GALACTIC WINDS AND MAGNETIC FIELDS FROM SPIRAL GALAXIES

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1. INTRODUCTION

Concentrating on our own Galaxy we discuss the dynamics of the outer halo, its magnetic structure and the occurrence of a supersonic mass loss in the form of a Galactic wind. The cosmic rays, as the nonthermal high energy component, de facto not influenced by gravity, play an essential role in the wind dynamics.

2. HALO DYNAMICS

In analogy to the solar corona we assume that on a large scale the Galaxy has open and closed magnetic field lines. The open field lines may correspond to a mass flow to infinity, whereas closed field lines should be mainly due to upwelling gas which cools and ultimately falls back towards the disk. This does not exclude localised infall of extragalactic material, for instance from the Magellanic Stream (Mirabel and Morras [1], van Woerden et al. [2]), however we will not consider infall effects here. Open field lines (Fig. 1) should be due to the production of hot gas and cosmic rays (CRs) by Supernova remnants and OB stars in the (upper) disk, or due to the Parker instability [3] in a vertically stratified disk. By diffusion as well as drift with roughly the Alfvén speed through the gas, the CRs can then transport energy through the moving gas in analogy to heat conduction in the solar corona. The gas itself is kept fully ionized by OB stars from the disk below, halo stars as well as globular cluster stars in situ, and quasars from outside. Thus even if the gas cools on its long journey away from the disk, it will remain fully ionized and thus couple well to the CRs.

The CRs are scattered by fluctuations ("turbulence") in the magnetic field's strength and direction. As long as independent strong sources of magnetic turbulence dominate, there should be little anisotropy in the propagation direction of MHD waves along the average field. In addition, the systematic outward gas motions in and near the disk at heights $|z| \lesssim 1$ kpc (above or below the disk) will by very slow because of the high gas density. Therefore we expect outward CR propagation to be mainly diffusive at such low heights, and this is consistent with their energy-dependent escape. At much higher levels $|z| \gg 1$ kpc however all external

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wave sources will be situated below. Also the waves resonantly excited by the outward CR pressure gradient will propagate away from the disk. This implies an Alfvénic drift of the CRs with the waves through the gas. At these greater distances ($|z| \gg 1$ kpc) we indeed expect wave excitation to be so effective that diffusion becomes negligible compared to Alfvénic drift. The combined pressure gradients of gas, CRs, and waves should then gradually accelerate the gas away from the disk.

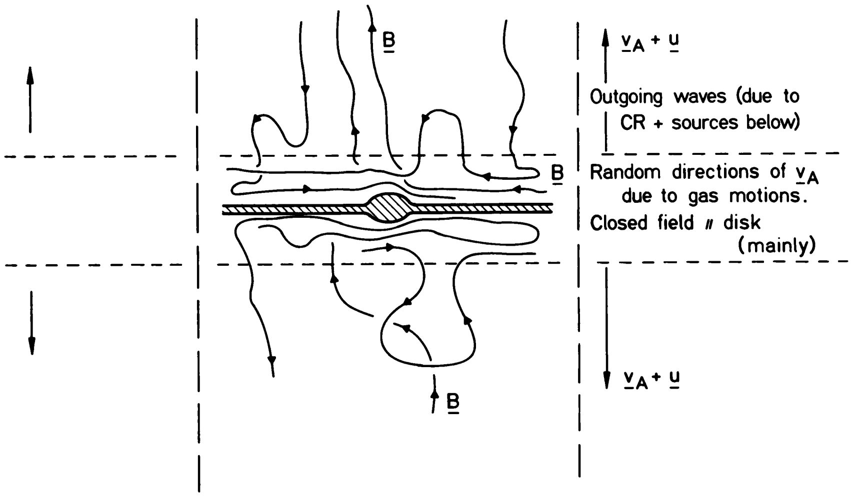

Fig. 1. Schematic overall configuration of the Galactic magnetic field $\underline{B}$ (middle panel), the wave propagation characteristics (right panel), and the cosmic ray propagation modes (left panel). The Galactic disk is cross-hatched. The quantities $\underline{v}_A$ and $\underline{u}$ denote the Alfvén speed and the gas mass velocity, respectively.

3. COSMIC RAY COMPONENT IN THE GALAXY (QUASISTEADY)

In the disk the CR pressure is $p_c \simeq 3 \cdot 10^{-13}$ dyn/cm^2 $\lesssim p_g \simeq 6 \cdot 10^{-13}$ dyn/cm^2; the total observed CR energy flux F_{co} from the disk amounts to $F_{co} \simeq 3.6 \times 10^{40} \cdot (A_{gal,o})^{-1}$ erg/sec, where $A_{gal,o}$ is the surface area of the Galactic disk. If we take into account that higher energy particles escape more rapidly than lower energy particles, then the CR energy flux as produced at the sources should be even higher by a factor of 3 or more. This brings the total CR energy flux to about 10 percent of the energy release rate from Supernova Remnants [4]. In addition the nucleonic component of the CR population suffers only negligible radiative cooling while scattering on the magnetic fluctuations. Thus the CR pressure can in principle transfer a large amount of momentum to the gas. This makes the distinction between outflow with the gas and diffusion and drift through a static halo a practically important one.

4. MODEL CALCULATIONS

Neglecting radiative gas cooling, CR diffusion, and wave dissipation we can consider an adiabatic flow of hot gas, CR's, and waves beyond $|z| \geq$

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few kpc. The Galactic magnetic field is presumably not very strong at such distances. We describe its effects in a stationary flux tube model of flow perpendicular to the disk where the flux tube cross section, A(z), is given by $A(z) = A_o \cdot (1 + z^2/z_o^2)$, for $|z| \geq$ few kpc, with $z = z_o = 15$ kpc and A_o = const. roughly indicating the transition to a spherically symmetric outflow. Centrifugal effects are neglected. Disregarding Galactic rotation for the time being, its kinematic effects are considered in section 5. The dynamical eqs. and their solutions are described elsewhere (e.g., Breitschwerdt et al. [5]). In a restricted form they were discussed for spherically symmetric winds by Ipavich [6].

Assuming typical numbers for a hot interstellar medium with a temperature $T_o = 10^6$ K, conservative values of CR pressure ($p_{co} = 10^{-13}$ dyn/cm^2) and magnetic field strength $B_o = 1$ μG at a reference level z = 1 kpc one obtains supersonic wind solutions at $|z| > z_c$ if the intergalactic pressure is neglected. The subsonic-supersonic transition takes place at distances z_c of the order of 10 kpc. The asymptotic wind velocities are of the order of the Galactic escape speeds (a few hundred km/sec [5]), depending on the radial position of the flux tube in the disk. This results in a Galactic mass loss of the order of 1 $M_\odot$/yr. Even if compensated by mass accretion [1] this could be significant for the chemical and dynamical evolution of the Galaxy as well as its star formation rate.

The Galactic center region, taken here with a linear scale of the order of 100 pc, may play a special role. The localised energy production, even in the absence of a massive central object, may be so high that the outflow is qualitatively different and determined only by the fact that energy is produced at a high rate in a small volume--an M82 in miniature [7].

5. MAGNETIC FIELD STRUCTURE

The large scale magnetic field topology which must take into account Galactic rotation should have the character of an Archimedean spiral (projected onto the Galactic disk) if field lines are assumed to be anchored in the disk [8,9]. In a rather simplistic sense, especially for $|z| \ll z_o$, this pattern is shown in Fig. 2, where Fig. 2a assumes halo corotation with the disk for $|z| < z_o$, whereas for $|z| > z_o$ the magnetic stresses become negligible with a wind flow tube cross section area equal to $A = A_o(1 + z^2/z_o^2)$. Fig. 2b depicts the case where the magnetic stresses are negligible everywhere and the field is drawn out by the flow. The configuration of Fig. 2a is more likely to approximate the actual situation, if for example the observed radio halo polarization directions for NGC4631 [10] were produced by a galactic wind.

Although magnetic stresses should not be very important for $|z| > z_o$, such field configurations might affect the dynamics indirectly through the CR propagation properties. However, it is easy to see that this is not the case for our approximation which neglects diffusion: the CR terms in the dynamical equations involve only the scalar product $(\underline{e}_z \cdot \underline{v}_A)$ where $\underline{e}_z$ denotes the unit vector in z direction and $\underline{v}_A$ the Alfvén velocity, except for the CR diffusion current whose z component has the form $(\underset{\approx}{K} \cdot \partial p_c/\partial \underline{x})_z = (K_\parallel \cos^2\alpha + K_\perp \sin^2\alpha)\partial p_c/\partial z$. Here $\underset{\approx}{K}$ is the diffusion tensor with components $K_\parallel$ and $K_\perp$, parallel and perpendicular to the

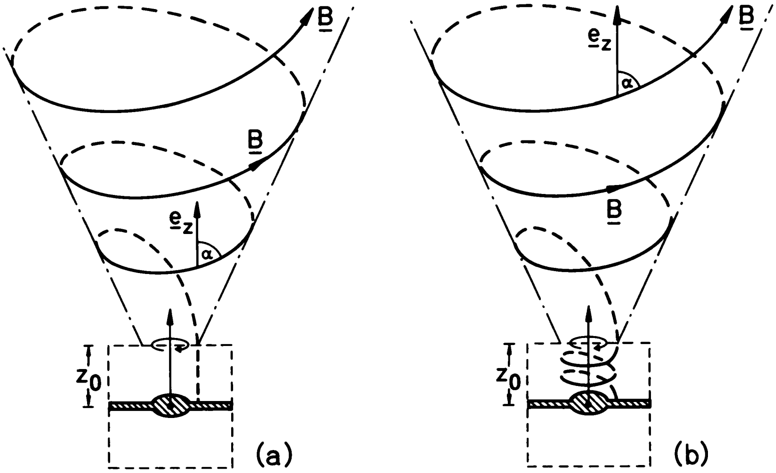

Fig. 2. Schematic $\underline{B}$ field pattern of the rotating Galaxy, described in section 5, as seen in an inertial frame of reference.

magnetic field $\underline{B}$, respectively; the angle α denotes the angle between $\underline{e}_z$ and $\underline{B}$. Since in general $K_\perp \ll K_\parallel$, CR diffusion in z direction is strongly diminished for $\alpha \to \pi/2$ compared to the nonrotating case $\alpha = 0$. Thus, an approximation with negligible z diffusion and otherwise unchanged dynamics relative to a flux tube geometry $A = A_o(1 + z^2/z_o^2)$ and no rotation tends to be reinforced by the inclusion of Galactic rotation.

Except near the Galactic pole, where $\alpha = 0$ for all z, the field should become quite strongly azimuthal at large $|z| > z_o$, e.g. $tg\alpha \simeq 10$ for $|z| = 100$ kpc, taking typical values for Galactic rotation and wind parameters.

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PUDRITZ: A magnetized wind from the disk at the mass loss rates you quote could transport away considerable angular momentum of material (ISM) *in the disk.* This can set up a disk accretion flow. Have you considered this in your model?

VÖLK: Yes, we have considered this qualitatively. Clearly there will be removal of angular momentum by torsional Alfvén waves. However, we do not believe this to be a large effect, since the strength of the open field should be considerably below that of the closed field component. Up to heights above the disk of the order of the disk radius, i.e. about 10 to 15 kpc, corotation enforced by the field will not transport angular momentum but only remove matter together with the angular momentum it had already in the disk. However, I agree with you that this question is important and should be studied further.

DUDOROV: Motion of charged dust grains with gas in a galactic magnetic field may be induced by a stellar wind and radiation. What can you say about this mechanism of galactic winds?

VÖLK: I think of a galactic wind as being driven on a large spatial scale and by the hot gas (plus cosmic rays) which contains comparably little dust. Therefore I believe that for a galactic wind mechanism radiation pressure on dust is less important than for cool stellar winds where the immediate circumstellar region can absorb and scatter the intense stellar photon flux.

ZANINETTI: Do you think that the stellar wind that is coming out from the Galactic center is some kind of regular wind or is rather due to the various SN explosions? In this last case we should not forget that we have more explosions in the plane with respect to the halo, and therefore the rotation axis is also the axis of least resistance.

VÖLK: What I meant to say is that in the inner few hundred pc of the Galaxy the activity, e.g. due to supernova explosions, is so high that the resulting hot gas cannot be retained, regardless of cosmic rays, and is simply blown out in the polar directions, the directions indeed of lowest resistance. This hot gas probably has to percolate through the massive clouds in this region which should therefore be in pressure balance with this hot gas. A similar effect appears to go on in M82. That is why I called the Galactic center a mini-M82.

TSINGANOS: What is the value of the polytropic index that you assume in the relationship between pressure and density?

VÖLK: Thermal gas and energetic particles are treated as distinct fluids, the gas having a polytropic index $\gamma_g = 5/3$, and the cosmic rays an index $\gamma_c = 4/3$. Thus $p_{total} = p_g + p_c$ has a polytropic index exceeding 5/3.

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