

The Role of Cosmic Rays and Alfvén Waves
in the Structure of the Galactic Halo.

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ABSTRACT

The effect that cosmic rays and the Alfvén waves they generate have on the structure of the plasma distribution perpendicular to the galactic disk is examined. It is shown that the plasma distribution exhibits two length scales and the predicted values of gas density far from the galactic plane indicate that models involving hydrostatic equilibrium should be replaced by those allowing for a galactic wind.

1. Introduction. It is now recognised [1,2,3] that since the energy densities of the interstellar gas, magnetic field and cosmic rays are of the same order ($\sim 1 \text{ eV cm}^{-3}$) in the interstellar medium, the coupling between these components, which must be taken into account in a self-consistent fashion, leads to important dynamical effects. Here we examine the role of cosmic rays and the Alfvén waves they generate on the distribution of the plasma perpendicular to the galactic plane.

2. General Equations. Hydrostatic equilibrium perpendicular (i.e. along z) requires

$$-\rho g_z = \frac{d}{dz} (p_g + p_m + p_w + p_c) \quad (1)$$

in which ρ = interstellar gas density with pressure p_g , p_c = cosmic ray pressure, p_m = magnetic pressure, p_w = Alfvén wave pressure and g_z is the z component of the galactic gravitational acceleration given by $-\frac{\partial \phi(r,z)}{\partial z}$ where $\phi(r,z)$ is an axisymmetric galactic gravitational

potential such as [3]

$$\phi(r,z) = \sum_{i=1}^2 \frac{G M_i}{[r^2 + (a_i + (z^2 + b_i^2)^{\frac{1}{2}})^2]^{\frac{1}{2}}} \quad (2)$$

$a_1, b_1; a_2, b_2$ are parameters for the bulge and disk components of the galaxy, M_i is the corresponding mass parameter, G the gravitation constant, and r the radial and z the axial coordinate.

Treating the cosmic rays hydrodynamically, that is, in terms of their pressure and effective diffusion constant κ , the effects of convection and diffusion are described by the cosmic ray transport equations [4]

$$\frac{dF_c}{dz} = v \frac{dp_c}{dz} + Q \quad (3)$$

$$F_c = \left(\frac{\gamma_c}{\gamma_c - 1} \right) v p_c - \left(\frac{\kappa}{\gamma_c - 1} \right) \frac{dp_c}{dz} \quad (4)$$

γ_c = adiabatic index, F_c = cosmic ray enthalpy flux, v = Alfvén wave velocity assumed $\propto \frac{1}{\sqrt{\rho}}$. The wave energy exchange equation which describes how the wave pressure is generated by the cosmic ray pressure gradient [4,5] is

$$\frac{d}{dz} (v^2 p_w) = -v \frac{dp_c}{dz} - L \quad (5)$$

In the absence of additional energy losses or gains, $Q = L = 0$, (3), (4) and (5) give the total energy flux conservation law as

$$\frac{\gamma_c}{(\gamma_c - 1)} v p_c - \frac{\kappa}{(\gamma_c - 1)} \frac{dp_c}{dz} + v^2 p_w = \text{constant} \quad (6)$$

3. Results for the cases of strong and weak scattering.

(a) Strong scattering ($\kappa \rightarrow 0$) If the cosmic ray diffusive flux is small compared with the cosmic ray enthalpy flux the cosmic ray transport equation (3) integrates immediately to yield the adiabatic form

$$p_c v^{\gamma_c} = \text{constant} \quad (7a)$$

$$\text{or } p_c \propto \rho^{\frac{\gamma_c}{2}} \quad \left(= \rho^{\frac{2}{3}}, \gamma_c = \frac{4}{3} \right) \quad (7b)$$

The total energy equation (6) then tells us how the wave pressure p_w is related to the plasma density, namely

$$p_w = p_{w0} \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{2}} + p_{c0} \frac{\gamma_c}{2(\gamma_c - 1)} \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{2}} \left[1 - \left(\frac{\rho}{\rho_0}\right)^{\frac{\gamma_c - 1}{2}}\right] \quad (8)$$

where the subscript "0" refers to the value of a quantity at some reference level, eg. at the galactic plane. It is often assumed that the magnetic pressure is proportional to the plasma pressure [3,6] which in turn we shall assume is related to the density by some polytropic law of the form

$$\frac{p_g}{p_{g0}} = \left(\frac{\rho}{\rho_0}\right)^{\gamma_g} \quad (9)$$

Under these assumptions the magnetic pressure may be simply incorporated into the gas pressure in the form of an effective sound speed also given by

$$a_{s0}^2 = \frac{\gamma_g (p_{g0} + p_{m0})}{\rho_0} \quad (10)$$

The above "equations of state" for p_g , p_w and p_c enable us to integrate the hydrostatic pressure balance equation immediately to yield

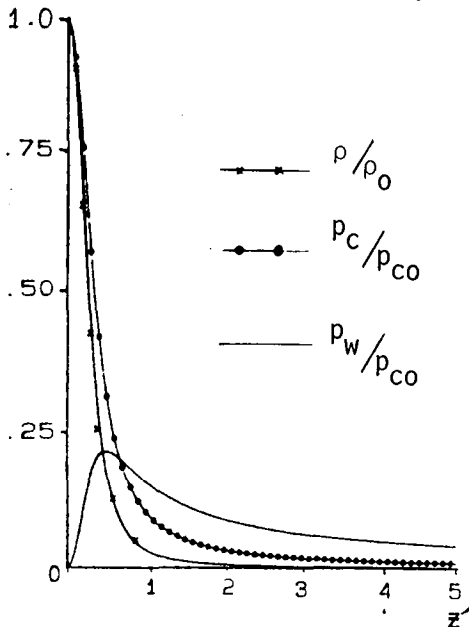


Figure 1 :

Distributions for $r = 5 \text{ kpc}$,

$$a_{c0} = 13.6 \text{ kms}^{-1},$$

$$a_{s0} = 3.8 \text{ kms}^{-1},$$

$$v_e = 500 \text{ kms}^{-1}; \text{ where } z' = z/b_2$$

$$\phi(r,0) - \phi(r,z) = \frac{a_{so}^2}{(\gamma_g - 1)} [1 - (\rho/\rho_0)^{\gamma_g - 1}] + a_{wo}^2 [(\rho_0/\rho)^{\frac{1}{2}} - 1] \\ + \frac{a_{co}^2}{(\gamma_c - 1)} (\rho_0/\rho)^{\frac{1}{2}} [1 - (\rho/\rho_0)^{\frac{\gamma_c - 1}{2}}] \quad (11)$$

$$a_{co}^2 = \frac{\gamma_c}{2} \frac{p_w}{\rho_0} \quad a_{wo}^2 = \frac{p_{wo}}{\rho_0}$$

Thus for a given shape for the galactic gravitational potential (such as equation (2)), equation (11) determines the plasma distribution as a function of r and z . Figure 1 shows the distributions of ρ/ρ_0 , p_c/p_{co} and p_w/p_{co} perpendicular to the galactic disk. It is interesting to note the qualitative agreement between the theory and observations [6,7] denoted by crosses. The main point to note is that the model predicts in a natural fashion that the plasma distribution will exhibit two length scales; a fast decay near the galactic plane (determined by the plasma and magnetic pressure) followed by a much slower decay determined by the self-excited Alfvén wave pressure.

(b) Weak Scattering (κ large) If we assume that the cosmic ray enthalpy flux is negligible compared to the diffusive flux in equations (3) and (4) then the wave energy equation may be written

$$\frac{d(V2p_w)}{dz} = \frac{(\gamma_c - 1)}{\kappa} V F_0 \quad (12)$$

where F_0 is the (constant) diffusive cosmic ray flux.

This equation (with some assumptions for the behaviour of κ) along with hydrostatic pressure balance generalizes the galactic halo model of Ghosh and Ptuskin (GP) to include Alfvén waves generated by the cosmic ray pressure gradient. The GP model and this generalization suffer from the defect that sufficiently far from the galactic plane the density (and therefore the gas and magnetic pressures) and wave pressures begin to increase and the cosmic ray pressure goes negative. This defect in the model arises because it is not consistent to simply assume that the diffusive flux is constant since in fact overall energy flux must be conserved (equation (6)). Thus the wave energy flux can only grow at the expense of the diffusive flux with the implication that the system will eventually drive itself into the strong scattering mode discussed above. We therefore expect that the results for $\kappa \neq 0$ will be similar to those for $\kappa = 0$ with some modifications which will maximize around the point of inflection of the distribution of p_c with z .

Conclusions

The strong scattering limit predicts two length scales describing the gas distribution; the larger one which prevails above the plane arises because the cosmic rays and the waves they generate lift the gas up and stretch it out far beyond the galactic plane, asymptotically approaching a constant value $\rho_{\infty} \sim \rho_0 (\gamma_C - 1)^2 / (V_e/a_{CO})^4$ (where V_e is the galactic escape speed). Although $\rho_{\infty}/\rho_0 \ll 1$ this asymptotic value for the density is nevertheless much greater than typical intergalactic densities ($2 \times 10^{-8} \times \rho_0$) with the implication that the hydrostatic model should be replaced with a galactic wind model.

4. References :

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