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Cosmic-ray driven winds

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The theory of Galactic Winds, driven by the cosmic-ray pressure gradient, is reviewed both on the magnetohydrodynamic and on the kinetic level. In this picture the magnetic field of the Galaxy above the dense gas disk is assumed to have a flux tube geometry, the flux tubes rising locally perpendicular out of the disk to become radially directed at large distances, with the cosmic-ray sources located deep within the Galactic disk. At least above the gas disk, the magnetic fluctuations which resonantly scatter the cosmic rays are selfconsistently excited as Alf'en waves by the escaping cosmic rays. The fluctuation amplitudes remain finite through nonlinear wave dissipation. The spatially increasing speed of the resulting outflow results in a diffusion-convection boundary whose position depends on particle momentum. It replaces the escape boundary of static diffusion models. New effects like overall Galactic mass and angular momentum loss as well as gas heating beyond the disk appear. Also particle re-acceleration in the distant wind halo suggests itself. The resulting magnetohydrodynamic flow properties and the cosmic-ray transport properties are compared with observations. On the whole they show remarkable agreement. General limitations and generalisations of the basic model arise due to the expected simultaneous infall of matter from the environment of the Galaxy. On an intergalactic scale the combined winds from the Local Group galaxies should form a “Local Group Bubble“. Its properties remain to be studied in detail.

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1. Characteristics of the Galactic cosmic rays

The Galactic cosmic rays (CRs) represent a flux of relativistic, fully ionized atomic nuclei with a power-law type energy distribution, impinging on the Earth's atmosphere. The flux of relativistic electrons is about 1 % of this by number. The total CR energy density is $E_{\rm c} \sim 1\,{\rm eV cm}^{-3} \sim {\rm B}^2/8\pi \sim {\rm E}_{\rm th} \sim {\rm E}_{\rm turb} \sim {\rm E}_{\rm rad}$ in the neighbourhood of the Solar System. γ-ray observations with satellite detectors at high energies (HE:$E_\gamma < 100$ GeV) suggest that this is true $\sim$ everywhere in the diffuse Interstellar Medium (ISM) of the Galactic gas disk, outside of the sources.

The momentum distribution is essentially *isotropic*, presumably due to frequent directional scattering in the irregular magnetic field, anchored in the *thermal* ionized gas. This implies a diffusive propagation process relative to the scattering centers of the ISM and eventual advection with these scattering centers. As a result the CRs constitute a nonthermal, relativistic gas of high pressure which is equal partner in the dynamics of the ISM.

The chemical abundances around 1 GeV/n are similar to those of the Solar System and of the ISM which implies that the sources mainly accelerate ordinary interstellar matter. However, there are notable exceptions: in particular the light CR nuclei Li, Be, B are strongly overabundant relative to this cosmic abundance. They are therefore interpreted as secondary spallation products of heavier primary CR nuclei, predominantly in the interstellar gas. The so-called grammage encountered by those particles at energies of a few GeV/n is $\simeq 8{\rm g\ cm}^{-2}$ which is small compared to the spallation mean free path. Thus for the majority of particles there is only limited confinement in the Galactic gas disk of density $\simeq 1$ particle ${\rm cm}^{-3}$, where they spend a few million years. The abundance ratio of secondary to primary CR nuclei, like the B/C-ratio, decreases with particle energy above about 1 GeV: higher-energy particles leave the spallation region faster than lower-energy particles and therefore the source spectra must contain more high-energy particles. Recent indications are that this does not continue into the TeV range [8, 15, 1], which is likely due to the fact that secondary particles produced *inside* the sources are also re-accelerated there to a resulting hard spectrum, e.g. [2, 4, 3]. An empirical conclusion for the CR source energy spectrum is then: $dN/dE \propto (E/n)^{-\gamma}$, with $\gamma \simeq 2.1\,{\rm to}\,2.2$, at least up to energies $E/n \sim$ few $\times\, 10^2$ GeV.

The absolute life time of the particles that return to the Solar System at a few $100{\rm MeV/n}$ is approximately 1.5×10^7 yrs from an analysis of the fraction of the radioactive ^{10}Be nuclei in the arriving CRs, see e.g. [20]. This suggests that we have to imagine that even nonrelativistic CRs predominantly propagate in a low-density halo before "escaping". For higher-energy particles this appears to be even more likely.

2. CR propagation and the Galactic Wind

The traditional picture holds that CRs propagate diffusively from the sources in the dense gas disk into a fixed, static confinement volume. From there they escape to infinity upon reaching the "boundary"of this halo. This picture is kinematically consistent. For a recent review, see [18].

The alternative picture, which we shall discuss here, is a dynamic one of a nonlinear character: the gas and CR pressure gradients jointly drive a Galactic Wind (GW) in which the CRs are diffusively confined by *self-excited* magnetic field fluctuations, the relativistic CRs trying to establish an infinite scale height.

A basic question is then, whether the CRs escape with the gas, producing ever more extending magnetic loops as a result of the Parker instability [16], or whether they escape by carrying only a very small amount of gas with them, effectively in a boyant bubble of reconnected magnetic field, leaving behind a dynamo for the Galactic magnetic field. Presumably both CR loss processes operate in the Galaxy with comparable CR removal rates, as argued in [6].

The first analytical attempt to describe a CR-driven wind flow was made in spherical symmetry [12]. Later on wind flows were studied in a Galactic disk symmetry (including a dark matter halo), assuming flow tube configurations out of the disk that allowed a local description. Flow tubes start perpendicular to the disk in z-direction with constant cross-section $A(s)$ along flow lines s to become spherical, $A(s) \propto s^2$ at distances exceeding the disk radius $\simeq 15$ kpc [5]. These solutions were subsequently generalized to include Galactic rotation and the corresponding azimuthal magnetic field effects, as well as gas heating due to wave dissipation [21], and CR kinetics [17].

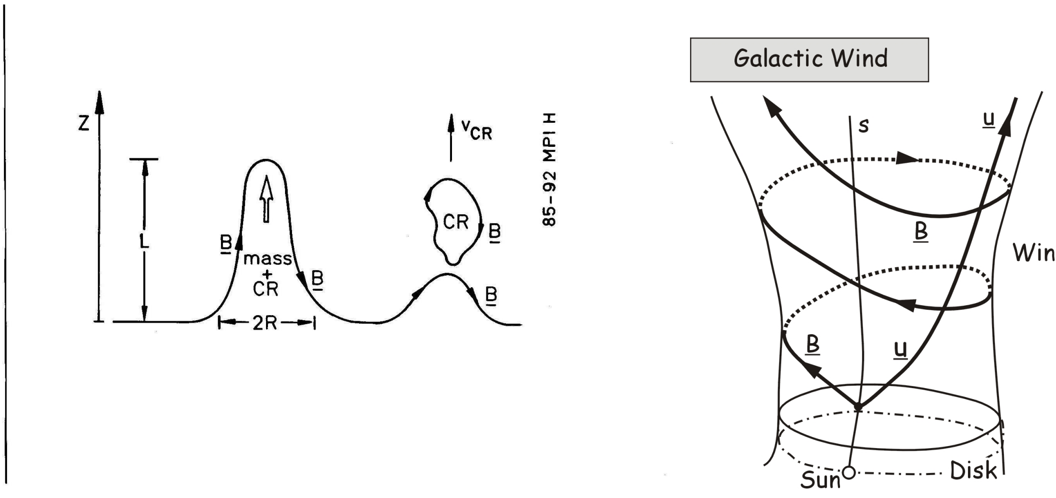

Figure 1: Left: Extension of magnetic field lobes in z-direction, perpendicular to the Galactic disk. In the left part of the figure the lobes are expanding ultimately to infinity with the CRs and the thermal gas in a Galactic Wind. In the right part the competing magnetic reconnection process allows CRs to move out by boyancy without a substantial accompagnying gas component (from [6]). Right: Schematic of a CR-driven Galactic Wind from the Sun in the inner disk. The coordinate along flow lines is s, with the flow velocity $\underline{u}$ increasing with s, while the magnetic field $\underline{B}$ develops into a so-called Parker spiral. The flow is assumed to become radial at large s, starting perpendicular to the disk at low heights. (Adapted from [17]).

The flow is mainly driven by the outward force of the CR pressure gradient $-\mathrm{grad}\, P_\mathrm{c}$. Outward diffusion of the CRs excites resonantly scattering Alfvénic field fluctations in a selfconsistent way: $u \cdot \mathrm{grad}\, B^2/8\pi = -v_\mathrm{A} \cdot \mathrm{grad}\, P_\mathrm{c}$ in the halo plasma above the dense gas disk; here v_A denotes the Alfvén speed. Eventually the mass overburden is small enough to be lifted up in the form of a wind. The amplitude of the waves remains finite due to nonlinear wave dissipation, especially *nonlinear Landau damping* of the Alfvén waves [13, 17] which keeps the thermal gas warm/hot despite the adiabatic expansion. Ultimately, for distances $s > 20$ kpc, the outflow becomes supersonic. The total mass loss rate from the Galaxy is estimated to be $\simeq 1 \mathrm{M}_\odot$/yr, while the asymptotic wind velocity $u(\infty) = \mathrm{few}\, 100\, \mathrm{km/s}$ is of the order of the escape velocity. The angular momentum los is about 20 % of the Galactic total in a Hubble time for the present-day parameters of the Galaxy

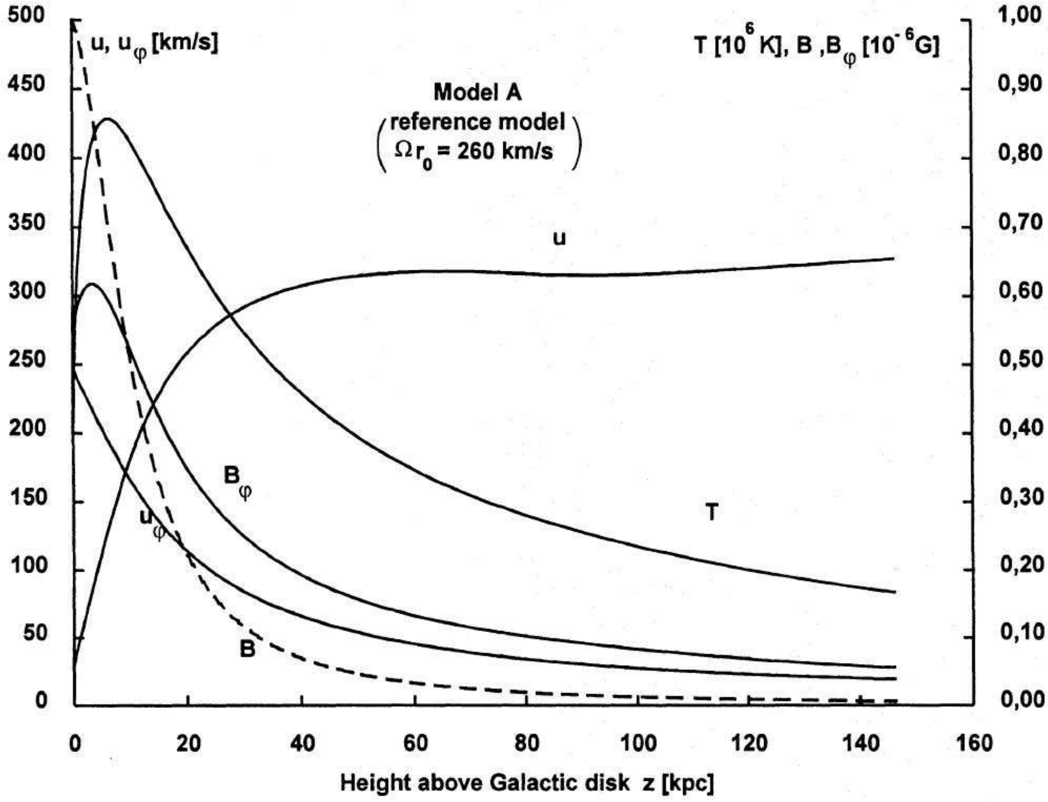

Figure 2: Variation of the meridional and azimuthal flow velocities u and u_φ, azimuthal and meridional magnetic field strengths B_φ and B, and gas temperature T, with distance z from the the disk, for a rotational velocity of the Sun $\Omega r_0 = 260$ km/s at a galactocentric distance $r_0 = 8.5$ kpc [21].

[21]. The wind termination shock is estimated to be roughly at a distance of 300 kpc. The wind velocity decreases over the disk with increasing Galactrocentric radius. Therefore, the density of CRs in the Galaxy should be rather independent of radius, despite the enhanced star formation rate in the inner Galaxy. This is also a possible explanation for the weak Galactocentric gradient of the diffuse γ-ray emission [7].

Globally speaking, the resulting CR transport is diffusive close to the Galactic disk. It becomes convective further out, i.e. without return of particles to the disk. The characteristic spatial boundary $s^\star$ between these two propagation modes occurs where the diffusion time equals the convection time and is roughly given by $(s^\star)^2/\kappa \sim s^\star/u(s^\star)$. Here $\kappa(p)$ is the selfconsistent diffusion coefficient along the flow lines s. It depends on particle momentum p. For the momentum spectrum $Q(p) \propto p^{-\gamma}$ of the CR sources deep in the disk, $s^\star \propto p^{(\gamma-3)/2)}$ and $\gamma \simeq (2\gamma_{\rm d}+3)/3 \simeq 4.1$, where $\gamma_{\rm d} \simeq 4.7$ is the observed spectral index at the Solar System. This means that the diffusion-advection boundary moves out with increasing energy, approximately $s^\star \propto p^{0.55}$ as long as the flow velocity increases l̃inearly with s /, ; at 1 TeV $s^\star \simeq 15$ kpc. However, the diffusion time to reach the boundary $s^\star(p)$ is approximately energy-independent $\simeq 2\times 10^7$ yr and is roughly consistent with the ^{10}Be survival fraction at 100 MeV/n. In this way a natural boundary condition for the propagation of the CRs in the Galaxy appears. It goes together with a general mass and angular momentum loss phenomenon for a normal star forming galaxy like the Milky Way, even at the present epoch of its evolution.

The local increase of the CR intensity above the rotating spiral arms in the disk leads to a series of shocks in the wind that re-accelerate CRs produced in these regions of enhanced star formation [19]. Similarly, time variations of the conditions at the base of the wind due to assumed localised starbursts should induce strong wind shocks that also accelerate particles beyond the “knee” of the observed spectrum [9].

2.1 The real world of the Galactic environment

Obviously such models are necessarily idealized, in spite of their comparably sophisticated physics. Reality should be more complex. For example the local picture shows so-called high-velocity clouds falling back to the disk, presumably through radiative cooling of hot upward expanding material which gives rise to “Galactic fountains”. In addition, a population of “very high-velocity clouds” is observed which may represent true accretion of the Galaxy, perhaps from the Magellanic Stream. *Infall* in this or other forms appears also required to slow down the chemical evolution of the Galaxy, in particular to keep the D/H-ratio high in the ISM [11]. In addition, a diffuse, hot Galactic gas halo has been inferred to exist with a wind-like density profile $\propto r^{-2.1}$ and a total mass within ~ 200 kpc of $\leq 10^{10} \mathrm{M}_\odot$ [14]. It may be the result of a Galactic mass loss rate of $\simeq 1\mathrm{M}_\odot$/yr on average over a Hubble time, but might also be a reservoir of ongoing accretion. The observed, diffuse soft X-ray and radio continuum emissions also require a global halo model. Longitude-averaged GW models have been constructed to explain the latitude profiles of the ROSAT 0.65 keV and 0.85 keV bands together with the 408 MHz radio band [10]. Such fits appear to require a concentration of the wind to disk radii R within rather narrow limits $3.5 < R < 4.5$ kpc, with the B-field assumed to be vertical and decreasing $\propto z^{-2}$. It will be interesting to see how such restricted base regions for the GW can be made consistent with the known radial dependence of the star formation conditions in the disk.

3. A Local Group Bubble

The distance of the Galactic Wind termination shock lies at several 100 kpc – about half way to M31. Beyond this a shocked wind bubble develops. Therefore it is likely that the wind bubbles of the Local Group galaxies push against each other, so to say shoulder to shoulder. Possibly some winds even interact directly. In any case, the wind bubbles should merge into a single “Local Group Bubble” and the nuclear CRs may play a dynamical role in this structure. The radio synchrotron emission is rather uncertain due to synchrotron and Inverse Compton losses over these large distances, despite the expected occurrence of re-acceleration processes in the winds and their termination shocks. We should therefore look forward to the prospect of determining the *low-frequency* Extragalactic radio synchrotron morphology on scales of the Local Group of galaxies. LOFAR and SKA should be very suitable instruments for this endeavour.

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