

Spectra of Cosmic Ray Protons and Helium Produced in Supernova Remnants

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ABSTRACT

Data obtained in the ATIC-2 (Advanced Thin Ionization Calorimeter), CREAM (Cosmic Ray Energetics and Mass) and PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) experiments suggest that elemental interstellar spectra of cosmic rays below the knee at a few times 10^6 GeV are not simple power laws, but they experience hardening at magnetic rigidity above about 240 GV. Another essential feature is the difference between proton and Helium energy spectra, so that the He/p ratio increases by more than 50 % in the energy range from 10^2 to 10^4 GV. We consider the concavity of particle spectrum resulting from the nonlinear nature of diffusive shock acceleration in supernova remnants (SNR) as a possible reason for the observed spectrum hardening. Helium-to-proton ratio increasing with energy can be interpreted as a consequence of cosmic ray acceleration by forward and reverse shocks in SNRs. The contribution of particles accelerated by reverse shocks makes the concavity of the produced overall cosmic ray spectrum more pronounced. The spectra of protons and helium nuclei accelerated in SNRs and released into the interstellar medium are calculated. The derived steady state interstellar spectra are in reasonably good agreement with observations.

Subject headings: acceleration of particles — shock waves — ISM:supernova remnants

1. Introduction

High-accuracy measurements have revealed deviations of cosmic ray spectra from plain power laws at energies 10 to 10^5 GeV/n. This refers, in particular, to the ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010; Yoon et al. 2011) and PAMELA (Adriani et al. 2011) experiments; see Lavalle (2011) for additional references. The general conclusion from these measurements is the presence of hardening in the spectra of protons, helium and probably heavier nuclei at magnetic rigidity about 240 GV and the increase of He/p ratio in the above energy range.

A number of explanations of these results have been suggested: the hardening may reflect the contribution of two distinct populations of cosmic ray sources (Zatsepin & Sokolskaya 2006); the action of numerous sources with the dispersion of source injection spectra (Yuan et al. 2011); fluctuations produced by local cosmic ray sources (Thoudam & Hörandel 2012); specific conditions of cosmic ray transport in the local bubble (Erlykin & Wolfendale 2012); interstellar diffusion with a diffusion coefficient that is not separable in energy and space (Tomassetti 2012); or the combination of diffusion on the cosmic ray induced turbulence and the background turbulence (Blasi et al. 2012). The energy dependent He/p ratio may be due to acceleration by shock propagating through the medium with varying chemical composition, including the helium wind of a Wolf-Rayet star (Ptuskin et al. 2010), the stratified material of a bubble (Ohira & Ioka 2011), or rate of ionization (Drury 2011), and the specifics of thermal ion injection in the process of shock acceleration (Malkov et al. 2012). Biermann et al. (2010) suggested that the spectral hardening and enrichment in heavy nuclei is due to the contribution of a polar cap cosmic-ray component produced by supernova explosions in winds of massive progenitor stars. The consideration of various interpretations of cosmic ray spectral peculiarities can be found in the paper Vladimirov et al. (2012).

In the present work we further develop our model of cosmic ray acceleration in supernova remnants (Ptuskin et al. 2010) (Paper I) to explain both of the required features. To a good approximation, the model in Paper I explains the observed overall spectrum of cosmic rays in a wide range of energies up to about 10^9 GeV. An important improvement of the code used in Paper I was made in our work (Zirakashvili & Ptuskin 2011) (Paper II), where particle acceleration by a reverse (backward) shock moving through the material of supernova ejecta was included in the calculations. This is in addition to the acceleration by the forward shock moving through the circumstellar medium studied in Paper I. The code described in Paper II was used by Zirakashvili (2011); Zirakashvili & Aharonian (2011) for modelling particle acceleration in SNRs RXJ1713.7-3946 and Cas A.

It is worth noting that similar numerical models of nonlinear production of cosmic rays in SNRs, where time-dependent cosmic-ray transport equations are solved together with gas-dynamic equations in spherical symmetry were developed by two other groups of authors (Berezhko et al. 1994; Berezhko & Völk 2007) and (Kang & Jones 2006). They give results analogous to our model for particle acceleration by forward SNR shocks, but they do not include acceleration by reverse shocks. Cosmic-ray acceleration by reverse SNR shocks was earlier considered by Berezhinskii & Ptuskin (1989). The process was recently analysed by Telezhinsky et al. (2012) in a test particle approximation.

Two effects considered below in the frameworks of our model of particle acceleration in SNRs are of particular importance: the nonlinear shock modification that leads to the concave spectrum of accelerated particles with a pronounced hardening; and taken into account acceleration of supernova ejecta material poor in hydrogen by a reverse shock that leads to the difference between the overall proton and helium spectra and increases their concavity.

2. Modelling of cosmic-ray acceleration in supernova remnants

Cosmic ray acceleration in shell SNRs proceeds through the diffusive shock acceleration mechanism that is a version of the first order Fermi acceleration in the shock vicinity, where the gas with a frozen magnetic field is compressing. The fast, charged background particles are scattered by random magnetohydrodynamic (MHD) waves and inhomogeneities, and they gain energy crossing the shock, see e.g. Malkov & O’C Drury (2001) for a review. The process of efficient acceleration should be modelled simultaneously with the SNR hydrodynamics, because the pressure of accelerated particles modifies the gas flow and the shock structure that affects the particle spectrum. Also, the current of accelerated particles results in the streaming instability that amplifies the background MHD waves. These waves in turn determine the value of particle spatial diffusion.

Hydrodynamical equations for the gas density $\rho(r, t)$, gas velocity $u(r, t)$, gas pressure $P_g(r, t)$, and the equation for the isotropic part of the cosmic-ray proton momentum distribution $N(r, t, p)$ in the spherically symmetrical case take the form (see also Paper II):

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2} \frac{\partial}{\partial r} r^2 u \rho, \quad (1)$$

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial r} - \frac{1}{\rho} \left(\frac{\partial P_g}{\partial r} + \frac{\partial P_c}{\partial r} \right), \quad (2)$$

$$\frac{\partial P_g}{\partial t} = -u \frac{\partial P_g}{\partial r} - \frac{\gamma_g P_g}{r^2} \frac{\partial r^2 u}{\partial r} - (\gamma_g - 1)(w - u) \frac{\partial P_c}{\partial r}, \quad (3)$$

$$\begin{aligned} \frac{\partial N}{\partial t} &= \frac{1}{r^2} \frac{\partial}{\partial r} r^2 D(p, r, t) \frac{\partial N}{\partial r} - w \frac{\partial N}{\partial r} + \frac{\partial N}{\partial p} \frac{p}{3r^2} \frac{\partial r^2 w}{\partial r} \\ &+ \frac{\eta^f \delta(p - p_f)}{4\pi p_f^2 m} \rho(R_f + 0, t) (\dot{R}_f - u(R_f + 0, t)) \delta(r - R_f(t)) \end{aligned}$$

$$+ \frac{\eta^b \delta(p - p_b)}{4\pi p_b^2 m} \rho(R_b - 0, t) (u(R_b - 0, t) - \dot{R}_b) \delta(r - R_b(t)). \quad (4)$$

Here $P_c = 4\pi \int p^2 dp v p N/3$ is the cosmic-ray pressure, $w(r, t)$ is the advective velocity of cosmic rays, γ_g is the adiabatic index of the gas, and $D(r, t, p)$ is the cosmic-ray diffusion coefficient. It was assumed that the diffusive streaming of cosmic rays results in the generation of MHD waves. Cosmic-ray particles are scattered by these waves. That is why the cosmic-ray advective velocity w may differ from the gas velocity u . In our modelling they differ on the value of the radial component of the Alfvén velocity calculated in the isotropic random magnetic field: $w = u + \xi_A V_A / \sqrt{3}$, $V_A = B / \sqrt{4\pi\rho}$. Here the factor ξ_A describes the possible deviation of the cosmic ray drift velocity from the gas velocity. The values $\xi_A = 1$ and $\xi_A = -1$ are assumed upstream of the forward and reverse shocks respectively, where Alfvén waves are generated by the cosmic ray streaming instability and propagate in the corresponding directions. The damping of these waves heats the gas upstream of the shocks, McKenzie & Voelk (1982), which is described by the last term in Eq. (3) and limits the total compression ratios by a number close to 6. In addition, we use the value $\xi_A = -1$ downstream of the shocks because the cosmic ray gradient is positive in this region. The Alfvén drift here strongly influences the slope of the particle momentum spectrum, since magnetic fields are compressed downstream of the shocks, and the gas velocity in the shock frame falls below the sound speed. This leads, in particular, to noticeable steepening of the particle spectrum at the forward shock, see Paper I.

The two last terms in Eq. (4) correspond to the injection of thermal protons with momenta $p = p_f$, $p = p_b$ and mass m at the fronts of the forward and reverse shocks at $r = R_f(t)$ and $r = R_b(t)$, respectively. The indexes f and b are used for quantities corresponding to the forward and reverse shock respectively. The dimensionless parameters η^f and η^b determine the injection efficiency. The magnetic energy density is relatively small, so it does not appear explicitly in Eq. (2).

Shocked ejecta and interstellar gas are separated by the contact discontinuity at $r = R_c$. The spatial dependence of the magnetic field at $r > R_c$ is taken in the form

$$B(r, t) = \sqrt{\frac{4\pi}{\rho_0} \frac{\rho \dot{R}_f}{M_A}} \sqrt{1 + (M_A V_{A0} / \dot{R}_f)^2}, \quad r > R_c, \quad (5)$$

where ρ_0 is the gas density of the circumstellar medium, V_{A0} is the Alfvén velocity there, and M_A is some constant. We employ the results of Völk et al. (2005) in analysis of X-ray radiation from young SNRs, and we assume that magnetic energy density $B^2/8\pi$ downstream of the shock is 3.5% of the ram pressure $\rho_0 \dot{R}_f^2$ that determines the constant $M_A = 23$. According to Eq.(5) the far upstream energy density of the amplified magnetic field is a small $0.5/M_A^2$ part of the ram pressure. Note that this relation is consistent with modelling of the cosmic ray streaming instability in young SNRs (Zirakashvili & Ptuskin 2008). We assume that the magnetic field is compressed in accordance with plasma density upstream and downstream of the forward shock. We also assume that there is no decay of the magnetic field in the downstream region. The magnetic amplification is weak in old remnants with the forward shock speed $\dot{R}_f < M_A V_{A0}$. The magnetic field strength B is close to the interstellar value B_0 in these SNRs (see Eq. (5)). We assume that the magnetic field does not depend on radius downstream of the reverse shock at $R_b < r < R_c$, but depends on **density** similarly to Eq. (5) upstream of the reverse shock, $r < R_b$.

The diffusion coefficient is of the form

$$D = \kappa D_B. \quad (6)$$

Here $D_B = vpc/(3ZeB)$ is the so called Bohm diffusion coefficient for particles of charge Ze and velocity v (c is the speed of light). The function $\kappa = (1 + (M_A V_{A0} / \dot{R}_f)^2)^3$ at $r > R_c$ and $\kappa = 3$ at $r < R_c$ approximates the dependence of the diffusion coefficient on shock velocity. It corresponds to the case when the MHD turbulence in the shock vicinity is amplified by cosmic ray streaming instability, which is balanced by the Kolmogorov-type

nonlinearity, see Ptuskin & Zirakashvili (2005) and Paper II for details. We assume that the diffusion coefficient is close to its Bohm limit in young SNRs when the shock velocity exceeds ~ 700 km/s. This slightly underestimates the diffusion coefficient of particles at the very end of the energy spectrum. This is because these particles are scattered by small-scale magnetic inhomogeneities generated by the non-resonant streaming instability and their diffusion coefficient is several times higher than the Bohm diffusion coefficient (Zirakashvili & Ptuskin 2008). The value of D grows with time because the wave generation is becoming less efficient as the shock velocity is decreasing.

The equation for ions is similar to Eq. (4). For ions with mass number A and mass $M = Am$, it is convenient to use the momentum per nucleon p and the normalization of the ion spectra N_i to the nucleon number density. Then, the number density of ions n_i is $n_i = 4\pi A^{-1} \int p^2 dp N_i$. The ion pressure $P_i = 4\pi \int p^2 dp v p N_i / 3$ is also taken into account in the total cosmic ray pressure P_c .

The numerical procedure we use to solve Eqs. (1)-(4) was described in detail in Paper II. A finite-difference method is employed to Eqs. (1)-(4) upstream and downstream of the forward and reverse shocks. A non-uniform numerical grid upstream of the shocks at $r > R_f$ and $r < R_b$ allows to resolve small scales of hydrodynamical quantities resulting from the pressure gradient of low-energy cosmic rays. The gases compressed at the forward and reverse shocks are separated by a contact discontinuity at $r = R_c$ between the shocks. An explicit conservative TVD scheme for hydrodynamical equations (1)-(3) and uniform spatial grid are used between the shocks.

3. Spectra of cosmic rays produced by supernova remnants

To demonstrate a possible effect of acceleration by reverse shocks on cosmic-ray composition, we make calculations for two classes of supernovae: Type I where Hydrogen is absent in the outer layers of ejecta and Type II where Hydrogen strongly prevails. The relative rates of these types of supernovae in the Galaxy are 0.46 and 0.54 respectively (Smith et al. 2011). The following characteristics of Type Ia and Type IIP SNRs as representative of these two classes of supernovae are accepted in the calculations.

Type Ia SNRs have kinetic energy of explosion $E = 10^{51}$ erg, number density of the surrounding interstellar gas $n = 0.1 \text{ cm}^{-3}$, and mass of ejecta $M_{\text{ej}} = 1.4M_{\odot}$. Also important for accurate calculations is the index k , which describes the power law density profile $\rho_s \propto r^{-k}$ of the outer part of the star that freely expands after supernova explosions; $k = 7$ for Type Ia supernova. Type IIP SNRs have parameters $E = 10^{51}$ erg, $n = 0.1 \text{ cm}^{-3}$, $M_{\text{ej}} = 8M_{\odot}$, and $k = 12$.

Fig.1 shows the overall spectra of relativistic nuclei produced in Type Ia and Type IIP SNRs during 10^5 years of their evolution by forward (solid lines) and reverse (dash lines) shocks. It is assumed for illustration that the interstellar medium and the ejecta of Type II SNRs consist of protons; the ejecta of Type I SNRs consist of nuclei with the mass number A ($A > 1$) and the charge $Z = A/2$. The accepted value of the interstellar magnetic field is $5\mu\text{G}$. The pressure of accelerated particles modify the profiles of forward and reverse shocks that leads to the concave spectra of cosmic rays. The plotted function is defined as $Q(p) = 4\pi p^2 F(p)$, where $F(p)$ is the distribution of all accelerated nucleons injected in the interstellar medium over the SNR lifetime. The total number of accelerated nucleons is $\int Q(p) dp$. The procedure for calculating SNR evolution and simultaneous cosmic-ray acceleration was described in-depth in Paper II. One can also find there the plots that show the calculated profiles of the gas density, velocity and pressure, and the cosmic ray pressure

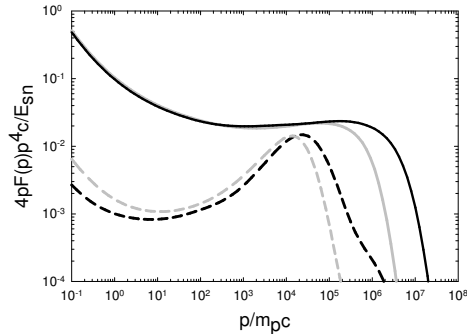


Fig. 1.— Spectra of nucleons produced during SNR lifetime by forward (solid lines) and reverse shocks (dash lines) in Type I (black lines) and Type II (gray lines) SNRs as functions of momentum per nucleon p . The case is shown when only protons are accelerated by forward shocks in the interstellar medium and by the reverse shocks in Type II SNRs whereas only nuclei with mass to charge ratio $A/Z = 2$ are accelerated by the reverse shocks in Type I SNRs.

in evolving SNRs.

The spectra of particles accelerated at reverse shocks are harder than the spectra at forward shocks, in spite of the same level of the shock modification for both shocks. This is because the shocks propagate in the media with different properties. When the reverse shock reaches the flat part of the ejecta density distribution it propagates in the medium density which is decreasing with time. That is why the number of freshly injected ions is low in comparison with higher energy particles accelerated earlier, thereby leaving to spectral hardening. This effect is absent at the forward shock propagating in the medium with constant density.

Particles accelerated in the numerous SNRs are injected into interstellar space, diffuse in galactic magnetic fields, interact with interstellar gas, and finally escape through the

cosmic ray halo boundaries into intergalactic space, where cosmic ray density is negligible. We employ the plain diffusion model with a flat cosmic ray halo (Ginzburg & Ptuskin 1976; Strong et al. 2007) for calculations of cosmic ray propagation in the Galaxy. The leaky-box approximation to the diffusion model can be used for our purpose - the determination of proton and helium intensities, see Ptuskin et al. (2009). The cosmic ray intensity obeys the relation $I \propto \nu_{\text{sn}} Q (X_e^{-1} + \sigma/m_a)^{-1}$, where X_e is the escape length (the average matter thickness traversed by cosmic rays before they exit from the Galaxy), σ is the nuclear spallation cross section for a given type of relativistic nuclei moving through the interstellar gas, and m_a is the mean interstellar atom mass. The escape length is determined from the relative abundance of secondary nuclei (primarily from the Boron-to-Carbon ratio) in cosmic rays. The approximation formula $X_e = 19\beta^3 \text{ g/cm}^2$ at $R \leq 3 \text{ GV}$ and $X_e = 19\beta^3(R/3\text{GV})^{-0.6} \text{ g/cm}^2$ at $R > 3 \text{ GV}$ was given in Ptuskin et al. (2009) (here R is the particle magnetic rigidity; $\beta = v/c$). According to the last equation, the resulting spectrum is steeper than the source spectrum by 0.6 at high enough energies, but the uncertainty in the last value is about 0.1, and statistically accurate measurements of the Boron-to-Carbon ratio are not available at energies above $\sim 30 \text{ GeV/nucleon}$. In the present calculations we assume the dependence $X_e \propto R^{-0.7}$ at $R > 3 \text{ GV}$ up to rigidity $\sim 10^6 \text{ GV}$. It corresponds to dependence of the cosmic-ray diffusion coefficient on rigidity in the interstellar medium $D_{ISM} \propto R^{0.7}$ at relativistic energies.

The interstellar proton and helium cosmic-ray spectra determined in the framework of this propagation model, and use the source functions calculated as described above, are presented in Fig.2. It is assumed that the reverse shocks accelerate only hydrogen nuclei in Type II SNRs and only helium nuclei in 65% of all Type I SNRs; the reminding 35% are Type Ic SNRs, which do not have significant amounts of hydrogen and helium in their ejecta. The forward shocks produced by Type I and Type II supernovae propagating through the interstellar gas of standard composition with the relative injection efficiency

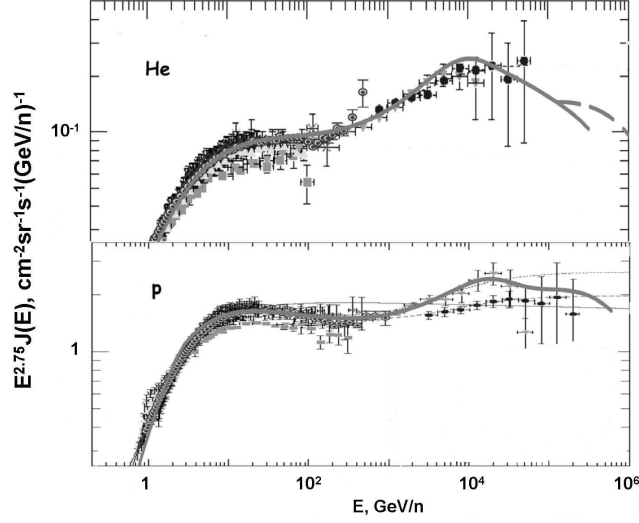


Fig. 2.— Calculated interstellar spectra of protons and helium are shown by thick gray lines. Data of the BESS, CAPRICE, AMS-01, ATIC-2 and CREAM experiments corrected for solar modulation effects are taken from the review of Lavalley (2011), where the corresponding references and detailed description of observations can be found. The PAMELA experiment data are taken from the paper Adriani et al. (2011) and corrected for solar modulation.

of hydrogen and helium ions at the forward shocks is chosen to fit the observed He/p ratio at the 100 GeV/nucleon reference energy. The shock acceleration of background particles with different elemental composition leads to the difference in the overall proton and helium spectra seen in Fig.2. The forward shock in Type Ib/c SNRs (59% of all Type I SNRs) moves through the helium wind of the progenitor Wolf-Rayet star, the last stage of a progenitor star evolution for these supernovae, that enriches cosmic rays in helium at energies above approximately 10^5 GeV/n. The possible contribution of this process is shown by dash line in Fig.2.

The calculated spectra in Fig.2 exhibit hardening at ~ 240 GV and reproduce the

energy dependent He-to-proton ratio in fair agreement with observations. Thus, the explanation of these features in terms of acceleration of cosmic rays in SNRs by forward and reverse modified shocks seems quite possible.

4. Discussion and conclusion

The processes of cosmic-ray acceleration by supernova shocks and subsequent diffusion in the interstellar magnetic fields at relativistic energy depend on particle Larmor radius so the spectra of different ions might be expected to have similar shapes when expressed as functions of particle magnetic rigidity. However, the data of ATIC-2 (Panov et al. 2009), CREAM (Ahn et al. 2010; Yoon et al. 2011) and PAMELA (Adriani et al. 2011) experiments showed that the He/p ratio is changing with energy at 10 to 10^5 GeV/n. Also, the spectra of these ions demonstrate deviations from the plain power laws with hardening at about 240 GV. Thus, modern statistically accurate measurements confront the traditional power-law paradigm for the source spectrum and escape length of Galactic cosmic rays below the knee. A number of possible explanations of these experimental results were proposed in the papers cited in the Introduction, but a clear picture does not yet emerge.

In the present paper, the interpretation of both features (spectral hardening and changing of the He/p ratio) is provided in the framework of our model of cosmic ray acceleration by SNR shocks developed in Papers I and II (the first version of this work was presented in the conference paper Ptuskin et al. (2011)). The hardening of cosmic ray spectrum results mainly from modification of gas flow in the shock precursor by the cosmic ray pressure, which shapes the concave energy spectrum of cosmic rays. This effect is well known in the theory of diffusive shock acceleration, see e.g. early papers Ellison & Eichler (1985); Berezhko et al. (1994). It manifests itself here in the presence of Alfvén drift of

accelerated particles and the strong dependence of cosmic-ray diffusion on shock velocity as a pronounced hardening at rigidity ~ 240 GV in the overall spectrum of accelerated particles produced by SNRs. The account of particle acceleration by a reverse shock moving through the supernova ejecta results in the production of an additional component of cosmic rays that has a specific hard energy spectrum and is depleted in hydrogen composition. This makes hardening of the overall cosmic ray spectrum more pronounced, and it produces the difference between hydrogen and helium spectra.

The results of our calculations of the interstellar spectra of cosmic-ray hydrogen and helium shown in Fig. 2 demonstrate good agreement with observations. It is assumed that reverse shocks accelerate only protons in Type II SNRs and only helium nuclei in Type I SNRs. Forward shocks accelerate interstellar protons and helium nuclei in both cases.

Clearly more work is needed and planned to establish the adequacy of the suggested scenario. This refers both to the detailed analysis of the dispersion properties of SNRs (the SN explosion energy, the mass and complex composition of ejecta, the structure of circumstellar medium, etc.) and assumptions about the process of particle acceleration (the value of M_A , the parametrization of diffusion coefficient, etc.). Also, a single power-law dependence of cosmic-ray diffusion in the interstellar magnetic fields on rigidity, $D_{ISM} \propto vR^{0.7}$, used in the present calculations in the entire range of rigidities from 10 to 10^6 GV is most probably a significant oversimplification. The explanation of low anisotropy of Galactic cosmic rays seems incompatible with such a strong dependence of diffusion on rigidity (Ptuskin et al. 2006; Blasi & Amato 2012).

In principle, the last difficulty could be relieved by increasing M_A from its $M_A = 23$ value taken from Paper I and accepted in the present calculations. This would lead to a steeper source spectrum and require weaker dependence of interstellar diffusion on rigidity to fit the observations of cosmic ray spectra. Another possibility is a possible suppression

of cosmic-ray anisotropy in the Local Bubble with enhanced turbulence where the Solar system resides, Zirakashvili (2005).

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