Cosmic Ray Acceleration by Spiral Shocks in the Galactic Wind

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Abstract

The spiral structure of the Galactic disk results in a strong nonuniformity of the Galactic Wind flow and in spiral shock formation at distances of 50 to 100 kpc. It is shown that the collective reacceleration of the cosmic ray particles with charge Ze in the resulting shock ensemble explains the observable cosmic ray spectrum beyond the "knee" up to energies of the order of $10^{17}Z$ eV.

1. Introduction

We propose that CRs from the disk are reaccelerated in the *Galactic Wind* to energies between the knee and the ankle of the observed spectrum. The wind is mainly driven by the CRs and the hot gas generated in the disk [1,2,3,4], reaches supersonic speeds at about 20 kpc above the disk, and is very extended (several 100 kpc) before it ends in a termination shock. Even on a large scale this Galactic Wind must be far from regular in space and time. Due to Galactic rotation the differences in flow speed will lead to strong internal wind compressions, bounded by *smooth CR shocks* [5] in the expanding halo gas because its internal energy density is dominated by that of the CRs from the disk (Disk-CRs). These shocks therefore do not inject and accelerate suprathermal particles, but rather *reaccelerate* the most energetic particles from the disk by about 2 orders of magnitude in rigidity. Re-acceleration essentially ensures the continuity of the energy spectrum at the knee. A fraction of the re-accelerated particles (Wind-CRs) will return to the disk, filling a very thick (several tens of kpc) region including the Galactic mid-plane rather *uniformly and isotropically*. Since at these energies the propagation in the average wind environment is diffusive [4], also their spatial density in the disk is about equal to that of the knee particles.

These Galactic Wind shocks are reminiscent of the so-called Corotating Interaction Regions in the Solar Wind [6]. However, Galactic interaction regions are due to the fact that much of the high-mass star formation in the Galaxy and the associated active regions such as superbubbles and OB-associations, including most of the SNRs, is concentrated in the spiral arms. These rotate relative to

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the interstellar gas in a quasi-stationary wave pattern with a related pattern in wind velocity (see also [7]). Since the magnetic field is rather anchored in the gas, we speak of "Slipping Interaction Regions" (SIRs). In the Parker spiral-type magnetic field structure faster wind streams from more active regions will begin to overtake slower streams after the wind has formed in the upper halo. If the relative flow speed was supersonic, the interaction would lead to a shock pair. However, as long as the flow speed of the wind is still low for a given rotation rate of the wind source region, quasi-periodic magnetosonic compression regions will form that rather lead to a sawtooth series of forward shocks after a steepening time. This distinct situation applies to the Galaxy.

According to the *selfconsistent nonlinear* model of CR propagation in a magnetized Galactic Wind flow [4], the scattering waves are produced by the CR streaming instability above the dense gas disk, and the wave amplitude is determined by nonlinear wave-particle interactions, giving rise to a distance-independent diffusion coefficient $D_{\|}^{\mathrm{s}} \simeq 10^{27}(p/m_p c)^{\gamma_{\mathrm{d}}-3}\mathrm{cm}^2\mathrm{s}^{-1}$ along the increasingly azimuthal magnetic field. Here p is momentum of the particle, m_{p} is the proton mass and $\gamma_{\mathrm{d}} \sim 4$ is the power law index of the momentum distribution of the CR sources in the disk. Advection begins to overpower diffusion at some distance $R_{\mathrm{da}} \propto p^{(\gamma_{\mathrm{d}}-3)/3}$. For the diffusion coefficient mentioned above, and a wind velocity $u = 300$ km s^{-1}, $R_{\mathrm{da}}(1\ \mathrm{TeV}) \approx 15$ kpc, approximately equal to the disk radius. Since it creates a strongly turbulent wave field, the termination shock acts as a reflecting boundary condition on all particles whose propagation characteristics are diffusive. This is roughly true up to a rigidity determined by $D_{\mathrm{B}} \sim uR_{\mathrm{s}}$ where $D_{\mathrm{B}} = vr_{\mathrm{g}}/3$ is the Bohm diffusion coefficient of particles with gyroradius r_{g} and velocity v. This gives a maximum energy of about $Z \cdot 10^{17}$eV. Therefore the knee cannot be the result of a change in the propagation characteristics. It must be a feature of the source spectrum itself.

2. Spiral structure of the Galaxy, wind shocks, and reacceleration

The characteristic distance of shock formation is about 60 kpc. The velocity perturbation is half of the velocity jump at the shock formed. Numerical results obtained in two-dimensional numerical calculations of the relevant MHD equations including the CR pressure confirm this estimate (Fig. 1).

The SIR shock system will not modify the spectral form of the Disk-CRs below the knee, and no net adiabatic number or energy density increase of the Disk-CRs will occur. Since the magnetic field in the Galactic Wind is rather strong, we expect that SIR shocks are not very strong and that the spectrum of the particles accelerated by a single shock of the SIR shock system will be fairly steep. On the other hand, particles with energies of the Wind-CRs are diffusively locked inside the termination shock and can be continuously reaccelerated by the system of SIR shocks. The resulting spectrum of accelerated particles will

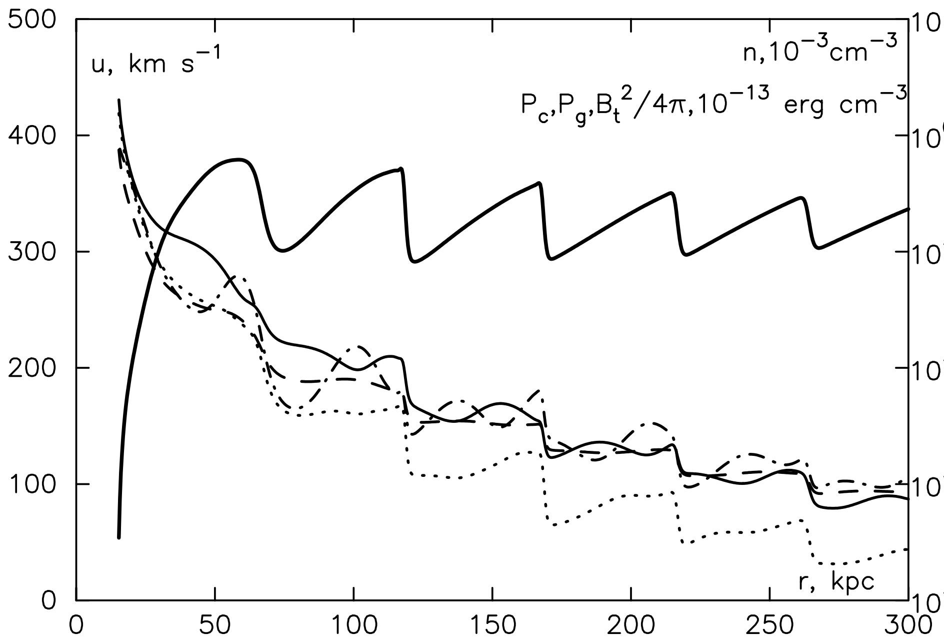

Fig. 1. Radial dependencies, taken at one azimuth angle. The values of the radial gas velocity u (thick solid), the cosmic ray (thin solid) and gas (dotted) pressures P_c and P_g, respectively, the gas number density n (dashed), and the total magnetic field tension $B_t^2/4\pi$ (dash-dotted) are given. Forward SIR shocks form a saw-tooth velocity profile at large distances in the Galactic Wind flow.

be harder than that due to a single shock, and both, efficient acceleration and observability of the reaccelerated in the disk, are possible.

For the numerical calculations a spectral index of Disk-CR sources $\gamma_\mathrm{d} = 4.0$ and a self-consistent cosmic ray diffusion coefficient $D_\parallel^\mathrm{s} = 10^{27} p/(m_\mathrm{p} c)$ 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 [4]. We also used a spectrum of Disk-CRs sources $Q(p) \propto p^{-\gamma_\mathrm{d}} \exp(-p/p_\mathrm{max})$, characterized by an exponential cutoff p_max in momentum, its amplitude corresponding to the known CR source power of the Galaxy. The value of the maximum momentum of Disk-CR sources was taken as $p_\mathrm{max} = 3Z \cdot 10^6 m_\mathrm{p} c$. The overall energy spectrum is given in Fig. 2.

We conclude that it is possible to explain the continuation of the CR spectrum beyond the knee up to the ankle in a natural way, by considering the dynamics of the interstellar medium of the Galaxy and its selfconsistent extension into a large-scale halo by the Galactic Wind. Its is equally clear that within this picture there is no way to produce higher energy CRs. Their sources must be of a different nature.

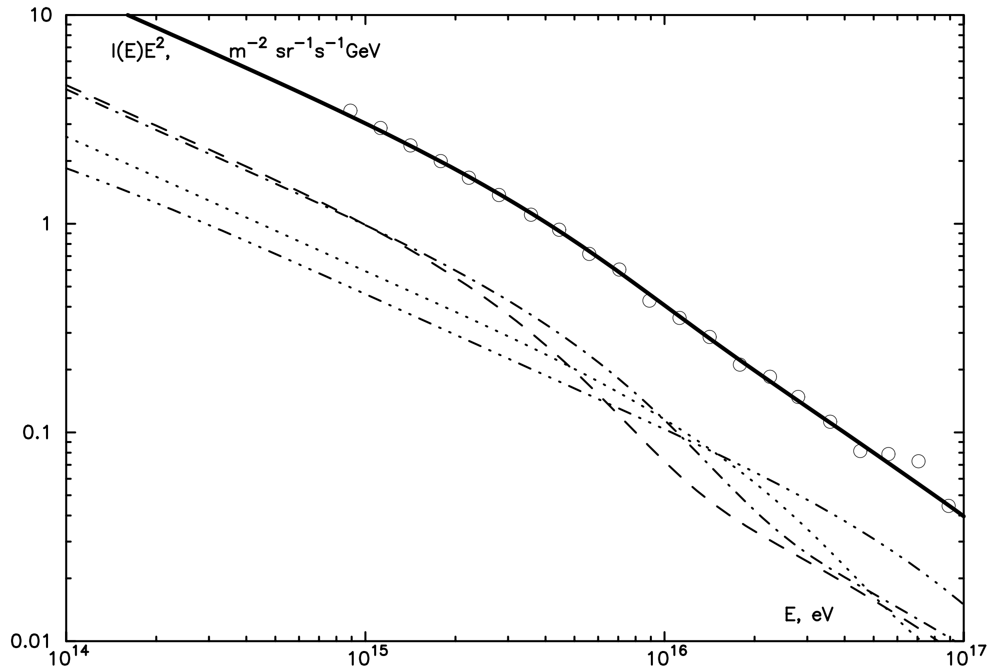

Fig. 2. Calculated differential spectral flux $I(E)$ of the CR protons (dashed), helium nuclei (dash-dotted), carbon (dotted), iron (dash-dot-dotted), all-particle (solid) in the Galaxy for the exponential cut-off, and the all-particle spectral flux observed [8] by the KASCADE collaboration (empty circles). The chemical composition has been fixed at $E = 9 \cdot 10^{14}$ eV from Fig.5 of [8].

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3. References

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