DYNAMICAL GALACTIC HALOS

Effect of Magnetic Field And Galactic Rotation

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Abstract. It is argued that the description of the magnetic field in halos of galaxies should take into account its dynamical coupling to the other major components of the interstellar medium, namely thermal plasma and cosmic rays (CR's). It is then inevitable to have some loss of gas and CR's (*galactic wind*) provided that there exist some "open" magnetic field lines, facilitating their escape, and a sufficient level of self-generated waves which couple the particles to the gas. We discuss qualitatively the topology of the magnetic field in the halo and show how galactic rotation and magnetic forces can be included in such an outflow picture.

Key words: Galactic Halos – Magnetic Fields – Cosmic Rays

1. Introduction

The major constituents of the Interstellar Medium (ISM) in late type galaxies such as gas, magnetic field and Cosmic Rays (CR's) cannot be confined to the galactic plane of young stars and molecular gas. There is growing evidence that they populate a region extending several kiloparsecs away from the disk. UV-absorption line studies (CIV, SiIV, NV) towards background stars indicate the presence of hot ($T \sim 2 \times 10^5$ K) gas (Savage and Massa, 1987) with a scale height $H \sim 3$ kpc. Further, 21 cm studies (Giovanelli 1980) show infalling gas with $V_{\rm LSR} \sim -200$ km/s, so-called high velocity clouds. Non-thermal radio emission of edge-on galaxies (eg. Hummel et al. 1988) gives clear evidence for "thick CR disks" and halo magnetic fields. If the energy densities of the ISM components in the solar neighbourhood are not fortuitously comparable, a strong dynamical coupling between them is rather suggestive. This is physically not unreasonable, since CR's as charged particles are naturally coupled to field lines and, because of the high magnetic Reynolds number in the ISM, the magnetic field is essentially frozen into the plasma. The coupling between the gas and the CR's is provided by the streaming instability, meaning that a large scale spatial gradient introduces an anisotropy in the particle distribution function in phase space, which leads to the resonant generation of hydromagnetic waves at which the CR's are scattered efficiently. As a result the CR's drift through the plasma at roughly the Alfvén speed and thereby transfer momentum to the gas. We have developed a self-consistent hydrodynamical model (Breitschwerdt et al. 1991, henceforth Paper I) that takes this non-linear coupling into account, but neglects the effect of galactic rotation and the back-reaction of the magnetic field via $\mathbf{J} \times \mathbf{B}$-forces on the flow. It is the aim of this paper, after a qualitative discussion of the magnetic field topology, to briefly outline how one can include these effects in such a model.

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2. Magnetic Field Structure in the Halo

The structure of the large scale magnetic field in the disk of spiral galaxies can be inferred from the analysis of the linearly polarized radio emission and the rotation measures. It is found that the field is largely parallel to the disk and runs roughly along the optical spiral arms. In the galactic halo (i.e. perpendicular to the disk) the observational situation is less clear. Although there seems to be a predominance in favour of disk-parallel fields there are two examples of perpendicular (z-direction) magnetic field lines, viz. in NGC 4631 and partially in NGC 891. In the following we give a number of reasons why, at least locally, in spiral galaxies an extended z-component of the magnetic field should exist.

Firstly, due to a dynamic instability driven by the pressure of the CR's, field lines bulge out of the galactic disk, while the gas accumulates at the footpoints of the field, thus preventing the lines of force from escaping to infinity (Parker 1966). The unstable modes have a wavelength of typically 1 kpc and a growth time of the order of 10^7 years. Secondly, stellar winds (SW's) and supernova remnants (SNR's), in particular when they are spatially and temporally correlated, so-called superbubbles (SB's), tend to break out of the disk and expand into the halo, elongating in z-direction due to the density stratification of the disk-halo connection. This has been observed as X-ray emitting shells in the Cygnus region (Cash et al. 1980) and also as HI-holes in M31 (Brinks and Bajaja 1986).

Next we point out a few possibilities of how the z-component of such a field might evolve. Recently, Parker (1991) has addressed the problem of the secular loss of CR's in the Galaxy. He argues that field line reconnection should operate either at the footpoints of an individual lobe or between two adjacent lobes. In the first case, the time scale for reconnection may be somewhat larger, because the Alfvén speed is smaller in the disk. In the latter case, neighbouring lobes are required for reconnection to be fast enough; however magnetic flux is lost in this case. Under these circumstances a time scale of 10^8 years seems to be a lower limit. The essential feature of this change of magnetic field topology is the production of closed loops, filled with CR's, that rise by buoyancy and eventually leave the Galaxy, containing only very little gas. We have recently added another process that will result in a different field structure, namely the creation of "open" field lines (cf. Breitschwerdt et al. 1992). It is shown that in competition with field line reconnection, there is a possibility of pushing a fraction of these expanding lobes up to a distance of $z_h \sim 10$ kpc, where the magnetic field strength starts to decrease due to geometrical dilution. This is achieved by the dynamic pressure of the CR's alone, but the thermal and kinetic energy of expanding SB's will definitely add to it. The typical time scale for the lobes to reach z_h is a few times 10^8 years, which is comparable to the flow time scale of a steady-state galactic wind over that distance, which will be running through these channels, pushing the field out to infinity. Therefore it seems very likely, that once such a structure has been established, it will remain as de facto "open" field lines as long as the conditions for a galactic wind are prevailing. We have found that the energy available in CR's is suffucient to produce a large number of such lobes, so that the surface filling factor is about ten. Thus only a small fraction need to survive magnetic reconnection. It is worth noting that "open" field lines offer an alternative loss mechanism of CR's. Moreover, the total energy available in energetic particles in intergalactic space is reduced, as a consequence of adiabatic cooling in a galactic wind (see also Biermann, 1991). It should be emphasized that the processes described here do not explain the ***origin*** of galactic magnetic fields, however we consider them as essential for a realistic galactic halo ***field topology***. A solution of the former problem may be attempted in the framework of a modified mean field dynamo picture. Like in the classical α-ω dynamo, the azimuthal field is generated by shearing motions due to differential galactic rotation and the poloidal field may be produced by cyclonic motion of expanding lobes (α-***effect***). However turbulent diffusivity might have to be replaced by the more efficient process of reconnection (Parker, 1991). We expect smaller amplification times than in the classical model, which suffers from low growth rates in the case of the Galaxy or M31 (e.g. Krashenninikova et al. 1990), because field line mixing occurs over much larger scales in a halo dynamo.

3. Dynamical Halo Model

The details of a dynamical model for the galactic halo have been described elsewhere (Breitschwerdt et al. 1991; 1992). Here we just briefly summarize the main ideas, assumptions and results. Firstly, the transport of CR's depends heavily on the source of hydromagnetic waves. Close to the disk, SW's and SNR's are the major contributors to turbulence and thus the waves will have no preferential direction and the CR's will ***diffuse*** in a volume that stretches over the entire disk and extends to $z_0 \sim O(1\ \mathrm{kpc})$. There will also be ion-neutral damping of the waves, because the plasma density is still high enough to allow for a sufficient number of recombinations. Secondly, at a distance $z \geq z_0$, the major source of waves will be the CR streaming and therefore ***convective*** transport of particles together with mainly outwards propagating waves will occur. This is modelled by assuming that the CR diffusion coefficient jumps from a value of $\bar{\kappa} \approx 3 \times 10^{28}$ to $\bar{\kappa} = 0\ \mathrm{cm}^2/\mathrm{s}$ at $z = z_0$. We have calculated steady-state outflows from $z_0 = 1$ kpc out to large distances, using a gravitaional field that consists of a bulge, a disk and a dominating (by mass) dark matter halo. The existence of "open" field lines was assumed, which represent flux tubes with constant area cross section for $z < 15$ kpc and a spherical divergence above. For simplicity, radiative cooling of the thermal gas was not included (this is the subject of current investigations). For our Galaxy, it was found that galactic wind base velocities are typically of the order of 10 km/s, implying a total mass loss rate of about 1 $M_\odot$/year. These solutions were matched to the region of diffusive CR transport, and it turned out that the necessary amount of gas could be transported up to z_0 by the combined pressures of gas and CR's. However, it is likely that the mass flux into the halo due to SB's is larger by a factor of five or so. This "excess" gas cannot be coupled to the CR's and therefore has to fall back to the disk in a galactic fountain.

4. Dynamical Effect of Magnetic Field and Galactic Rotation

In our previous description of the topology of the magnetic field we did not include differential galactic rotation, which will wind up the frozen-in field lines and generate an azimuthal magnetic field component, B_ϕ, and a corresponding velocity component u_ϕ. The treatment presented here is in many respects similar to the solar wind problem (e.g. Weber and Davis, 1967). We choose a cylindrical geometry, write $\mathbf{B} = (B_r, B_\phi, B_z)$ and $\mathbf{u} = (u_r, u_\phi, u_z)$ and make use of axisymmetry ($\partial/\partial\phi \equiv 0$). In a steady state and ideal MHD, we supplement the galactic wind equations (cf. Paper I) by the appropriate form of Maxwell's equations:

$$\nabla \times [\mathbf{u} \times \mathbf{B}] = 0 , \tag{1}$$

and, as before, $\nabla \mathbf{B} = 0$. Thus, in a corotating frame, the electric field vanishes. Again, the flow is described in a flux tube geometry. Tubes are perpendicular to the galactic plane, and the area cross section $A(s)$ is taken to be an annulus between two adjacent surfaces S (in which $\mathbf{u}$ and $\mathbf{B}$ are coplanar) and it is a function of the meridional coordinate s, connecting differentiation with respect to r and z as follows:

$$\frac{\partial}{\partial s} = \frac{B_r}{B}\frac{\partial}{\partial r} + \frac{B_z}{B}\frac{\partial}{\partial z} = \frac{u_r}{u}\frac{\partial}{\partial r} + \frac{u_z}{u}\frac{\partial}{\partial z} , \tag{2}$$

with $B = \sqrt{B_r^2 + B_z^2}$ and $u = \sqrt{u_r^2 + u_z^2}$. Then we may write $A(s) = A_0[1 + (s/s_g)^2]$ and for the radial distance to a point on the flux tube surface, as measured from a galactocentric coordinate system, $r(s) = R_0\sqrt{1 + (s/s_g)^2}$, where R_0 is the location of the footpoints of the tube in the galactic plane. Here s_g is a typical scale at which spherical flux tube divergence becomes important ($\approx$ 15 kpc for the Galaxy). The approach of prescribing the flow geometry by defining ad hoc flux tubes circumvents the considerable mathematical difficulties that arise from the solution of the transverse momentum equation, and should be considered as a first step to the problem.

The momentum equation has to be supplemented by an additional term $\mathbf{J} \times \mathbf{B} = (c/4\pi)[(\nabla \times \mathbf{B}) \times \mathbf{B}]$, which accounts for the dynamical effects of the magnetic field; here $\mathbf{J}$ is the electric current density. The azimuthal component of this equation then simply describes the conservation of total angular momentum, $L = \Omega(R_0)r_a^2$, which is fixed at the Alfvén critical point $r = r_a$, at which the meridional Alfvén Mach number $M_a = \sqrt{4\pi\rho u^2/B^2}$ equals unity. Let u_a denote the meridional velocity at $r = r_a$, then the azimuthal components u_ϕ and B_ϕ can be written as

$$u_\phi = \Omega r \frac{1 - M_a(r_a^2/r^2)}{1 - M_a^2} , \tag{3}$$

$$B_\phi = \frac{B_a\Omega}{u_a r}\frac{M_a r^2 - r_a^2}{1 - M_a^2} . \tag{4}$$

In the energy equation the Poynting flux term $-(1/4\pi)[(\mathbf{u} \times \mathbf{B}) \times \mathbf{B}]$ has to be included in order to account for the transport of magnetic energy. It can be shown that in the same manner as in Paper I, it is possible to derive a galactic wind equation. The difference here is that the critical solution has to pass through three critical points, corresponding to the three characteristic disturbances that can propagate, namely slow and fast magnetosonic waves and Alfvén waves.

We have performed preliminary calculations for a flux tube located in the solar vicinity ($R_0 = 10$ kpc), starting the flow at a reference level of $z_0 = 3$ kpc with the following parameters: CR pressure $P_{c0} = 2.0 \times 10^{-13}$ dyne/cm^2, a meridional component for the regular magnetic field of $B_0 = 10^{-6}$ G, an azimuthal component $B_{\phi 0} = 0.5 \times 10^{-6}$ G, a number density of $n_0 = 10^{-3}$cm^{-3} and a temperature of $T_0 = 4 \times 10^5$ K for the plasma, a rotational velocity appropriate for the Galaxy, $v_{\rm rot}(R_0) = 250$ km/s, and adiabatic indices $\gamma_g = 1.6$ and $\gamma_c = 1.2$ for the plasma and the CR's, respectively. Note that in contrast to our previous calculations the waves that are geneated by the CR streaming were damped efficiently by non-linear Landau damping, resulting in additional heating of the plasma. Preliminary results show that the meridional base velocity is given by $u_0 = 28.4$ km/s, slightly higher than in the case without rotation. The critical points are located at $s_s = 5.3$ kpc, $s_f = 30$ kpc and $s_a = 8.1$ kpc, where the flow velocity equals the slow and fast magnetosonic and the Alfvén wave speed, respectively. It is also found that at large distances s, the magnetic field is purely azimuthal and falls off like $1/s$.

5. Conclusions

In spiral galaxies, star formation processes are responsible for the production of hot gas and CR's with energy densities comparable to that of the large scale magnetic field, suggesting a strong dynamical coupling between them. Since neither the gas nor the CR's can be confined to the galactic disk, but populate an extended halo, their overall dynamics has an important influence on the topology of the halo field. In particular, Parker instability and a galactic wind will push a fraction of the field lines out to large distances, where the energy density decreases rapidly ("open" field lines). Competitive are reconnection processes, that form magnetic loops filled with CR's which escape. Superposed on the overall outflow, galactic rotation generates an azimuthal component of the magnetic field. The backreaction of the field on the flow by magnetic stresses enforces corotation of the halo out to a vertical distance of the order of 10 kpc, leading to some loss of angular momentum of the Galaxy.

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