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Random magnetic fields in the galactic wind flow

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Abstract. The transport of random magnetic fields by a galactic wind driven by cosmic rays is considered. Magnetic field disturbances are advected by the gas flow from the upper part of the galactic disk to the halo. The magnetic field inhomogeneities become very elongated due to the flow acceleration. Applications for cosmic ray transport in the galactic wind are considered.

1 Introduction

The galactic wind driven by cosmic rays is a prominent example of the dynamical importance of energetic particles in our Galaxy (Ipavich, 1975; Breitschwerdt et al., 1987, 1991; Zirakashvili et al., 1996). Cosmic ray sources in the galactic disk generate energetic particles which can not freely escape from the Galaxy but rather generate Alfvén waves (see e.g. Wentzel, 1974). In spite of strong nonlinear Landau damping (Livshits and Tsytovich, 1970; Lee and Völk, 1973; Kulsrud, 1978; Achterberg, 1981; Achterberg and Blandford, 1986; Fedorenko et al., 1990; Zirakashvili, 2000) such waves lead to an efficient coupling of thermal gas and energetic particles (Ptuskin et al., 1997) and cosmic rays drive galactic wind flow due to their pressure gradient. In the simplest approximation one can assume that a frozen-in magnetic field is advected from near the galactic disk region to the galactic halo. Such a field and its tension was taken into account by Zirakashvili et al., (1996) for calculations of the galactic wind flow. An idealized regular magnetic field configuration was considered. This short report develops these ideas further. In particular we shall take into account the random magnetic field component that exists in galactic disk and dynamically dominates over the regular component.

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2 Equations for random magnetic field.

Magnetohydrodynamic (MHD) turbulence is created in the galactic disk mainly by the numerous supernovae. It seems that turbulent diffusion and helicity really provide dynamo action in the disk of our Galaxy (Parker, 1992). Those effects can be less important in the galactic halo, especially if galactic wind flow exists. The approximation used here is that at heights of several hundred pc the magnetic inhomogeneities created in the upper part of the disk are picked up by the wind flow and transported into galactic halo. We shall neglect turbulent magnetic diffusion and reconnection here. The magnetic field $\mathbf{B}$ is frozen into the galactic wind gas and evolves according to equation

$$\frac{\partial \mathbf{B}}{\partial t} = [\nabla \times [\mathbf{u} \times \mathbf{B}]] \tag{1}$$

We shall assume that gas velocity $\mathbf{u}$ and density ρ are nonrandom quantities and are described by steady state equations

$$\nabla(\rho \mathbf{u}) = 0 \tag{2}$$

$$\rho(\mathbf{u}\nabla)\mathbf{u} = -\nabla(P_g + P_c) + \rho\nabla\Phi - \frac{1}{4\pi}\langle[\mathbf{B} \times [\nabla \times \mathbf{B}]]\rangle \tag{3}$$

Here P_g and P_c are the pressures of gas and cosmic rays respectively, Φ is the gravitational potential. Angular brackets mean averaging over volume. It is easy to see from last eq. (3) that dynamical effects of magnetic field can be described if one knows the mean tensor $B_{ij} = \langle B_i B_j \rangle$. The equation for this tensor can be derived from equation (1)

$$\frac{\partial B_{ij}}{\partial t} = -u_k\nabla_k B_{ij} - 2B_{ij}\nabla_k u_k + B_{kj}\nabla_k u_i + B_{ik}\nabla_k u_j \tag{4}$$

We shall consider steady state solutions of equation (4) corresponding to the steady state equations (2),(3). This is a development of our previous results (where the steady state equation (1) for the regular magnetic field was used) to the case including random magnetic fields.

3 Random magnetic field effects

Assuming azimuthal symmetry of the galactic wind flow it is convenient to introduce the coordinate s in meridional direction and the azimuthal angle ϕ. The tensor components B_{ij} should be written in terms of those coordinates. The gas velocity has the meridional and azimuthal components u_s and u_ϕ respectively. For the sake of simplicity we shall assume that the magnetic field is tangent to the surface S along which the galactic wind streams. Therefore we have only three independent components: B_{ss}, $B_{s\phi}$ and $B_{\phi\phi}$. Introducing the flux-tube cross-section $A(s)$ we obtain

$$B_{ss}A^2(s) = const \tag{5}$$

$$\frac{u_\phi}{r} - \frac{u_s B_{s\phi}}{rB_{ss}} = \Omega \tag{6}$$

$$\frac{u_s^2}{r^2}\left(\frac{B_{\phi\phi}}{B_{ss}} - \frac{B_{s\phi}^2}{B_{ss}^2}\right) = const \tag{7}$$

Using the ϕ-component of eq. (3) one finds angular momentum conservation along the surface S:

$$ru_\phi - \frac{rB_{s\phi}}{4\pi\rho u_s} = C \tag{8}$$

Here, the quantities Ω and C are constant along the surface S, and r is the distance from the axis of rotation. Expressions for u_ϕ and $B_{s\phi}$ can be found using equations (6) and (8). They contain the denominator $1 - M_a^2$, where $M_a = \sqrt{4\pi\rho u_s^2/B_{ss}}$, the meridional Alfvén Much number. Assuming acceleration of the wind flow from sub-Alfvénic to super-Alfvénic velocities one can find a relation between C and Ω which leads to finite values of u_ϕ and $B_{s\phi}$

$$C = \Omega r_a^2 \tag{9}$$

Here, r_a is distance from the Alfvénic point $M_a = 1$ to the axis of rotation. As a result

$$u_\phi = \frac{\Omega}{r}\frac{r^2 - r_a^2 M_a^2}{1 - M_a^2} \tag{10}$$

$$B_{s\phi} = B_{ss}\frac{\Omega}{ru_s}\frac{M_a^2\left(r^2 - r_a^2\right)}{1 - M_a^2} \tag{11}$$

It is easy to see that these expressions are similar to those for the azimuthal components of gas velocity and magnetic field in our previous investigation (Zirakashvili et al., 1996) and in the theory of azimuthal symmetric MHD flows (Weber and Davis, 1969; Yeh, 1976; Sakurai, 1985). The only difference is the definition of the Alfvén Much number. Here it contains B_{ss} instead of the square of the meridional regular magnetic field component. Equation (7) shows that $B_{\phi\phi}$ is not reduced to the square of the azimuthal field component in our previous investigation but rather contains an additional term. Nevertheless this term is inversely proportional to the square of meridional velocity and hence quickly drops with height over the disk. Therefore, at large heights over the disk, $B_{\phi\phi}$ is given by

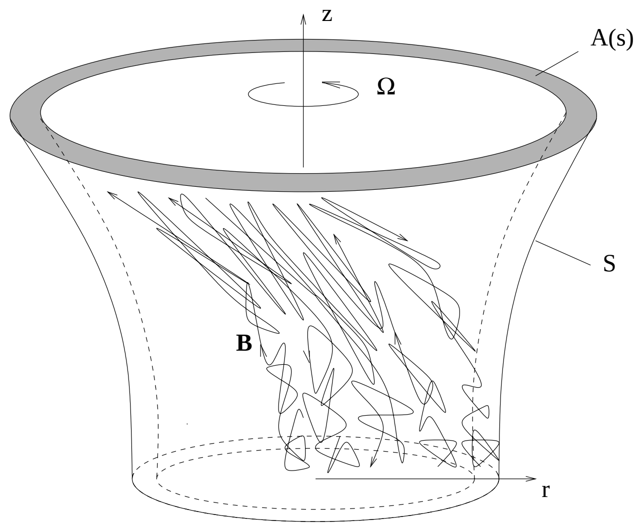

Fig. 1. Flux-tube geometry characterized by the surface S which contains the wind stream lines. The flux-tubes of cross section $A(s)$ have axial symmetry around z-axis. In the disk ($z = 0$) the gas rotates with angular velocity $\Omega(r)$. Near isotropic in the galactic disk magnetic field disturbances become strongly elongated in the galactic halo.

$$B_{\phi\phi} = B_{ss}\frac{\Omega^2}{r^2 u_s^2}\frac{M_a^4\left(r^2 - r_a^2\right)^2}{(1 - M_a^2)^2} \tag{12}$$

In the general case when magnetic field components perpendicular to the surface S are present, equation (4) also describes the generation of a random magnetic field due to differential rotation of neighboring surfaces. Nevertheless all B_{ij} components except (5),(11) and (12) tend to zero as the wind accelerates. Hence, expressions (5),(10),(11) and (12) are valid in the general case for large heights above the disk. It is easy to picture the magnetic field geometry in the galactic halo (see Fig.1). Magnetic field lines are strongly elongated in one direction due to wind acceleration and bend away from the meridional direction because of the rotation of the Galaxy. This picture is similar to the one obtained in our previous investigation for the regular magnetic field. The presence of magnetic field gives some properties of elastic body to the surface S, that can now resist to velocity shear. This feature allows magnetic connection and corresponding transport of angular momentum along this surface even for the zero regular magnetic field case.

4 Numerical results

Galactic wind calculations were performed for the same parameters of our Galaxy as described in our previous investigation (Zirakashvili et al., 1996). They include the gravitational potential of Miyamoto and Nagai (1975) and take into account a dark matter halo of our Galaxy (Innanen, 1973).

The geometry of the flow is prescribed. The surface S is chosen to have a hyperboloidal form

$$\frac{r^2}{r_0^2} - \frac{z^2}{z_0^2 - r_0^2} = 1, \quad (13)$$

where $z_0 = 15$ kpc is galactic disk radius, and r_0 is that galactocentric radius where the flux-tube under consideration originates. Energy conservation along the surface S was assumed (see (Zirakashvili et al., 1996) for a discussion)

$$\frac{u_s^2}{2} + \frac{u_\varphi^2}{2} - \Omega r u_\varphi + \frac{\gamma_g}{\gamma_g - 1}\frac{P_g}{\rho} - \Phi + \\ + \frac{\gamma_c}{\gamma_c - 1}(M_a + 1)\frac{P_c}{\rho} = const, \quad (14)$$

where γ_c and γ_g are the adiabatic indices of cosmic rays and gas respectively. We used the values $\gamma_c = 1.2$, $\gamma_g = 1.6$. The only difference in comparison with our previous consideration is the substitution of the z-component of the regular magnetic field B_z by $B_{zz}^{1/2}$. These components coincide with the meridional ones at small heights above the disk. Observations of the regular magnetic field in the galactic disk show a regular field about 2μG which is parallel to the galactic disk (Rand and Kulkarni, 1989). This means that the vertical component of the regular field in the galactic halo is small and hardly exceeds 1μG. On the other hand, a random field about 6μG exists in the disk. Assuming its isotropy one finds $B_{zz}^{1/2} \sim 3.5\mu$G. The corresponding component can be smaller in galactic halo, say 1.0μG. In that case the results of our previous calculations with 1.0μG regular magnetic field (Zirakashvili et al., 1996) can be used. On the other hand larger values of magnetic field strength are also possible. We take for our calculations value $B_{zz}^{1/2} = 3.0\mu$G. In addition we used a smaller value of cosmic ray pressure $P_{c0} = 1.0 \cdot 10^{-13}$ erg/cm^3 at the base level 3 kpc over the disk in order to maintain approximately the same cosmic ray energy flux in comparison with our previous calculations. A gas number density $n_0 = 10^{-3}$ cm^{-3} at this base level was assumed. Radiative cooling losses are relevant for denser gas at smaller heights above the disk. Numeric results for the flux tube originating at galactocentric distance $r_0 = 8.5$ kpc (Sun's position) are shown on Fig.2 and Fig.3. The height of the slow magnetosonic point is practically the same $z_s = 7.1$ kpc above the disk. The Alfvén point $z_a = 21.6$ kpc and the fast magnetosonic point $z_f = 84.8$ kpc move further out into the flow. The initial wind velocity at the base level is $u_0 = 31.5$ km/s, and the terminal velocity is $u_f = 698$ km/s. The magnetic pressure dominates gas and cosmic ray pressures practically everywhere. Nevertheless this is a cosmic ray driven wind because cosmic rays give approximately half of the kinetic energy flux, the second half given by rotational effects (see equation (14)).

5 Discussion

We conclude that the inclusion of the random field component in our galactic wind model results in the possibility that our Galaxy is surrounded by a large wind halo with a rather strong magnetic field even though this field strength is probably an upper limit. The field geometry is rather simple. The magnetic field disturbances are nearly isotropic in the galactic disk and have a size about 100 pc. They are strongly elongated in the galactic halo. The elongation estimated is 1:10-1:100. This magnetic field leads to an effective angular momentum transport and a correspondent additional centrifugal acceleration of the flow, which then results in larger terminal velocity of the wind. At large distances the field is practically azimuthal and sign dependent with fluctuating direction. One can expect that cosmic ray diffusion in such a field is highly anisotropic, enhanced diffusion being in elongation direction. It can be also expected that high energy protons with energies larger than $3 \cdot 10^{17}$ eV are hardly be held by such a sign dependent field. The gas heating due to damping of Alfvén waves generated by the cosmic ray streaming instability is rather effective, the wind halo being filled by a hot rarefied gas with a temperature of about one million degrees. The angular momentum loss rate of the Galaxy is mainly due magnetic torque and is about 50% in 10^{10} years.

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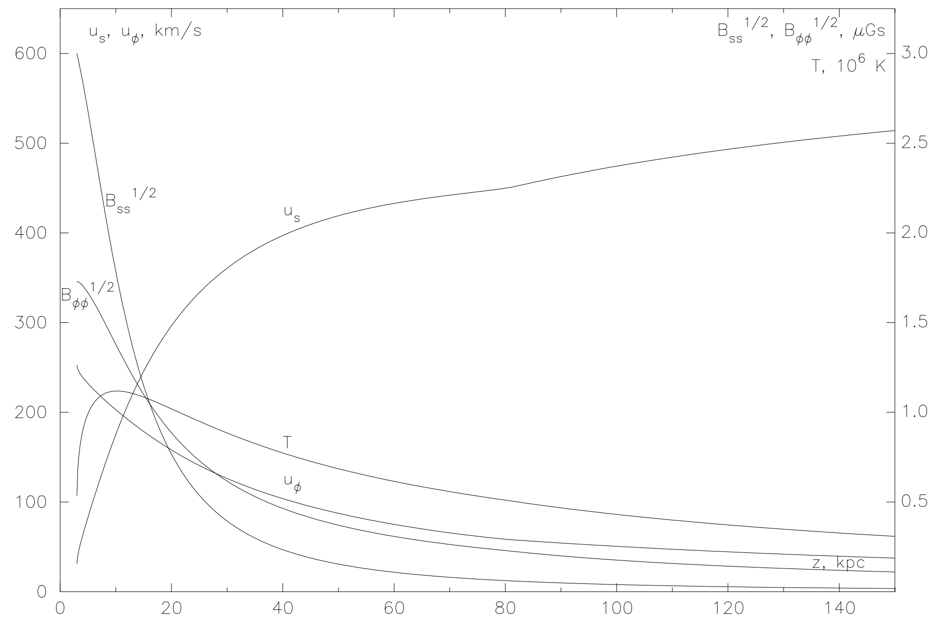

Fig. 2. Variation of the meridional and azimuthal velocities u_s and u_ϕ, azimuthal and meridional magnetic field strength $B_{\phi\phi}^{1/2}$ and $B_{ss}^{1/2}$, and gas temperature T, with distance from the disk. The resulting initial velocity is $u_0 = 31.5$ km/s, and the critical points positions are $z_s = 7.1$ kpc, $z_a = 21.6$ kpc, and $z_f = 84.8$ kpc. The terminal velocity is $u_f = 698$ km/s.

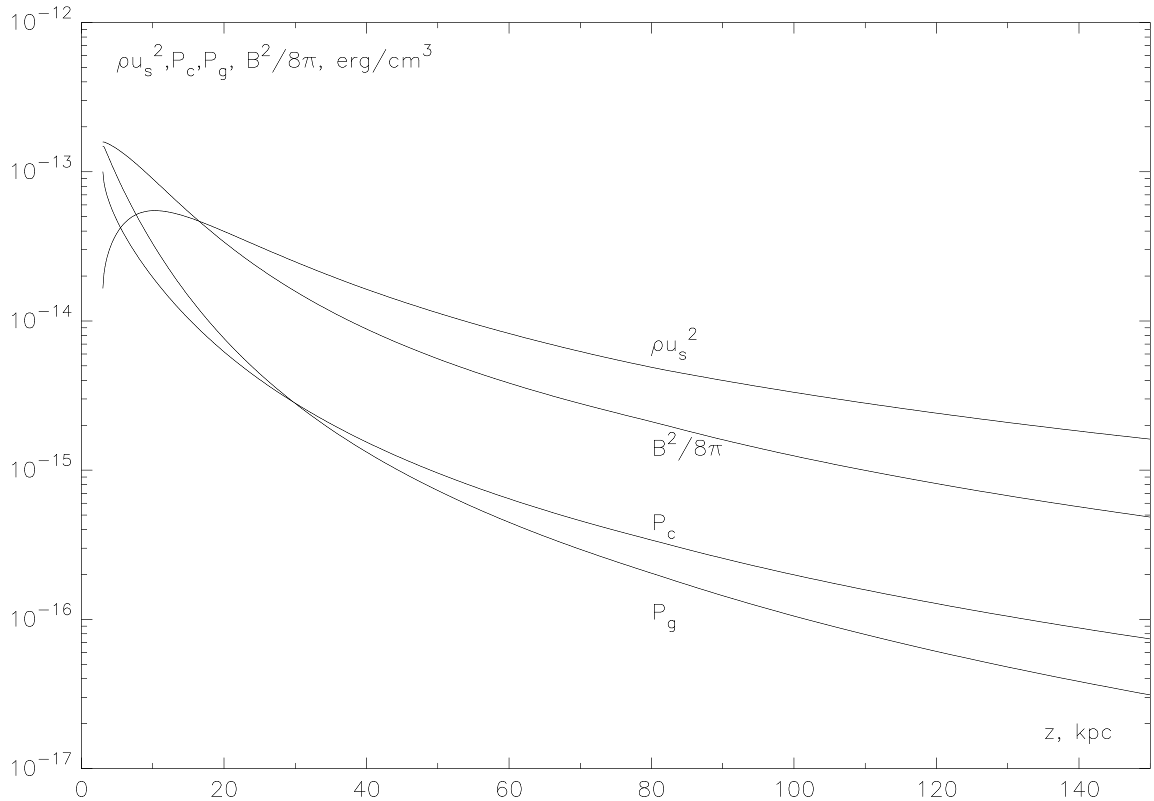

Fig. 3. Variation of dynamic pressure ρu_s^2, cosmic ray pressure P_c, gas pressure P_g, and magnetic pressure $B^2/8\pi$ with distance from the disk.