Cosmic Ray Acceleration beyond the Knee up to the Ankle in the Galactic Wind Halo

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Abstract. Reacceleration of cosmic rays produced by galactic sources in the galactic wind flow is considered. The particles can be reaccelerated by the shocks propagating in the galactic wind flow and at the termination shock. The problem of the cosmic ray spectrum continuity is investigated. Numeric results are presented and discussed. Applications are given for an explanation of the cosmic ray spectrum beyond the "knee".

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1. Introduction

The existence of a Galactic Wind driven by cosmic rays (CR) in our Galaxy has been discussed extensively in recent years [10, 5, 6, 7, 23]. Cosmic ray sources in the galactic disk produce energetic particles which can not freely escape from the Galaxy but rather amplify Alfvén waves (see e.g. [22]). Such waves lead to an efficient coupling of the thermal gas to energetic particles [17], and pressure gradient of cosmic rays drive a Galactic Wind flow. Typically, the gas flow becomes supersonic at distances of about 30 kpc. This radially directed flow should terminate in a so-called termination shock at distances of several hundreds kpc. It was recognized quite a while ago that this shock may reaccelerate cosmic ray particles [11, 12]. However this idea faces two problems. The first one is the difficulty of observation of accelerated particles in the Galaxy. In fact the condition of efficient acceleration coincides with the condition of strong modulation of particles in the Galactic Wind flow. The second problem arises because near the termination shock the number density of CRs that were produced in the inner Galaxy is expected to be small in comparison with the actual CR number density in the inner Galaxy. All this means that one cannot expect continuity of the CR spectrum between the reaccelerated particles and those produced by the disk sources.

The second problem is avoided in the self-consistent model of CR propagation in the Galactic Wind [17]. CR particles with energies in the neighborhood of 10^{15} eV have approximately the same Galactic CR number density everywhere in a huge halo with radius 100 kpc in this model. This size is not small compared to the distance to the termination shock. In fact, particles which are reaccelerated in this extended halo by multiple interactions with so-called slipping interaction region (SIR) shocks [21] that propagate from the disk towards the termination shock, can for the same reason also be observed in the disk with essentially the same intensity as in their production region. And this is an attractive reacceleration mechanism to produce the observed

CRs beyond the so-called knee at several $\times 10^{15}$ eV to the so-called ankle at a few $\times 10^{18}$ eV total energy as demonstrated recently by Völk and Zirakashvili [21].

Nevertheless, we should not dismiss the possibility of reacceleration at the termination shock completely. It may play a rôle in a very different parameter regime.

If we however concentrate on the possibility of reacceleration on the termination shock, the first problem is unavoidable, and the CR spectrum should be discontinuous.

As we shall show below, this is indeed the case if the maximum energy of accelerated particles is the same at different parts of the termination shock. However, one can expect that the Galactic Wind flow originating from small galactocentric radii in the disk should be more powerful and more turbulent in comparison with the flow originating from larger radii. The distance to the termination shock will be correspondingly larger, and the cosmic ray diffusion coefficient will be smaller at small galactic colatitudes. The maximum energy of particles, accelerated at termination shock, will be larger near the poles in that case. We shall show in this paper that it is possible to obtain spectral continuity if the maximum energy varies from the "knee" value $3{\cdot}10^{15}Z$ eV at the Galactic equator to about $10^{17}Z$ eV at the Galactic pole. Here Z is the nuclear charge number of particles. The "knee" energy is presumably the maximum energy for Galactic CR sources in the Galactic disk. This value can be larger than estimated earlier [14, 19, 1] if the magnetic field strength at supernova shocks substantially exceeds the typical interstellar values of several μG. Such high field configurations might be unusually strong stellar fields in the winds of very massive stars [3, 20, 4], or the strong Alfvénic wave turbulence excited at strong shock waves, as speculated by Völk [18] and recently calculated in a simplified nonlinear model by Lucek and Bell [15] and Bell and Lucek [2].

2. Energetic constraints

Let us assume that our Galaxy is surrounded by a Galactic Wind with radial velocity u. The energy input rate necessary for such a flow is

$$\dot{\epsilon} = 2\pi\rho r^2 u^3 \ . \tag{1}$$

Here ρ is the gas density at the radial distance r in the Galactic Wind. The distance to the termination shock R_s can be found from the condition $\rho u^2 \sim P_{IG}$, where P_{IG} is the intergalactic pressure. Using Eq. (1) we obtain

$$R_s = \sqrt{\frac{\dot{\epsilon}}{2\pi P_{IG} u}} = 180 \text{ kpc} \left(\frac{\dot{\epsilon}}{10^{41}\text{erg s}^{-1}}\right)^{1/2} \left(\frac{10^{-15}\text{erg cm}^{-3}}{P_{IG}}\right)^{1/2} \left(\frac{500\text{km s}^{-1}}{u}\right)^{1/2} \tag{2}$$

The magnetic field is almost azimuthal at large distances in the Galactic Wind flow and its strength is given by Parker's formula [16]

$$B \approx B_{\mathrm{g}} \frac{R_{\mathrm{g}}^2 \Omega(\theta) \sin\theta}{ru}, \tag{3}$$

where B_{g} is the poloidal field strength at galactocentric distance $r = R_{\mathrm{g}}$ where R_g is the Galactic radius, $\Omega(\theta)$ is the angular velocity of the Galactic rotation and θ is the galactic colatitude. Using this equation one can find the magnetic Mach number in the galactic wind flow M_a:

$$M_a = \frac{u}{v_a} = \frac{\sqrt{2\dot{\epsilon}u}}{B_g \Omega R_g^2 \sin\theta} = \frac{1.6}{\sin\theta}\left(\frac{\dot{\epsilon}}{10^{41}\text{erg s}^{-1}}\right)^{1/2} \times$$
$$\left(\frac{5\times 10^{-16}\text{s}^{-1}}{\Omega(\theta)}\right)\left(\frac{u}{500\text{km s}^{-1}}\right)^{1/2}\left(\frac{2\mu\text{G}}{B_g}\right)\left(\frac{15 \text{ kpc}}{R_{\mathrm{g}}}\right)^2 \tag{4}$$

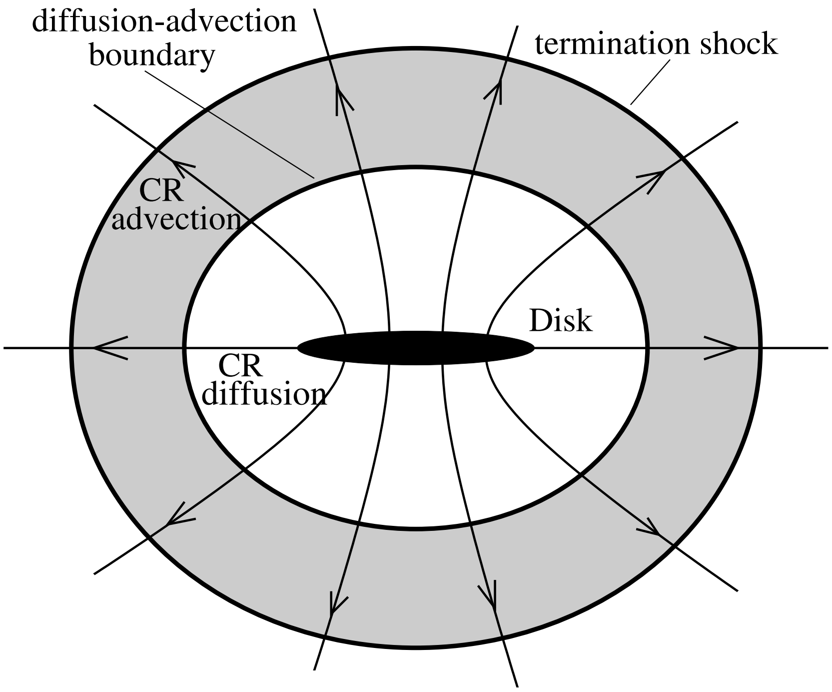

Figure 1. Meridional cross-section of the Galactic Wind flow. The direction of the gas velocity is shown by the arrows. The supersonic gas flow is bounded by the termination shock. CR transport is mainly diffusive inside the diffusion-advection boundary; outside this boundary it is determined by convection in the gas flow (in the dashed region). The galactic disk is indicated by the black ellipse.

This value should be large enough for the termination shock to be strong. Since the Galactic Wind is mainly driven by cosmic rays, $\dot{\epsilon}$ should be of the order of the galactic CR sources power that hardly exceed 5×10^{41} erg s^{-1}. Strictly speaking it should be smaller because a part of that energy is "lost" in the Galactic gravitational field (the escape velocity is comparable with u). However, the Galactic Wind flow can be partially centrifugally driven if B_g is larger then 1 μG (Zirakashvili et al. 1996). In this case some part of the kinetic energy of the Galactic Wind is supplied by the Galactic rotation.

3. Cosmic ray propagation in the Galactic Wind flow

A schematic picture of the Galactic Wind flow geometry is given in Fig.1. The azimuthally symmetric flow originates in the Galactic disk and extends the frozen-in magnetic field. At small heights above the disk the gas velocity is perpendicular to the galactic disk. The flow is approximately radial at large distances from the Galaxy. The gas is assumed to be fully ionized in the wind, supporting magnetohydrodynamic waves. These may also be resonantly excited by the anisotropic streaming of the CR component. Their amplitudes will ultimately be limited by damping through nonlinear wave-particle interactions.

Cosmic ray transport in the Galactic Wind is strongly affected by the properties of the magnetic field. Since the average poloidal magnetic field component is weak in our Galaxy [9], we shall assume that the Galactic Wind streams originating from different parts of the Galactic disk drag out the magnetic field together with closed magnetic loops with sizes of the order 1 kpc. These magnetic disturbances become strongly elongated at large distances from the Galaxy due to the acceleration and spherical expansion of the Galactic Wind flow [25]. Hence, the distant wind is filled by almost azimuthal, sign-dependent magnetic fields. But Parker's formula (3) and similar expressions remain valid. CR diffusion in such a field should be very anisotropic. Random drift motions and wandering of magnetic field lines would produce an anomalous transport across magnetic lines that is disregarded in this paper.

In the following we shall use the self-consistent model of cosmic ray propagation in the Galactic Wind flow [17]. Cosmic ray diffusion is considered along field lines alone. The parallel diffusion coefficient $D_{||}$ is determined by Alfvén waves generated by the cosmic ray streaming instability. Its value does not depend on distance and is given by [17]

$$D_{||} = 10^{26} \div 10^{27} \frac{p}{Zm_p c} \text{ cm}^2\text{s}^{-1} \tag{5}$$

Here p is the momentum of particles, m_p is the proton mass. The numerical factor in Eq. (5) is inversely proportional to the Galactic CR power. It is not exactly known because uncertain characteristics of the nonlinear damping of Alfvén waves propagating in a one direction [24]. In addition, the strong CR gradient near the termination shock can result in even weaker diffusion. This requires a special investigation that is beyond the scope of this paper. We shall use a simplified approach here and consider the CR diffusion coefficient (5) as a free parameter.

Assuming azimuthal symmetry the isotropic part of a CR distribution function $N(r, \theta, p, t)$ evolves according to the following equation

$$\frac{\partial N}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D_{||} \cos^2\alpha \frac{\partial N}{\partial r} - u\frac{\partial N}{\partial r} + \frac{2up}{3r}\frac{\partial N}{\partial p} + \hat{R}N + Q(p)\frac{\delta(r-R_g)}{4\pi R_g^2} \tag{6}$$

Here α is the angle between the magnetic field and the radial direction, and $Q(p)$ describes the source of CR particles at the radial distance $r = R_g$=15 kpc from the galactic center. The CR distribution function N is normalized in the form $n = 4\pi \int p^2 dp N$, where n is the CR number density. It was assumed that the Galactic Wind flow is radial and that the Galactic Wind velocity u is constant. The linear operator $\hat{R}$ describes the cosmic ray reacceleration by SIR shocks (see Sect.6). The value of $\cos\alpha$ in the radial Galactic Wind flow is given by [16]

$$\cos\alpha = \frac{u}{\sqrt{\Omega^2 r^2 \sin^2\theta + u^2}}. \tag{7}$$

The Galactic Wind flow is bounded by the termination shock at the distance $R_s(\theta)$ that depends on the galactic colatitude θ. It might be partially smoothed due to the Galactic CR pressure. One has to expect that the termination shock creates strong MHD turbulence downstream, towards intergalactic space. CR diffusion is strongly reduced in this case and should be close to the Bohm limit. This holds up to a maximum particle rigidity that is determined by the condition $D_{\rm B} \sim uR_{\rm s}$ where $D_{\rm B} = vr_{\rm g}/3$ is the Bohm diffusion coefficient of particles with gyroradius $r_{\rm g}$ and velocity v. Its numerical value is determined by the local magnetic field strength. At large distances in the radial Galactic Wind flow the magnetic field strength is given by Eq. (3). Then, the estimate gives the following maximum energy

$$E_{\rm max} = Z\sin\theta \left(\frac{\Omega(\theta)}{5\times 10^{-16}\text{s}^{-1}}\right)\left(\frac{B_{\rm g}}{2\mu\text{G}}\right)\left(\frac{R_{\rm g}}{15\text{kpc}}\right)^2 0.6\cdot 10^{17}\text{eV}, \tag{8}$$

We should note that this energy is not small for small θ because the angular velocity of the galactic rotation Ω increases toward the galactic center. Higher energy particles cross the termination shock diffusively. We shall disregard CR diffusion beyond the termination shock.

The boundary condition at the termination shock is given by the continuity of N and of the flux density:

$$\left.\left(D_{||}\cos^2\alpha\frac{\partial N}{\partial r} + u\left(1-\frac{1}{\sigma}\right)\frac{p}{3}\frac{\partial N}{\partial p}\right)\right|_{r=R_{\rm s}(\theta)} = 0. \tag{9}$$

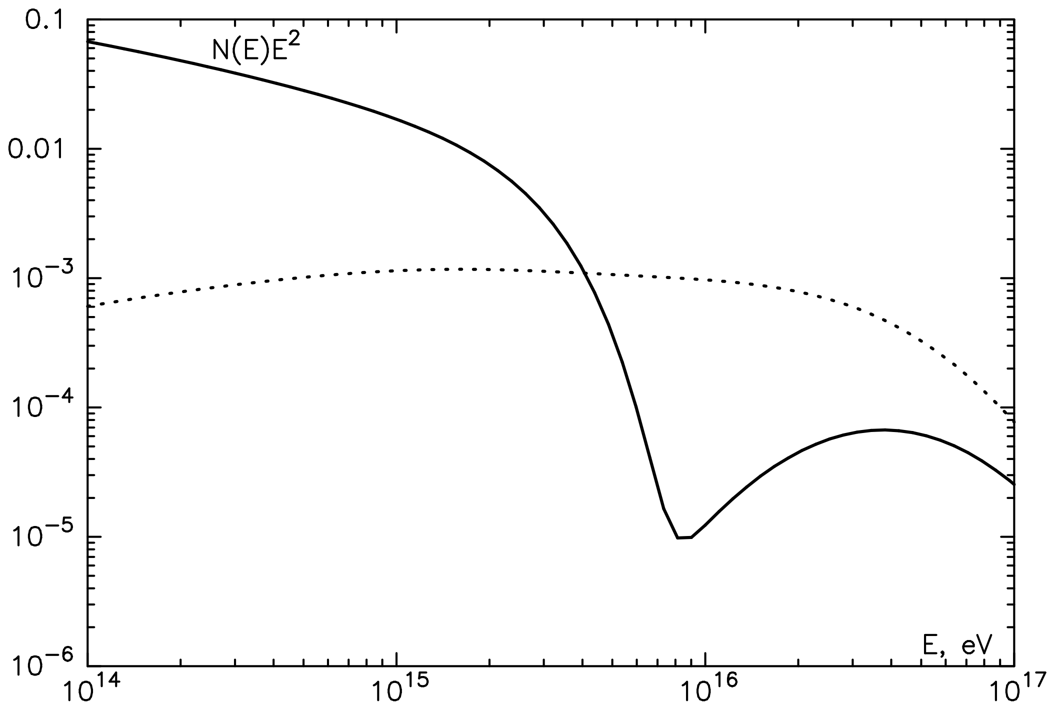

Figure 2. Spectral energy distributions (in arbitrary units) of the CR protons in the Galaxy (solid curve) and at the spherical termination shock (dotted curve).

Here σ is the termination shock compression ratio.

CR diffusion in latitude direction is disregarded in Eq. (6). However, we shall assume that CR particles from different flux tubes are mixed near and in the Galaxy. This means that the CR distribution is independent of colatitude at the inner boundary at $r = R_g$. Particles that were accelerated at one part of the termination shock can return to the Galaxy and reach another part of termination shock in this case.

4. Numerical results. The case without reacceleration by SIR shocks.

We obtained a steady-state numerical solution of Eq. (6) for a wind velocity $u = 500$ km s^{-1} and a termination shock compression ratio $\sigma = 4$. This relatively large compression ratio is possible even for magnetic Mach number $M_a \sim 3$ since the termination shock should be partially smoothed due to presence of relativistic small energy cosmic rays which have adiabatic index 4/3. The angular velocity of galactic rotation was taken as $\Omega(\theta) = 0.5 \cdot 10^{-15}/\sin\theta$ s^{-1}. We used the following spectrum of galactic CR sources $Q(p) \sim p^{-\gamma_d}\exp(-p^2/p^2_{\max})$, where γ_d is the power-law index of the CR sources. The value $\gamma_d = 4.0$ was used. The value of the maximum momentum of Galactic CR source particles $p_{\max}$ was taken as $p_{\max} = 3 \cdot 10^6 Zm_pc$.

For a numeric solution of Eq. (6) we used an implicit finite-difference scheme with a non-uniform grid. The grid steps were taken smaller near the termination shock and close to the Galaxy.

The results obtained for a spherical termination shock at distance $R_s = 300$ kpc and diffusion coefficient $D_{\|} = 2.5 \cdot 10^{25} p/(Zm_pc)$ are shown in Fig.2. The CR spectral energy distribution (SED) at energies smaller then 3×10^{15} eV is formed in the Galactic Wind flow as a result of the interplay of diffusion and advection [17]. At larger energies, particles appear that were

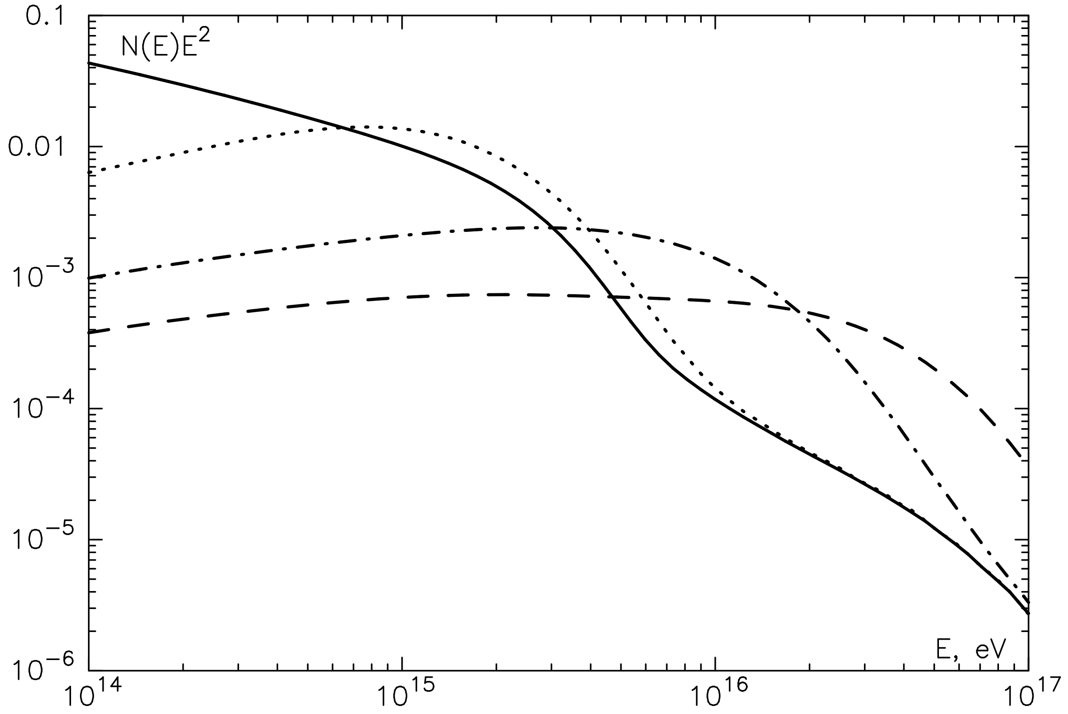

Figure 3. Spectral energy distributions (in arbitrary units) of the CR protons in the Galaxy (solid curve) and at different colatitudes of the non-spherical termination shock: $\theta = 0$ (dashed curve), $\theta = \pi/4$ (dash-dotted curve), $\theta = \pi/2$ (dotted curve).

reaccelerated at the termination shock. However, the SED is not continuous in the Galaxy for this case. It simple to see that the particles with maximum energy are not strongly modulated in the Galactic Wind flow. Hence one can expect that a non-spherical termination shock with different maximum energies at different colatitudes may provide a more continuous spectrum.

The numerical results for a non-spherical termination shock are shown in Fig.3. The termination shock shape and the dependence of the CR diffusion coefficient on latitude were taken as

$$R_s(\theta) = 150\sqrt{(1 + 3\cos^2\theta)} \text{ kpc} \tag{10}$$

$$D_{||} = 10^{26}\frac{p/(Zm_pc)}{(1 + 3\cos^2\theta)} \text{ cm}^2\text{s}^{-1} \tag{11}$$

It is simple to see that the SED is continuous in the Galaxy.

5. Spiral structure of our Galaxy, wind shocks.

Since potential CR sources in the disk are primarily concentrated in the spiral arms, we can assume that the CR pressure in and above the spiral arms is larger than between the arms. Hence, the CR-driven Galactic Wind flow should be modulated by the spiral structure. The situation differs from the Solar Wind case because of the relatively fast rotation of the Galaxy. Indeed, the Galactic Wind flow time to the (magneto)sonic point is about 100 million years and is comparable with the period of Galactic rotation. This means that the modulation by the spiral pattern should produce magnetosonic waves, propagating in the Galactic Wind flow. At large distance from the Galaxy these spiral compression waves propagate in the radial direction and approximately perpendicular to the wind magnetic field which is by then practically azimuthal. The radial and azimuthal wavenumbers for these waves are

$$k_r = \frac{\Omega_{\rm p} m}{u_{\rm s}}, k_\phi = \frac{m}{r}, \tag{12}$$

where Ω_p is the angular velocity of the spiral pattern, m is the number of spiral arms and $u_{\rm s}$ is the radial velocity of the wave. This value is approximately the sum of the wind velocity u and the phase velocity of the fast magnetosonic waves $c_{\rm f}$ traveling in the radial direction. At large distances we simply have

$$c_{\rm f} = \sqrt{V_{\rm a}^2 + c_{\rm s}^2}$$

where $V_{\rm a}$ and $c_{\rm s}$ are the Alfvén and the sound velocity, respectively.

The nonlinear steepening of magnetosonic waves can produce a train of forward shocks at large Galactocentric distances. The characteristic distance can be found from the following estimate. The inverse steepening time is $k_r \delta u$, where δu is the velocity perturbation in the wave. During this time the wave propagates the distance $\delta r \sim (u + c_{\rm f})/(k_r \delta u)$. Using the expression for the radial wave number we obtain

$$\delta r \sim \frac{(u + c_{\rm f})^2}{m \Omega_{\rm p} \delta u}$$

For $u + c_{\rm f} \sim$400 km s^{-1} , $\delta u \sim$ 50 km s^{-1} , $\Omega_{\rm p} = 30$ km s^{-1} kpc^{-1} [8] and $m = 2$, δr is about 50 kpc. The velocity perturbation δu is half of the velocity jump at the shock formed. We therefore conclude that spiral shock formation is possible at distances of 50 to 100 kpc.

The results of numerical calculations of SIR shocks [21] are shown in Fig.4. One can see that SIR shocks with a velocity jump of the order 100 km s^{-1} are formed at distances exceeding 50 kpc. These SIR shocks form a saw-tooth wave velocity profile. The compression ratio $\sigma_{\rm s}$ of these shocks is about 2.0. In the sequel we shall call the entire saw-tooth wave the "SIR shock system". These spiral shocks should not be confused with the spiral density wave in the Galactic disk. The radial dependence of the spiral density wave in the Galactic disk will be transformed into a latitude dependence of the spiral shocks in the Galactic Wind flow (see Fig.1).

We should underline that the shocks in the Galactic Wind have two distinct features in comparison with the Solar Wind.

First of all the shock structure is stationary in the frame of reference corotating with the spiral pattern. Material Galactic rotation still exists in this frame except at special Galactocentric radii. Therefore these shocks are not in corotation with the matter in the Galactic disk but rather slip through it and this is why we called them SIR shocks.

The second feature is the absence of backward SIR shocks. Outward moving large-amplitude periodic waves steepen into a train of shocks (saw-tooth wave), where forward shocks are followed by rarefaction waves, like in a gas at rest.

6. Reacceleration by SIR shocks

The cosmic ray reacceleration by SIR shocks is described by the linear operator $\hat{R}$ [21]:

$$\hat{R}N = \frac{\Delta u}{L} \left(\frac{p}{3} \frac{\partial N}{\partial p} - \frac{1}{\ln \sigma_{\rm s}} \int_0^p \frac{dp'}{p'} \left(\frac{p'}{p} \right)^{\gamma_{\rm s}} \frac{N(p') - N(p)}{\ln(p'/p)} \right) \tag{13}$$

It combines the adiabatic energy losses of the particles between the SIR shocks of compression ratio $\sigma_{\rm s}$ with multiple reacceleration at these shock fronts (the first and second terms in the

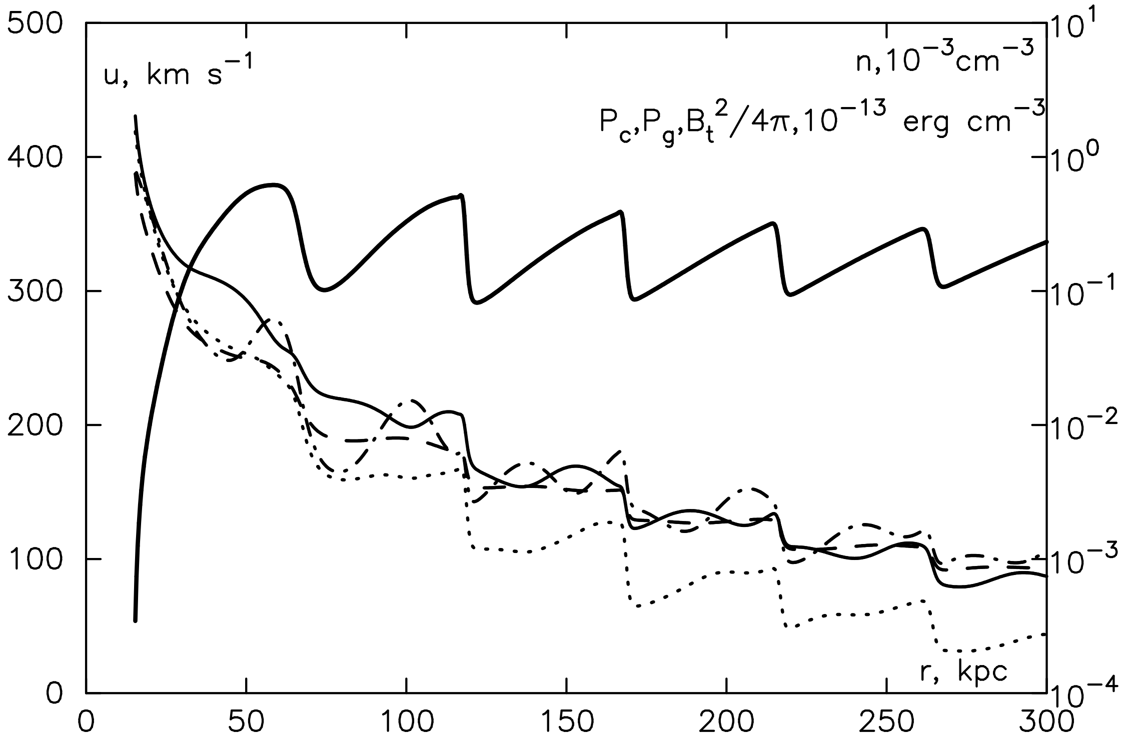

Figure 4. Radial dependencies, taken at one azimuth angle. The values of the radial gas velocity u (thick solid line, in units of km s^{-1}) are given on the left abscissa. The right abscissa shows the values of the cosmic ray and gas pressures $P_{\rm c}$ (thing solid line) and $P_{\rm g}$ (dotted line), respectively (in units of 10^{-13} erg cm^{-3}), the gas number density n (dashed line, in units of 10^{-3}cm^{-3}), and the total magnetic field tension $B_t^2/4\pi$ (dash-dotted line, in units of 10^{-13} erg cm^{-3}). Forward SIR shocks form a saw-tooth velocity profile at large distances in the Galactic Wind flow.

round brackets, respectively). Here L is the distance between shocks and $\gamma_{\rm s} = 3\sigma_{\rm s}/(\sigma_{\rm s} - 1)$ is the single shock spectral index.

The numerical solutions of Eq. (6) was obtained for the Galactic Wind velocity u=300 km s^{-1}, the radius of the spherical termination shock $R_{\rm s}$=300 kpc, $\sigma = 3$, $m = 2$, $u_{\rm s} = 450$ km s^{-1}, $\Delta u = 100$ km s $^{-1}$, $\Omega_{\rm p} = 30$ km s^{-1} kpc^{-1}, $\Omega = 20$ km s $^{-1}$ kpc^{-1}. We also take $\gamma_{\rm s} = 6$ which corresponds to the SIR shock compression ratio $\sigma_{\rm s} = 2$.

Also, a spectral index of galactic CR sources $\gamma_{\rm d} = 4.0$ and a self-consistent cosmic ray diffusion coefficient $D_{\|} = 10^{27} p/(m_{\rm p}c)$ cm^2 s^{-1} independent of r were used. These values approximately correspond to those obtained in the self-consistent model of CR propagation in the Galaxy [17]. The high energy cut-off of galactic CRs was taken as $p_{\rm max} = 3 \cdot 10^6\ Zm_{\rm p}c$.

The differential spectral flux calculated for the different cosmic ray nuclei and the corresponding all-particle spectral flux, as well as the experimental all-particle spectrum measured by the KASCADE collaboration [13], are shown in Fig.5.

7. Discussion

The numerical results obtained in this paper permit us to conclude that the reacceleration of galactic cosmic rays by shocks in the Galactic Wind flow can explain the observable CR spectrum beyond the "knee" energy.

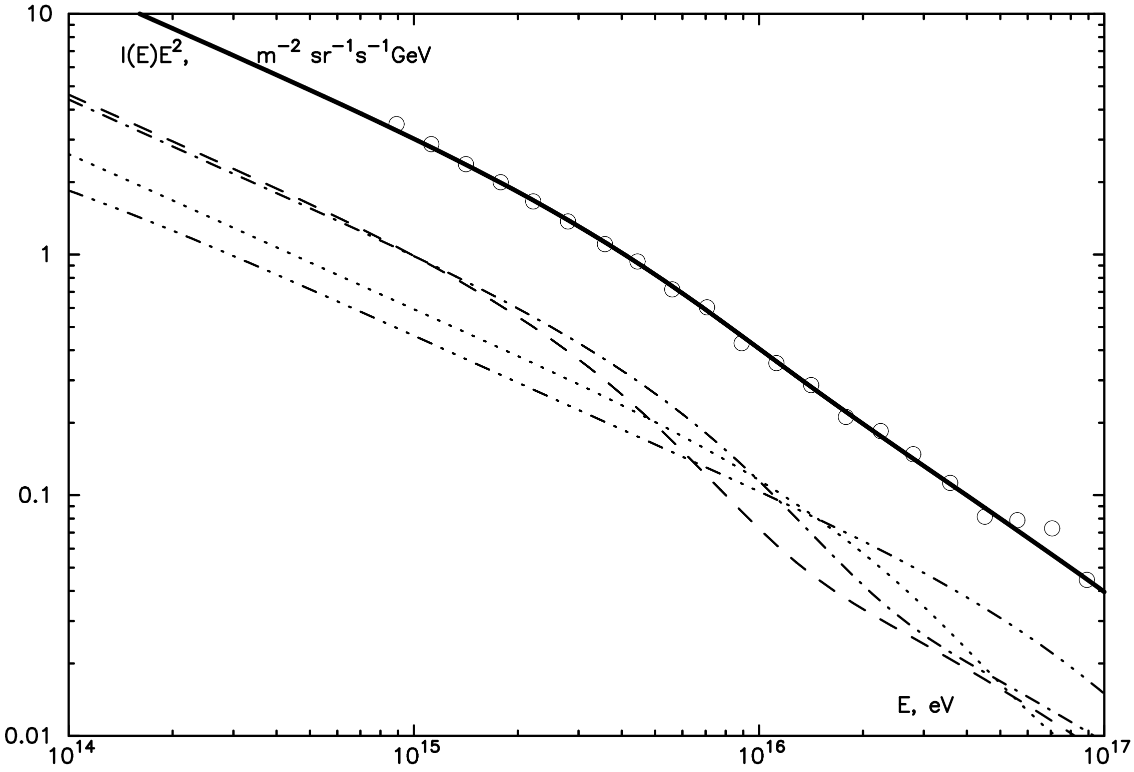

Figure 5. Calculated differential spectral flux $I(E)$ (in units of $\mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$) of the CR protons (dashed curve), helium nuclei (dash-dotted curve), carbon (dotted curve), iron (dash-dot-dotted curve), all-particle (solid curve) in the Galaxy for the exponential cut-off, and the all-particle spectral flux observed by the KASCADE collaboration (empty circles). The chemical composition has been fixed at $E = 9 \cdot 10^{14}$ eV from Fig.5 of Kampert et al. [13]. The data for the all-particle spectrum are also taken from Kampert et al. [13].

We expect that the all-particle spectrum will be continuous even in the case of CR reacceleration on the spherical termination shock. This is because the discontinuity of the proton spectrum in Fig.2 will be smoothed after adding other nuclei.

However, if the preliminary experimental results of the KASCADE collaboration [13] will be confirmed and if the observable spectra of different nuclei are continuous at the "knee", we should prefer the reacceleration on the non-spherical termination shock. It can provide a continuous CR spectrum beyond the "knee" (see Fig.3). This is so because different parts of the termination shock have different maximum energies for the accelerated particles.

We consider this version of CR reacceleration as an alternative possibility of reacceleration at quasi-perpendicular spiral shocks in the Galactic wind flow [21] (see Sect.5,6). It is possible if moderately strong shocks are formed in the Galactic Wind flow. This type of reacceleration will work even for larger values of the parallel diffusion coefficient $D_{\|} \sim 10^{27} p/(Zm_p c)$ cm^2 s^{-1} when the reacceleration at the termination shock is weak. The CR reacceleration at termination shock would be realized in the case of small CR diffusion coefficient and relatively weak spiral shocks in the Galactic Wind flow. The reacceleration on spiral shocks [21] is more important in the case of larger diffusion coefficient and stronger spiral shocks.

The maximum energy in our model is not larger than the energy given by Eq.(8), i.e. it is about 10^{17} eV for CR protons. Iron nuclei have a maximum energy which is a factor of 26 larger.

Higher energy particles should be considered as extragalactic or accelerated downstream from the termination shock.

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