock is relatively weak and thus CR backreaction not significant, the freshly produced CR spectrum has a pure power law form $n \propto p^{-\gamma}$, bounded by an exponential cutoff at some maximum momentum $p_m(t)$. At the same time, the overall CR spectrum is influenced by the nonlinear shock modification during the previous active period of the SNR evolution, by the adiabatic cooling of CRs in the downstream region, and by the so-called escape effect (see Berezhko et al. 1996 for details) and therefore has a much more complicated form. Only at very low energies $\epsilon_k \lesssim 1$ GeV it has a form similar to $n(p,t)$, whereas at higher energies it becomes progressively flatter and is bounded by the cutoff momentum $p_{max} = p_m(t_0) > p_m(t)$, a value which is determined by the very early Sedov phase (Berezhko 1996). This is an additional and significant difference between our model, based on the kinetic nonlinear time-dependent approach, and Wandel's (1988) estimates, based on a plane-wave approximation, which does not include these important physical effects.

In section 2 we present the relevant relations within the standard leaky box model. In section 3 the GCR injection problem within the nonlinear kinetic model for CR production in SNRs is described and the relevance of secondary nuclei production in SNRs for the resultant source spectra $N(\epsilon_k)$ and for the s/p ratio are estimated. Numerical results for the boron and carbon spectra produced in SNR and the expected B/C ratio are presented and discussed in section 4. The final section contains the main conclusions.

2. Source contribution to the secondary to primary ratio

We shall use the simple leaky box model to describe the transport and nuclear fragmentation of comic rays in the Galaxy. It is well known that the more adequate diffusion model of cosmic ray propagation with an extended flat halo gives essentially the same results as the leaky box model for the abundances of the stable primary and secondary nuclei. The approximate equivalence of these two models holds provided that cosmic ray nuclear fragmentation and reacceleration occur in regions much thinner than the cosmic ray halo size. This last condition is fulfilled in the Galaxy where the disk thickness of the order 0.5 kpc is much smaller than the halo thickness (which is at least an order of magnitude larger) (Berezinskii et al. 1990).

For a simple estimate we consider the case when the secondary nuclei of a species "s" are the result of spallation of some primary CR nuclei of species "p", and the contribution of all other primary parent nuclei can be neglected. Within this approach the differential number density of some primary CR species $n_p(\epsilon_k)$ is determined by the balance equation

$$\frac{n_\mathrm{p}}{\tau_\mathrm{c}} = \frac{N_\mathrm{p}}{V_\mathrm{c}}\nu_\mathrm{SN} - \sigma_\mathrm{p} N_\mathrm{g} v n_\mathrm{p}, \qquad (2)$$

where V_c is the residence volume occupied by the GCRs, τ_c is the mean residence time in this volume V_c, σ_p is the spallation cross section, $N_p(\epsilon_k)$ is the total differential number of CRs created during the entire evolution of a single SNR (overall CR spectrum), ν_{SN} is the galactic SN explosion rate, 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 denotes the proton mass.

Within the same approach the number density of secondary nuclei n_s obeys the equation

$$\frac{n_\mathrm{s}}{\tau_\mathrm{c}} = \frac{N_\mathrm{s}}{V_\mathrm{c}}\nu_\mathrm{SN} + \sigma_\mathrm{ps} N_\mathrm{g} v n_\mathrm{p} - \sigma_\mathrm{s} N_\mathrm{g} v n_\mathrm{s}, \qquad (3)$$

where σ_{ps} is the partial cross section for creation of secondary nuclei in hadronic collisions of primaries with the ISM gas nuclei, N_s is the total number of secondary CRs created during the evolution of a single SNR. Compared with the standard leaky box model the above equation contains an additional source term which describes the production of secondaries in SNRs. In the above equations all variables are functions of the same kinetic energy per nucleus ϵ_k.

One can easily find the s/p ratio from the above two equations:

$$\frac{n_{\rm s}}{n_{\rm p}}=\frac{\sigma_{\rm ps}N_{\rm g}v\tau_{\rm c}}{1+\sigma_{\rm s}N_{\rm g}v\tau_{\rm c}}+\frac{N_{\rm s}}{N_{\rm p}}\frac{(1+\sigma_{\rm p}N_{\rm g}v\tau_{\rm c})}{(1+\sigma_{\rm s}N_{\rm g}v\tau_{\rm c})}. \qquad (4)$$

Since the residence time $\tau_{\rm c}$ in the GCR confinement volume is a decreasing function of CR energy for $\epsilon_{\rm k}\gg 1$ GeV/n, we have

$$\sigma N_{\rm g}v\tau_{\rm c}\ll 1, \qquad (5)$$

and the expression for the ratio can be drastically simplified:

$$\frac{n_{\rm s}}{n_{\rm p}}=\frac{\sigma_{\rm ps}x}{m_{\rm p}}+\frac{N_{\rm s}}{N_{\rm p}}, \qquad (6)$$

where we have introduced the escape length

$$x=m_{\rm p}N_{\rm g}v\tau_{\rm c}, \qquad (7)$$

in the form of the mean matter thickness traversed by GCRs in the course of their random walk in the Galaxy. Expression (6) shows that apart from the usual term proportional to the escape length x, the s/p ratio contains an additional term which describes the source contribution in the production of secondaries. Since the primary spectra $N_{\rm p}(\epsilon_{\rm k})$, and the secondary spectra $N_{\rm s}(\epsilon_{\rm k})$, presumably produced in SNRs, have a similar energy dependence, we expect the term $N_{\rm s}/N_{\rm p}$ to dominate at sufficiently high energies in the s/p ratio.

One can also get an expression for the escape length x from Eq. (4) in terms of the observed s/p ratio $r_{\rm g}=n_{\rm s}/n_{\rm p}$ and the source s/p ratio $r_{\rm s}=N_{\rm s}/N_{\rm p}$:

$$x=\frac{m_{\rm p}(r_{\rm g}-r_{\rm s})}{\sigma_{\rm ps}+r_{\rm s}\sigma_{\rm p}-r_{\rm g}\sigma_{\rm s}}. \qquad (8)$$

In the simplest case when the source produces only primary CRs ($r_{\rm s}=0$), we have the usual expression

$$x=m_{\rm p}/(\sigma_{\rm ps}/r_{\rm g}-\sigma_{\rm s}), \qquad (9)$$

which makes it possible to extract the value of x from the measured s/p ratio $r_{\rm g}$. Note that in the general case, when an unknown number of secondary CRs are produced in the CR sources, there is no one to one correspondence between $r_{\rm g}$ and x.

3. Acceleration and reacceleration of CRs in SNRs

There are two different suprathermal particle populations in the ISM which are injected into the diffusive shock acceleration process in SNRs. The first and most general one is the injection of some fraction of the postshock thermal particle distribution. It occurs for all ions present in the background medium and usually supplies enough particles to convert an significant part of the SN shock energy into that of an energetic particle population.

The second possibility is the acceleration of preexisting GCR particles which have a sufficiently high energy $\epsilon_{\rm k}\gtrsim 100$ MeV/n so that they participate naturally into the acceleration process. Note that for those elements which are strongly underabundant in the thermal ISM, like Li, Be, B, this is the only practical possibility for acceleration. To distinguish these two different injection mechanism we use here the term "acceleration" for the first case and "reacceleration" for the second.

We shall employ here a simple CR injection model, in which a small fraction η of the incoming thermal protons is instantly injected at the gas subshock with a speed that exceeds the postshock gas sound speed $c_{\rm s2}$ by a factor $\lambda>1$ (Berezhko et al. 1996):

$$N_{\rm inj}=\eta N_{\rm g1},\ p_{\rm inj}=\lambda m c_{\rm s2}. \qquad (10)$$

Here $N_{\rm g}=\rho/m_{\rm p}$ is the gas number density, and the subscripts 1(2) refer to the point just ahead (behind) the shock.

GCR nuclei (primary and secondary) have a spectrum which in the subrelativistic region rises as a function of $\epsilon_{\rm k}$ due to ionization and nuclear losses. The spectrum has a maximum at $\epsilon_{\rm k}=\epsilon_{\rm GCR}\approx 600$ MeV/n and then falls of in a steep power law for higher energies. Therefore in the case of reacceleration it is assumed that the existing GCR population is injected at the SN shock front into the diffusive acceleration with this energy

$$p_{\rm inj}=p_{\rm GCR},\ N_{\rm inj}=N_{\rm GCR}. \qquad (11)$$

Here $N_{\rm GCR}$ is the total number of GCR nuclei per unit volume and $p_{\rm GCR}$ is their mean momentum, that corresponds to $\epsilon_{\rm GCR}$.

Since the primary CRs come from both injection mechanisms, we can estimate their relative role for the final CR production in SNRs. In order to do that we compare the overall CR spectra (i.e. the particle numbers dN in the momentum interval dp) $N(p)$ and $N^{\rm re}(p)$ which correspond to these two injection mechanisms. The overall spectrum of CRs reaccelerated in each single SNR at $p\geq p_{\rm GCR}$ is determined by the simple relation

$$N^{\rm re}=\frac{V_{\rm SN}N_{\rm GCR}}{p_{\rm GCR}}\left(\frac{p}{p_{\rm GCR}}\right)^{-\gamma_{\rm s}}, \qquad (12)$$

where $V_{\rm SN}$ is the volume of the SNR at the latest evolutionary stage where efficient CR acceleration can occur. For the sake of simplicity we assume that the overall spectrum of CRs produced during the active period of SNR evolution has a pure power law form with index $\gamma_{\rm s}$.

After their release from the parent SNRs these reaccelerated CRs occupy the confinement volume $V_{\rm c}$ more or less homogeneously with a number density $n^{\rm re}_{\rm GCR}$ that can be found from the leaky box equation (2)(we neglect here the collision term):

$$n^{\rm re}_{\rm GCR}/\tau_{\rm c}=N^{\rm re}\nu_{\rm SN}/V_{\rm c}. \qquad (13)$$

Since GCRs have a power law spectrum $n_{\rm GCR}\propto p^{-\gamma_{\rm g}}$, their total number density is

$$N_{\rm GCR}=n_{\rm GCR}(p_{\rm GCR})p_{\rm GCR}/(\gamma_{\rm g}-1) \qquad (14)$$

and therefore we can write

$$\frac{n_{\rm GCR}^{\rm re}}{n_{\rm GCR}} = \frac{\nu_{\rm SN}\tau_{\rm c}V_{\rm SN}}{(\gamma_{\rm g}-1)V_{\rm c}}\left(\frac{p}{p_{\rm GCR}}\right)^{\gamma_{\rm g}-\gamma_{\rm s}}. \quad (15)$$

Note that this relation is valid for primary as well as for secondary elements. The only difference between them is the different momentum dependence of the ratio $n_{\rm GCR}^{\rm re}/n_{\rm GCR}$. For primary elements as it follows from the equation (2)

$$\gamma_{\rm g} = \gamma_{\rm s} + \mu, \quad (16)$$

where power law index μ determines the momentum dependence of the residence time $\tau_{\rm c} \propto p^{-\mu}$. Therefore the ratio $n_{\rm GCR}^{\rm re}/n_{\rm GCR}$ is independent of p in this case.

The spectrum of secondary elements, produced in the Galactic disk according to the equation (2), is considerably steeper, because

$$\gamma_{\rm g} = \gamma_{\rm s} + 2\mu, \quad (17)$$

and therefore in this case the contribution of GCR reacceleration

$$n_{\rm GCR}^{\rm re}/n_{\rm GCR} \propto (p/p_{\rm GCR})^{\mu} \quad (18)$$

increases with energy.

The overall CR spectrum is formed during the active period of SNR evolution which lasts up to the time when the SN shock becomes too weak to accelerate efficiently a new portion of freshly injected particles. According to calculations presented below this final stage corresponds to a shock size $R_{\rm s} \approx 10R_0$ in the case of an ISM with hydrogen number density $N_{\rm H} = 1$ cm^{-3}, and $R_{\rm s} \approx 3R_0$ in the case of a hot ISM with $N_{\rm H} = 0.003$ cm^{-3}, where $R_0 = (3M_{\rm ej}/4\pi\rho_0)^{1/3}$ is so the called sweep-up radius, $M_{\rm ej}$ is the ejecta mass, and $\rho_0 = N_{\rm g}m_{\rm p} = 1.4N_{\rm H}m_{\rm p}$ is the ISM density. Taking into account that $\tau_{\rm c}/V_{\rm c} = \tau_{\rm g}/V_{\rm g}$, where $\tau_{\rm g}$ is the residence time in the galactic disk volume $V_{\rm g} = 2.5 \times 10^{66}$ cm^3, and $\nu_{\rm SN} = 1/30$ yr^{-1}, we have for energies about 5 GeV, where $\tau_{\rm g} = 4.6 \times 10^6$ yr, a value $n_{\rm GCR}^{\rm re}/n_{\rm GCR} = 0.04$ for $N_{\rm H} = 1$ cm^{-3}, and $n_{\rm GCR}^{\rm re}/n_{\rm GCR} = 0.3$ for $N_{\rm H} = 0.003$ cm^{-3}. One can see that in an ISM which has a number density $N_{\rm H} = 1$ cm^{-3} typical for the galactic disk, the primary GCR reacceleration is not important. Only in the case of a rarefied ISM, like a hot ISM with a number density $N_{\rm H} = 0.003$ cm^{-3}, one can expect an important contribution of GCR reacceleration to their overall spectrum $n_{\rm GCR}(\epsilon_{\rm k})$. The same conclusion has been reached for CR acceleration in the ISM of elliptical galaxies that has similar parameters (Dorfi & Völk 1996).

Due to the additional factor $(p/p_{\rm GCR})^{\mu}$ the contribution of reacceleration becomes dominant in the secondary GCR spectra at high energies. The value of the critical energy above which the secondary spectra are expected to be as hard as the primary ones depends upon the mean gas density $N_{\rm g}^{\rm SCR}$ inside the SNRs: according to the above formulae, it is expected to be 100 GeV/n for $N_{\rm g}^{\rm SCR} \sim 10^{-2}$ cm^{-3}, and an order of magnitude larger if $N_{\rm g}^{\rm SCR} \sim 1$ cm^{-3}.

There is an additional mechanism of secondary GCR production inside SNRs: primary nuclei like GCRs in the Galactic disk produce light secondary as a result of nuclear spallation due to their interaction with the background gas. One can easily estimate the relative significance of this mechanism compared with the previous one. The total production rate of secondaries in SNRs due to the spallation of primaries is

$$Q_{\rm s}^{\rm SCR} \propto N_{\rm g}^{\rm SCR}N_{\rm SN}N_{\rm p}, \quad (19)$$

where $N_{\rm SN}$ is the number of existing SNRs in the Galaxy and $N_{\rm g}^{\rm SCR}$ is mean number density of the thermal gas in SNRs. GCRs generate the same kind of secondaries with the rate

$$Q_{\rm s}^{\rm GCR} \propto N_{\rm g}^{\rm GCR}V_{\rm g}n_{\rm p}, \quad (20)$$

where $N_{\rm g}^{\rm GCR} \approx 1$ cm^{-3} is mean gas number density in the Galactic disk. Taking into account that the SNR number $N_{\rm SN} = T_{\rm SN}\nu_{\rm SN}$ is determined by the CR confinement time $T_{\rm SN}$ inside a SNR, and that the GCR number density $n_{\rm p}$ is related to the overall CR spectrum produced in SNR $N_{\rm p}$ by the relation $n_{\rm p} = N_{\rm p}\nu_{\rm SN}\tau_{\rm g}/V_{\rm g}$, we have

$$\frac{Q_{\rm s}^{\rm SCR}}{Q_{\rm s}^{\rm GCR}} = \frac{N_{\rm g}^{\rm SCR}}{N_{\rm g}^{\rm GCR}}\frac{T_{\rm SN}}{\tau_{\rm g}}. \quad (21)$$

Like reacceleration, this mechanism produces a substantially harder spectrum of secondaries compared with the spectrum created by the GCRs in the Galactic disk. It has the opposite dependence on the ISM density: it is more efficient in a denser ISM.

Since $T_{\rm SN} \sim 10^5$ yr and since $\tau_{\rm g} \approx 5 \times 10^6$ yr at GeV energies (e.g. Berezinskii et al. 1990), we have $Q_{\rm s}^{\rm SCR}/Q_{\rm s}^{\rm GCR} = 2 \times 10^{-2}$ if on average SNe explode into the ISM with a gas number density $N_{\rm g}^{\rm SCR} = N_{\rm g}^{\rm GCR}$. This value is somewhat lower than the corresponding contribution of reacceleration to the production of secondary nuclei. At the same time, the spectrum of secondaries spectrum $N_{\rm s}(p)$ has in this case exactly the same form as that of the primaries, $N_{\rm p}(p)$. As demonstrated below, in the case of reacceleration the ratio $N_{\rm s}(p)/N_{\rm p}(p)$ decreases slightly with momentum p due to the fact that secondaries are more effectively produced at the late SNR evolutionary phase when the SN shock becomes weaker, whereas high energy primaries are mainly accelerated at the beginning of the Sedov phase, when the SN shock is extremely strong. Therefore one can expect that the secondary nuclei production due to the hadronic SCR collisions with the gas nuclei makes a considerable contribution at high energies $\epsilon_{\rm k} \gtrsim 100$ GeV/n.

The production of secondaries due to spallation of primary SCRs in SNRs is described in our model by the source term

$$q_{\rm s}(r,p,t) = \sigma_{\rm ps}vN_{\rm g}f_{\rm p}(r,p,t) \quad (22)$$

in the transport equation for the distribution function $f_s(r,p,t)$ of secondary nuclei. Here $f_p(r,p,t)$ is the distribution function of primary nuclei and N_g is the local gas number density, both of which are also functions of SNR evolutionary time and position. The distribution function $f(r,p,t)$, which determines all relevant CR characteristics, is calculated in our model selfconsistently for all CR elements considered (see Berezhko et al. 1996 for details).

The actual situation with the CR spectra in SNRs is rather more complicated than suggested by the above estimates. Due to nonlinear acceleration effects, CR spectra produced in SNRs are not pure power laws. Besides that particles with different energies are effectively produced during different phases of SNR evolution, whereas the above simple estimates suggest in fact that the entire overall CR spectrum $N(p)$ is produced at an epoch characterized by the SNR volume V_{SN} and age T_{SN}. To reach more definitive conclusions about the role of CR reacceleration in SNRs, we need to perform a selfconsistent consideration. This can only be done numerically.

Note that the source CR spectra $N(\epsilon_k)$ which are the time integral spectra of the CRs accelerated during the whole active period of SNR evolution, depend on the GCR spectra $n(\epsilon_k)$ since not only the injection of suprathermal particles leads to the formation of $N(\epsilon_k)$ but the injection and the reacceleration of existing background GCRs contribute as well. This means that the spectra $N(\epsilon_k)$ should be determined as the result of a selfconsistent solution of the equations which describe the GCR propagation and nuclear transformation in the Galactic confinement volume, together with the equations, which govern SNR evolution and CR acceleration. Fortunately this rather complicated problem can be considerably simplified without loss of accuracy. Indeed, as discussed before, due to the steep GCR spectra at relativistic energies $\epsilon_k \gg 1$ GeV/n, only the injection of GCRs with energies $\epsilon_k \lesssim 1$ GeV/n plays a role for the formation of the resultant spectra $N(\epsilon_k)$. Since the GCR spectra $n(\epsilon_k)$ at these subrelativistic energies are known from experiment, we use them as physical input like other ISM parameters in our selfconsistent nonlinear kinetic model for CR acceleration in SNR, so that the output of this model, which is the overall CR spectrum $N(\epsilon_k)$, can be considered as consistently determined together with the GCR spectra $n(\epsilon_k)$.

4. Results and discussion

In order to study the effect of GCR reacceleration in SNRs on the s/p ratio we consider the elements boron (B) and carbon (C) because carbon is the most abundant element in the GCRs and plays a major role in the production of boron which is usually considered as a pure secondary. We have performed selfconsistent calculations of CR acceleration in SNRs, based on the kinetic nonlinear model, for the simple case of a uniform ISM with different densities.

We use the values $E_{SN} = 10^{51}$ erg for the explosion energy and $M_{ej} = 1.4 M_{\odot}$ for the ejecta mass which are typical for SNe Ia in a uniform ISM. Note that the main

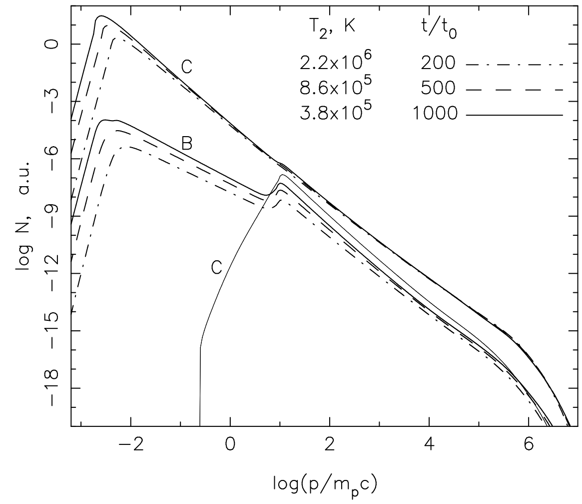

Fig. 1. The overall momentum spectra of B and C nuclei produced during the SNR evolution in the warm ISM ($N_H = 0.3$ cm^{-3}, $T = 10^4$ K, $t_0 = 367$ yr) up to three different moments of time. The carbon spectra, starting from $p/m_pc \ll 1$, are due to the acceleration of injected suprathermal particles and GCR reacceleration, whereas the boron spectra are the result of reacceleration of GCRs and the spallation of carbon and oxygen nuclei inside SNR. For clarity, the spectrum of purely reaccelerated GCR carbon nuclei, corresponding to $t/t_0 = 1000$, is shown by the thin solid line.

fraction of the core collapse SNe has relatively small initial progenitor star masses between 8 and 15 $M_{\odot}$ which therefore do not significantly modify the surrounding ISM through the main sequence wind of the progenitor star (e.g. Abbott 1982). SNR evolution in this case is very similar to that of SNe Ia.

Only in the case of type Ib and type II SNe with massive progenitor stars $M_i > 15 M_{\odot}$, SNRs expand into a nonuniform circumstellar medium strongly modified by the intense progenitor star wind. The SNR evolution looks differently compared to the case of a uniform ISM. At the same time, the main amount of CRs is expected to be produced when the SN shock propagates through the hot rarefied bubble, where the evolution and CR acceleration are roughly similar to that in the case of a uniform ISM which has the same parameters as the bubble (Berezhko and Völk 2000). Therefore the contribution of SNRs expanding in the strongly modified circumstellar medium effectively increase the filling factor of the hot phase of ISM.

We adopt an injection rate of suprathermal particles, characterized by the injection parameters $\eta = 10^{-4}$ and $\lambda = 4$, which are expected for a typical SNR (Völk et al. 2003). GCR nuclei B and C with number densities $N_B = 7.9 \times 10^{-14}$ cm^{-3} and $N_C = 2.6 \times 10^{-13}$ cm^{-3}, respectively, are injected at a kinetic energy $\epsilon_{inj} = 0.6$ GeV/n which corresponds to the mean GCR energy for these elements. We consider three essentially different phases of the ISM: a diluted, hot ISM with hydrogen number density $N_{\rm H} = 0.003$ cm^{-3} and temperature $T_0 = 10^6$ K, a warm ISM with $N_{\rm H} = 0.3$ cm^{-3} and $T_0 = 10^4$ K, and an "average" ISM with $N_{\rm H} = 1$ cm^{-3} and $T_0 = 10^4$ K. The ISM magnetic field values $B_0 = 3$ μG, 5 μG and 10 μG where taken for these three cases, respectively.

Numerical results, which correspond to the so-called warm ISM with $N_{\rm H} = 0.3$ cm^{-3}, are presented in Figs. 1 and 2. The overall momentum spectra of boron and carbon

$$N(p,t) = 16\pi^2 p^2 \int_0^\infty dr r^2 f(r,p,t), \quad (23)$$

which include all particles accelerated during the SNR evolution up to time t, are shown in Fig. 1 for three successive times t. One can see that reacceleration of GCRs makes quite a small contribution to the overall spectrum of carbon, in agreement with the earlier estimate. Note also that the late evolutionary phases are not very important for the highest energy part of the spectrum of primary nuclei: the C-spectrum at $p > 10^3 m_{\rm p}c$ is formed mainly at the beginning of the Sedov phase ($t \sim t_0$), and it is almost unchanged at late phases $t > 100t_0$. There are two physical factors which determine the above situation. The first is a geometrical factor which results in the most efficient acceleration of the highest energy CRs at the beginning of the Sedov phase (Berezhko 1996). Due to the decrease of the product $R_{\rm s}V_{\rm s}$, the maximum energy of freshly injected/accelerated CRs decreases with time in the Sedov phase. Therefore the late Sedov phases do not contribute significantly to the highest energy part of the resulting CR spectrum.

The second factor is the decrease of the injected suprathermal particle momentum $p_{\rm inj} \propto V_{\rm s}$ due to the shock deceleration. It diminishes the contribution of the late phases to CR production. As a result, the overall spectrum of CR primary nuclei is mainly formed during the early Sedov phase when the shock is extremely strong, and therefore it is quite hard.

In the case of secondaries the situation is very different. In the B-spectra two different components are clearly visible. The first one, peaking at $p = p_{\rm GCR} \approx 10 m_{\rm p}c$, is due to the injection of GCRs with momentum $p_{\rm GCR}$. Since $p_{\rm GCR}$ does not depend on time, the efficiency of their acceleration (reacceleration) progressively increases with time, roughly proportional to the total number of particles participating in the acceleration. This number is proportional to the shock volume $V_{\rm SN}$. Since in this case the late SN evolutionary phases, when the SN shock is no more so strong as during the early Sedov phase, are important for secondary CR production, their overall spectrum is much steeper than the spectrum of primary nuclei (see Fig. 1).

The second component in the B-spectra is due to the spallation of carbon and oxygen nuclei. Its spectrum is substantially harder than that of the first component, because it is directly related to the spectra of primaries. Therefore it contributes strongly at very high momenta $p \gtrsim 10^4 m_{\rm p}c$ and also dominates at very low momenta $p < p_{\rm GCR}$, where B production due to reacceleration is negligible.

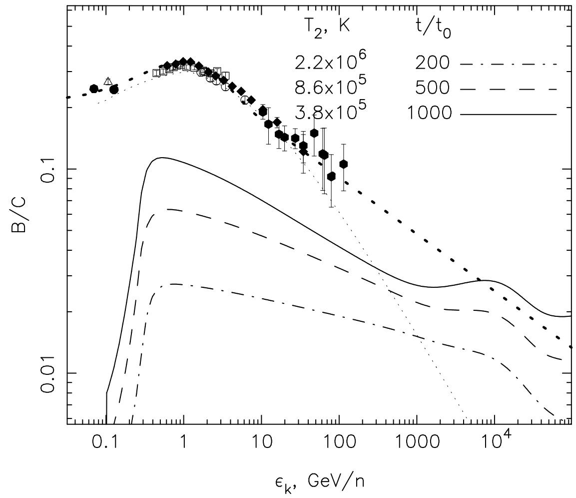

Fig. 2. The B/C ratio $r_{\rm g} = n_{\rm B}/n_{\rm C}$ as a function of kinetic energy per nucleus. *Solid, dashed and dash-dotted lines* represent the ratio $r_{\rm s} = N_{\rm B}/N_{\rm C}$ for the case presented in Fig. 1. *Dotted lines* represent the fit of the experimental data within the leaky box model (*thin dots*) on the one hand, and within the diffusive model with distributed reacceleration in the ISM (*heavy dots*) on the other. Experimental data (Engelmann et al. 1990) are also shown.

On account of the above factors the ratio $r_{\rm s}$, which is exclusively due to the production of secondaries in SNRs, becomes steeper and increases with time, as one can see from Fig. 2. Therefore the effect of GCR reacceleration on the s/p ratio depends on the confinement time $T_{\rm SN}$ which corresponds to the age of the SNR when the shock becomes an inefficient accelerator and release of previously accelerated CRs into the Galactic volume proceeds.

There are at least two conditions which determine the confinement time $T_{\rm SN}$.

The first one is the decrease of the shock Mach number during the SNR evolution. When it becomes so low, at some stage $t = t_4$, such that the shock compression ratio σ drops below 4, the acceleration of freshly injected particles becomes inefficient. This leads to the decrease of the turbulence level near the shock front and to subsequent escape of previously accelerated CRs due to increase of their diffusive mobility. This factor plays the major role in the case of a hot ISM.

In fact, the so-called effective compression ratio

$$\sigma_{\rm ef} = \sigma(1 - 1/M_{\rm a}), \quad (24)$$

rather than σ, plays the main role in CR acceleration and their final spectrum. Due to the fact, that Alfvén waves, excited by the accelerated CRs upstream of the shock, propagate in upstream direction with Alfvén speed $c_{\rm a}$, the effective compression ratio of scattering centers seen by CRs $\sigma_{\rm ef}$ is always smaller than σ. This effect is described in the above expression by the Alfvén Mach number $M_{\rm a} = c_{\rm a}/V_{\rm s}$. Therefore t_4 is the time when $\sigma_{\rm ef}$ drops below 4.

The acceleration process may also stop at some stage $t = t_6$ when the postshock temperature drops below 10^6 K, because radiative SNR cooling sets in strongly. Since the SNR looses a large amount of its energy, efficient CR acceleration terminates presumably at this stage.

We adopt here a confinement time, which is the minimum of these two:

$$T_{\rm SN} = min\{t_4, t_6\}. \quad (25)$$

In the case of a warm ISM, we have a postshock gas temperature $T_2 = 1.3 \times 10^6$ K at $t = 300t_0$, and therefore the confinement time is $T_{\rm SN} = t_6 \approx 10^5$ yr ($t_0 = 367$ yr in this case). The relevant ratio $r_{\rm s}$ in Fig. 2 is therefore given by the dashed line.

The significance of GCR reacceleration can be understood if one compares the expected source s/p ratio $r_{\rm s}$ with the ratio $r_{\rm g}$, extracted from the measured B/C ratio in the standard model.

Since the boron nuclei are produced in the ISM not only by spallation of carbon but also by spallation of oxygen, the expression (4) has to be rewritten in the form:

$$\frac{n_{\rm B}}{n_{\rm C}} = \frac{x}{m_{\rm p} + \sigma_{\rm B} x}\left(\sigma_{\rm CB} + \sigma_{\rm OB}\frac{n_{\rm O}}{n_{\rm C}}\right) + \frac{N_{\rm B}}{N_{\rm C}}\frac{(m_{\rm p} + \sigma_{\rm C} x)}{(m_{\rm p} + \sigma_{\rm B} x)}. \quad (26)$$

This expression is used in order to determine the expected B/C ratio with accounts for boron production inside the GCR sources (in SNRs). In the case when the secondaries are not produced in CR sources we have from this expression

$$r_{\rm g} = \frac{(\sigma_{\rm CB} + \sigma_{\rm OB}) x_{\rm g}}{m_{\rm p} + \sigma_{\rm B} x_{\rm g}}. \quad (27)$$

According to the standard leaky box model, the value of the escape length $x_{\rm g} \approx 14$ g/cm^2 at GeV energies with energy dependence $x_{\rm g} \propto \epsilon_{\rm k}^{-0.6}$ at $\epsilon_{\rm k} > 5$ GeV/n fits the existing B/C data (Engelmann et al. 1990).

Note however that the value of the escape length derived from the same experimental data depends also on the GCR propagation model, especially at high energies where the existing experimental data do not constrain it.

The galactic model with distributed stochastic reacceleration predicts a different (weaker) decrease of the B/C ratio at high energies $\epsilon_{\rm k} > 30$ GeV/n than does the standard leaky box model. According to Jones et al. (2001), $x_{\rm g} \propto \epsilon_{\rm k}^{-0.54}$ in the model without reacceleration, and $x_{\rm g} \propto \epsilon_{\rm k}^{-0.3}$ in the model with stochastic reacceleration. Both models give the same s/p ratio at $\epsilon_{\rm k} < 30$ GeV/n.

In order to demonstrate how significantly secondary CR production in SNRs changes the expected s/p ratio, we consider here two extreme predictions for $x_{\rm g} \propto \epsilon_{\rm k}^{-\mu}$. The first one, with $\mu = 0.6$, corresponds to the standard leaky box model (Engelmann et al. 1990). The second, with $\mu = 0.3$, corresponds to the diffusion model with distributed stochastic reacceleration (Jones et al. 2001). The B/C ratio calculated with these two functions $x_{\rm g}(\epsilon_{\rm k})$ according to the expression (26) with $N_{\rm B} = 0$, are shown in Figs. 2–6 by the dotted lines. The cross section values and the ratio $n_{\rm O}/n_{\rm C}$, required to calculate the B/C ratio, are taken from the paper by Engelmann et al. (1990).

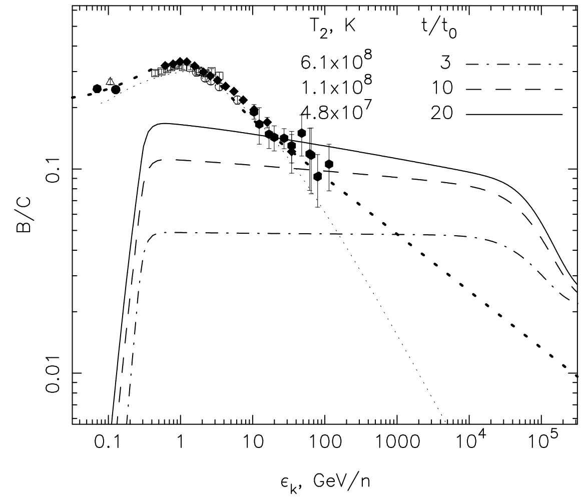

Fig. 3. The same as in Fig. 2 but for the case of a hot ISM ($N_{\rm H} = 0.003$ cm^{-3}, $t_0 = 1674$ yr).

In Figs. 2–4 we also present the ratio $r_{\rm s} = N_{\rm B}/N_{\rm C}$ of the boron and carbon spectra, produced in SNRs by the combination of all processes considered up to different times t/t_0 and calculated for three different ISM densities. One can see from Fig. 2, which corresponds to $N_{\rm H} = 0.3$ cm^{-3}, that the source ratio $r_{\rm s}$ exceeds the B/C ratio $r_{\rm g}$ predicted by the leaky box model at an energy $\epsilon_{\rm k} > 300$ GeV/n and only at $\epsilon_{\rm k} > 10$ TeV/n it becomes larger than $r_{\rm g}$ which corresponds to the diffusive model with distributed reacceleration if the CR confinement time is as large as $T_{\rm SN} = 4 \times 10^5$ yr. Note however, that at such a late time $t = 10^3 t_0 = 4 \times 10^5$ yr, the postshock temperature is already $T_2 \approx 4 \times 10^5$ K, and in addition the effective compression ratio drops up to $\sigma_{\rm ef} = 3.25$. Therefore the CR confinement time is taken to be equal $T_{\rm SN} = 500t_0 = 2 \times 10^5$ yr, because the postshock temperature at this stage is $T_2 = 9 \times 10^5$ K and the effective compression ratio has a value $\sigma_{\rm ef} = 3.8$ which is only slightly below 4.

In Fig. 3 we present the same as in Fig. 2 but for the rarefied, so-called hot ISM which is characterized by a temperature $T_0 = 10^6$ K and a hydrogen number density $N_{\rm H} = 0.003$ cm^{-3}. One can see that the ratio $r_{\rm s}$ exceeds at energies $\epsilon_{\rm k} \gtrsim 100$ GeV/n the measured value of B/C ratio already at $t = 3 \times 10^4$ yr.

We note that already at this stage the effective compression ratio drops below 4 and the acceleration of freshly injected particles becomes progressively less efficient. Therefore one can assume that in this case $T_{\rm SN} = t_4 \approx 3 \times 10^4$ yr. Even for this relatively short confinement time the contribution of the reacceleration process in the B/C ratio is strong at energies $\epsilon_{\rm k}$ greater than 10 GeV/n (solid curve in Fig. 3). Note that at such a low ISM density the production of secondary nuclei in SNRs is entirely due to their reacceleration.

At larger ISM densities secondary nuclei production due to the primary CR spallation becomes more important. This is illustrated in Fig. 4, where the expected B/C

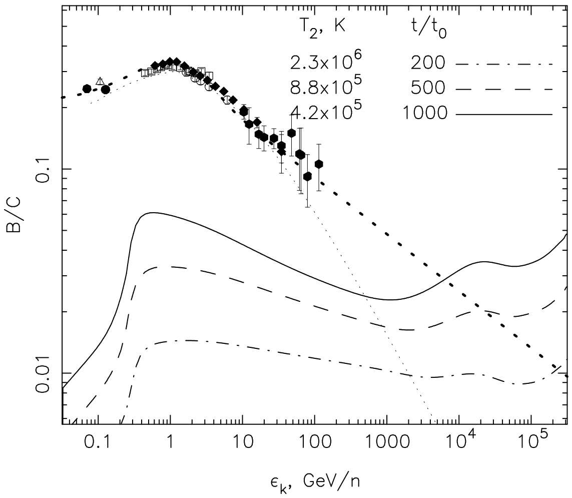

Fig. 4. The same as in Fig. 2 but for the case of an ISM hydrogen number density $N_\mathrm{H} = 1$ cm^{-3} ($t_0 = 246$ yr).

ratio r_s is represented for $N_\mathrm{H} = 1$ cm^{-3}. It is seen that at high energies $\epsilon_\mathrm{k} \gtrsim 10^4$ GeV/n the expected ratio r_s is higher than in the case $N_\mathrm{H} = 0.3$ cm^{-3}. Therefore, we conclude that the lowest efficiency of secondary nuclei production in SNRs occurs in the case of ISM number density $N_\mathrm{H} = 0.3$ cm^{-3}. It becomes larger both in a denser and a more diluted ISM because of efficient primary spallation and GCR reacceleration, respectively. Since at $t = 500t_0$ the postshock temperature $T_2 = 9 \times 10^5$ K is already lower than 10^6 K, the CR confinement time is $T_\mathrm{SN} = t_6 \approx 10^5$ yr in this case even though the effective shock compression ratio $\sigma_\mathrm{ef} = 4.2$ is still slightly higher than 4.

Since the typical ISM density in which the majority of SN explosions occurs is not well known, we present in Figs. 5 and 6 the possible range of the expected overall B/C ratios, calculated according to expression (26). The source ratios $r_\mathrm{s} = N_\mathrm{B}/N_\mathrm{C}$ are taken from the above calculations and the CR escape length

$$x = \delta x_\mathrm{g} \tag{28}$$

was assumed to be some fraction $\delta < 1$ of the escape length

$$x_\mathrm{g} = \frac{m_\mathrm{p} r_\mathrm{g}}{r_\mathrm{g}\sigma_\mathrm{B} - \sigma_\mathrm{CB} - \sigma_\mathrm{OB}}, \tag{29}$$

determined from the relation (27). The cross section values and the ratio $n_\mathrm{O}/n_\mathrm{C}$, required to calculate the B/C ratio, are taken from the paper by Engelmann et al. (1990). To fit the existing data one needs $\delta = 0.3$, 0.7 and 0.9 for the ISM number densities $N_\mathrm{H} = 0.003$ cm^{-3}, 0.3 cm^{-3} and 1 cm^{-3}, respectively. The B/C ratio is shown for these three densities. The production of secondary CRs in SNRs leads to a substantial decrease of the escape length x only if all SNRs explode into a diluted ISM with hydrogen number density $N_\mathrm{H} = 0.003$ cm^{-3}. In the two other cases, which are expected to be more probable, the relative decrease of x is not so important. It is significantly lower compared with the estimates of Wandel (1988), because we believe that the active period of SNR evolution stops much earlier than he assumed.

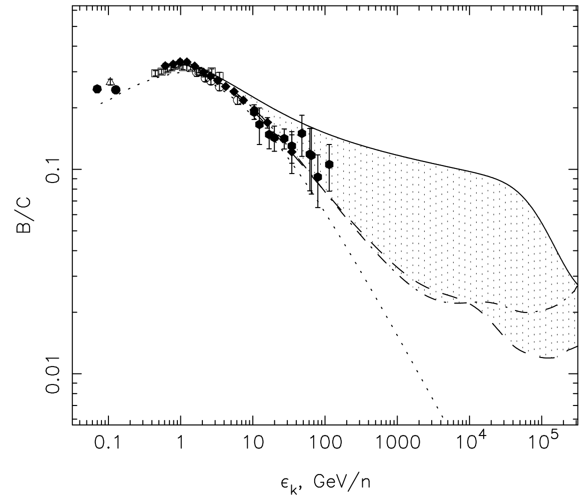

Fig. 5. The expected overall B/C ratio as a function of kinetic energy per nucleus. The three curves, corresponding to the three circumstellar hydrogen number densities $N_\mathrm{H} = 0.003$ cm^{-3} (*solid line*), $N_\mathrm{H} = 0.3$ cm^{-3} (*dashed line)*, and $N_\mathrm{H} = 1$ cm^{-3} (*dash-dotted line*) encompass a range given by the *dotted area.*

It is seen that for $N_\mathrm{H} = 0.003$ cm^{-3} the boron production in SNRs leads to considerably higher values of the B/C ratio at energies $\epsilon_\mathrm{k} > 100$ GeV/n than the observations show. There are however some experimental indications that the measured B/C ratio becomes indeed flatter at energies near 100 GeV/n. It is interesting to see that the theoretical curves do not change monotonically with gas density. In fact a weighted mixture of SN sites with very low densities, $N_\mathrm{H} = 0.003$ cm^{-3} (hot ISM), and moderate densities $N_\mathrm{H} = 0.3$ cm^{-3} (warm ISM) is able to approximate the observations. More precise measurements at these energies are needed, in order to draw definite conclusions about the actual role of GCR reacceleration.

We note that the wide spread of the B/C ratio at high energies is due to the unknown correlations of SNR sites with gas density. Nevertheless it is clear from Figs. 2–4, that at any given density the energy dependence of the B/C ratio is expected to be much flatter than predicted by the leaky box model.

We have a similar situation in the case when the GCR escape length $x_\mathrm{g}(\epsilon_\mathrm{k})$, predicted by the diffusive model with distributed reacceleration, is used for comparison with the theory, as one can see from Fig. 6 for the same three densities. Since the energy dependence of the ratio $r_\mathrm{g}(\epsilon_\mathrm{k})$ is much flatter in this case, the relative increase of the B/C ratio due secondary CR production in SNRs is much smaller than in the previous case. Nevertheless, the expected value of the B/C ratio for $\epsilon_\mathrm{k} \gtrsim 1$ TeV/n is still noticeably higher, by a factor of two on average, than predicted by the model which neglects secondary CR production in SNRs. The CR escape length values are determined by the factor $\delta = 0.2$, 0.6 and 0.8 for $N_\mathrm{H} = 0.003$ cm^{-3}, 0.3 cm^{-3} and 1 cm^{-3}, respectively.

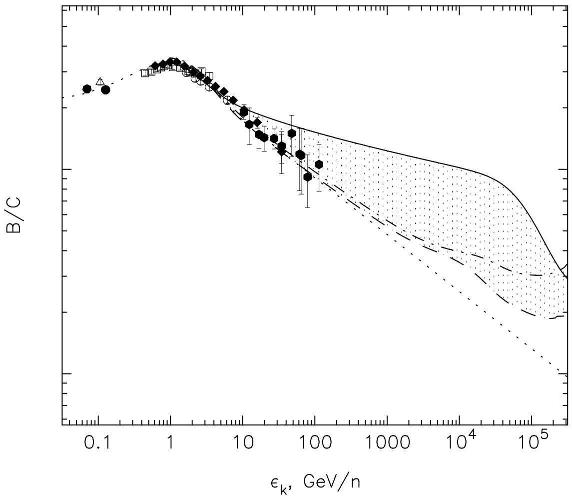

Fig. 6. The same as in Fig. 5 but comparing with the mean CR escape length $x_{\rm g}(\epsilon_{\rm k})$ predicted by the diffusion model with distributed CR reacceleration.

One could expect that we deal with a more realistic situation when a variety of existing SNRs in the Galaxy are expanding into ISM regions with different densities. In order to make a definite prediction about the expected B/C ratio one should determine properly weighted boron and carbon spectra:

$$N_{B,C}(\epsilon_k) = \Sigma \Delta\nu_{SN}^i N_{B,C}(\epsilon_k, N_g^i)/\nu_{SN} \quad (30)$$

for a given SN explosion rate $\Delta\nu_{SN}^i$ in an ISM with number density N_g^i. Unfortunately the explosion rates $\Delta\nu_{SN}^i$ are not known. At the same time, as it is clear from Figs. 5 and 6, the uncertainty in the B/C ratio is determined mainly by the value $\Delta\nu_{SN}^h$, which corresponds to the hot ISM. Since the boron spectrum is much more sensitive to the ISM density than the carbon spectrum, we can approximately write

$$B/C = (B/C)_h \Delta\nu_{SN}^h/\nu_{SN} + (B/C)_w(1 - \Delta\nu_{SN}^h/\nu_{SN}), \quad (31)$$

taking into account that within the ISM density range from 0.3 to 1 cm^{-3} the ratio B/C changes not so significantly. Here $(B/C)_h$ and $(B/C)_w$ are the B/C ratios produced in hot and warm ISM, respectively. This formula makes it possible to estimate the expected B/C ratio for a given value $\Delta\nu_{SN}^h/\nu_{SN}$ without making additional calculations.

5. Summary

Our considerations based on the selfconsistent kinetic nonlinear model for CR acceleration in SNRs show that the reacceleration of the existing GCRs and the spallation of primary CRs due to their collisions with the gas nuclei in SNRs strongly influence the energy spectra of secondary elements, like Li, Be, B. Due to this additional mechanism the spectra of secondaries become significantly flatter at high energies $\epsilon_{\rm k} > 100$ GeV/n. This effect can be directly studied from the s/p ratio: at high energies where reacceleration is important, the s/p ratio should be flatter than at lower energies $1 \lesssim \epsilon_{\rm k} \lesssim 100$ GeV/n.

Compared with previous considerations based on the plane-wave approach (Wandel 1988), our model selfconsistently includes a number of physical factors: i) nonlinear shock modification due to the CR backreaction; ii) CR adiabatic cooling inside the expanding SNR interior; iii) the so-called CR escape effect. In addition, all stages of SNR evolution contribute to the resulting overall CR spectra, in contrast to the assumption by Wandel that only very late SNR phases play a role.

Qualitatively, the efficiency of secondary CR nuclei production in SNRs depends in an important way on the density of the ISM in which SNRs are exploding. The lower the ISM density is, the larger is the volume of the SNR which is reached during the active period of its evolution. Correspondingly larger numbers of background GCRs are swept-up and reaccelerated compared with the number of particles injected from the thermal postshock distribution. If SNRs are on average exploding into a diluted ISM, then the influence of reacceleration becomes significant already at $\epsilon_{\rm k} \sim 10$ GeV/n. This is in contradiction to the existing data for the B/C ratio and means that the typical ISM density "seen" by SNe is greater than 0.003 cm^{-3}.

An increase of the ISM density leads to a decrease of the reacceleration effect. At the same time the production of secondaries in SNRs due to the spallation of primaries becomes more important. If the typical density is between about $N_{\rm H} = 0.3$ and 1 cm^{-3}, reacceleration and spallation produce roughly equal contributions to the B/C ratio at $\epsilon_{\rm k} \approx 1$ TeV/n, whereas at higher energies spallation becomes dominant. Quantitatively the effect depends upon the mean GCR escape length and its energy dependence. In the case $N_{\rm H} = 0.3$ cm^{-3} boron production in SNRs becomes dominant for $\epsilon_{\rm k} > 0.5$ TeV/n within the leaky box model, and comparable within the diffusion model with distributed reacceleration for $\epsilon_{\rm k} > 3$ TeV/n.

The value of the CR confinement time T_{SN} inside SNRs plays the crucial role for the secondary CR production inside SNRs: the larger T_{SN} is, the greater is the number of secondaries that are produced. In the case of a diluted ISM with number density $N_H = 0.003$ cm^{-3}, CR confinement is presumably restricted to times smaller than t_4 when the shock becomes too weak to support a high level of MHD turbulence near the shock front due to the CR streaming instability. In the case of a much denser ISM with $N_H \sim 1$ cm^{-3} the active period of CR production in SNRs is assumed to terminate when the postshock temperature drops below 10^6 K. For intermediate ISM densities $N_H \sim 0.3$ cm^{-3} both effects are equally important. Due to these two physical factors the CR confinement time T_{SN} is significantly lower in our model compared with previous considerations (Wandel 1988), where these factors were ignored. This is one of the reasons why the effect of secondary CR production in SNRs is significantly lower in our model compared with the prediction of Wandel 1988.

If on average SNe explode in the ISM with $N_{\mathrm{H}} = 1\ \mathrm{cm}^{-3}$ boron production in SNRs leads to an extremely flat, almost energy-independent B/C ratio at $\epsilon_{\mathrm{k}} > 1$ TeV/n and at $\epsilon_{\mathrm{k}} > 5$ TeV/n in the two above cases, respectively. A detection of this flat energy-dependent ratio would be consistent with GCR production in SNRs.

The actual mean galactic escape length x is smaller than in the models which neglect the production secondary nuclei inside the sources and only take into account spallation during the random walk of primaries in the Galactic disk after release from their sources. The extent of this reduction depends upon the mean ISM density at the SNR sites: x is from 10% to 30% smaller if SNRs on average explode in an ISM with hydrogen number density N_{H} between 0.3 and 1 cm^{-3}, respectively. This effect is much smaller compared with the estimates of Wandel (1988), who suggested efficient CR acceleration/reacceleration by much older and weaker SNR shocks. Only if the ISM number density is as low as $N_{\mathrm{H}} = 0.003\ \mathrm{cm}^{-3}$ one expects the mean escape length to be smaller by a factor of 3 compared with the standard models.

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