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Has the Galaxy a magnetosphere?

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The interaction between accreting intergalactic gas and the magnetic field of the Galaxy is discussed. If this field and the intergalactic gas have certain parameters, then a magnetosphere can develop around the Galaxy. Since no magnetic field would exist outside the magnetosphere, the galactic radio halo is identified with the magnetosphere. In view of observational evidence for a flattened radio halo ($Z < 10$kpc), a model magnetosphere extending to $Z \approx 5$–8 kpc is proposed; at its boundary the accreting gas would have a density of $\approx(1\text{–}3)\times10^{-29}$ g/cm^3 and the magnetic field strength would be $\approx(3\text{–}5)\times10^{-7}$ gauss. The mean intergalactic gas density in the Local Group would then be $\approx(0.3\text{–}1)\times10^{-30}$ g/cm^3. The undisturbed magnetic field generated by the Galaxy is specified by a law of the form $B=2\times10^{-6}\ (Z/H)^{-\kappa}$ gauss, where $2H$ represents the thickness of the gas disk and $1/2 \lesssim \kappa \lesssim 3/4$. This model will be valid if the density and temperature of the galactic gas inside the magnetosphere satisfy the conditions $\rho \lesssim (2-8)\times10^{-28}$ g/cm^3, $T \approx 10^6$°K.

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1. INTRODUCTION

There is no longer any doubt that the galactic disk has a magnetic field with a strength of several microgauss (see, for example, Parker[1]). Far less study has been made of the magnetic field away from the disk, although the presence of such a field is suggested by the nonthermal radio waves received from those regions.

The concept of a magnetic field existing outside the disk was worked out in 1957 by Pikel'ner and Shklovskii.[2] They regarded the Galaxy as having an extended (characteristic size of several tens of kiloparsecs) corona consisting of hot gas with a magnetic field and observed in the form of a radio halo. Further research has shown that the radio halo of the Galaxy is much smaller in size, probably extending less than 10 kpc along the Z coordinate. However, as interpretation of the radio data is rather problematical, the size of the galactic radio halo still remains an open question.[3]

In this paper we shall discuss how hot intergalactic gas should interact with the magnetic field of the Galaxy. It will be shown, in particular, that the size of the radio halo is determined by the parameters of the intergalactic gas and of the galactic magnetic field. We shall give an illustration of how these parameters might be evaluated from the observational data.

We begin with the fact that the radio halo of the Galaxy measures less than 10 kpc across. But since the view is sometimes held even today that the radio halo is more extensive (see, for example, Lipovka[4]), we would point out in advance that such a halo could signify either that the intergalactic gas density is substantially lower than 10^{-31} g/cm^3, or that active processes taking place in the Galaxy are so powerful as to cause a steady streaming of galactic gas out of the Galaxy.

2. INITIAL ASSUMPTIONS

Suppose that outside the galactic disk, at $|Z| \gtrsim 100$ pc, a large-scale magnetic field exists, generated by currents flowing within the disk and perhaps outside as well. To permit qualitative analysis of the problem we shall represent the strength of the magnetic field generated by the Galaxy in the form

$$B=B_d(R)\left(\frac{|Z|}{H}\right)^{-\kappa}. \tag{1}$$

Here $B_d(R)$ denotes the magnetic field strength in the disk ($|Z| = H$), R and Z are the ordinary cylindrical coordinates, and the half-thickness H of the disk will be taken to be 100 pc. The field strength in the disk will be assumed constant and equal to $2 \cdot 10^{-6}$ gauss (see, for example, Ruzmaikin and Sokolov[5]), although there is some evidence that $B_d(R)$ rises toward the galactic center. We shall further regard the pressure of the galactic gas as less than or comparable with the magnetic pressure.

3. MODEL MAGNETOSPHERE

According to current ideas the intergalactic gas has a mean density ρ_∞ of order 10^{-30} g/cm³. The density reaches 10^{-28} g/cm³ at the center of rich clusters of galaxies, where the temperature $T \approx 10^5$–10^6°K. Under such conditions the mean free path $l \approx 200 T_5^2 \rho_{30}^{-1}$ pc. Here T_5 denotes the temperature in units of 10^5°K and ρ_{30} is the density in unts of 10^{-30} g/cm³. Thus the gas-dynamical approximation will hold if $\rho_{30} \gtrsim 0.1$ and $T \lesssim 10^6$°K, and since the characteristic diffusion time of the magnetic field in such a gas is longer than 10^{10} yr, the intergalactic gas should be a diamagnetic plasma. At the present time there is no evidence to suggest the existence of an intergalactic magnetic field of strength above 10^{-8} gauss, so we shall neglect it.

The accretion regime of the intergalactic gas depends in an essential way on the ratio of three velocities: the velocity a_s of sound, the velocity v_0 of the Galaxy relative to the intergalactic gas, and the parabolic velocity v_p. If we suppose that the velocity v_0 is of the same order as the velocity dispersion of the galaxies in the Local Group (50–100 km/sec), we will have $a_s \sim v_p$ and $v_0 \lesssim v_p$ far away from the Galaxy (at distances of 80–100 kpc). Clearly, then, the regime of accretion by the Galaxy should be roughly spherically symmetric, with an anisotropy of several tens of percent.

The velocity of sound in the intergalactic gas should be comparable with the parabolic velocity at distances of order 50–70 kpc. Accordingly, in the vicinity of the Galaxy (at distances $\lesssim$ 10–15 kpc) the accreting plasma should fall in at parabolic velocity.[6] Because of the diamagnetism of the intergalactic plasma, the incoming flow will compress the galactic magnetic field until the pressure $P_A = \rho v_p^2$ of the accreting material becomes comparable with the pressure $P_m = B_m^2/8\pi$ of the magnetic field (B_m denotes the perturbed field strength of the Galaxy):

$$\rho_m v_p^2 = k^2 \frac{B^2}{8\pi}. \tag{2}$$

As a result a closed surface will develop beyond which no magnetic field exists – that is, a magnetosphere. In Eq. (2), ρ_m and v_p denote the density and velocity of the incoming flow at the boundary of the magnetosphere. The coefficient k has been introduced to allow for the enhanced field strength at the magnetosphere boundary compared with the undisturbed strength ($B_m = kB$). In the magnetosphere region, where there would be no singularities (neutral points or branch points), $k \approx 2$ for a flat magnetosphere and $k \approx 3$ for a spherical boundary.

Figure 1 illustrates how the magnetic pressure $P_m = 10^{-12}(Z/H)^{-2\varkappa}$ and the pressure $P_A = \rho m v_p^2$ of the accret-

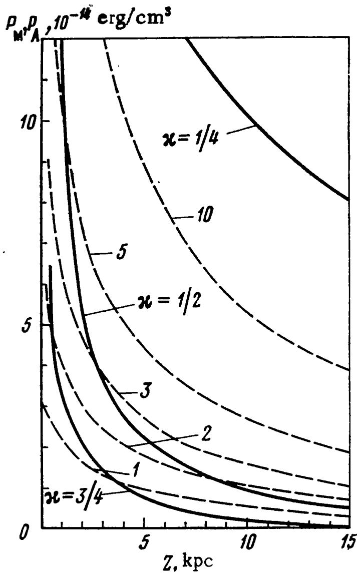

FIG. 1. Magnetic pressure P_m (solid curves) and pressure P_A of the accreting flow (dashed curves) as a function of height Z for selected values of the index $\varkappa$ and the intergalactic gas density ρ_m at the boundary of the magnetosphere. The latter curves are labeled on the right with the density ρ_m in units of 10^{-29} g/cm³. The value of Z_m at the point where the curves P_m and P_A intersect corresponds to the stationary boundary of the magnetosphere.

ing flow will depend on Z for various values of $\varkappa$ and various gas densities at the magnetosphere boundary. We have taken a coefficient $k = 2.5$, and the values of v_p correspond to the values of the axis of symmetry of the Galaxy in the Einastos' model.[7]

In order for a magnetosphere to develop we must evidently have $\varkappa \geq 1/2$, for otherwise the pressure of the magnetic field will fall off more slowly with increasing Z than the pressure of the incoming flow. On the other hand, if the magnetosphere is to have a size $Z_m \approx$ 3–10 kpc, then we should have $\varkappa \lesssim 1$, because if $\varkappa$ were as great as 1 the density of the incoming flow would have to be below 10^{-30} g/cm³, and as a result the density of the intergalactic gas 50–100 kpc away from the Galaxy would be too low: $\rho_\infty \approx \rho_m (R_m/R_\infty)^{3/2} \approx 3 \cdot 10^{-32}$ g/cm³. We therefore conclude that for $Z_m \approx$ 3–8 kpc:

$$1/2 \leqslant \varkappa \leqslant 3/4, \quad B_m \approx (3-5) \cdot 10^{-7} \text{ gauss},$$
$$\rho_m \approx (1-3) \cdot 10^{-29} \text{ g/cm}^3.$$

The intergalactic gas density ρ_∞ far from the Galaxy (at $\approx$ 50–100 kpc) should thus be of order $(0.3\text{–}1) \cdot 10^{-30}$ g/cm³. The extent of the magnetosphere in the direction along the disk evidently will not be much different from the size of the gas layer, or $R_m \approx$ 15–20 kpc.

4. MAGNETOSPHERE AND RADIO HALO

Since no magnetic field would exist beyond the galactic magnetosphere, the dimensions of the nonthermal radio-emitting halo will clearly be determined by the size of the magnetosphere. Hence in order to refine the size of the galactic magnetosphere and to determine the parameters of the intergalactic gas and the magnetic field of the Galaxy, it is especially important to have observations of the Galaxy's nonthermal radio emission.

Our model for the galactic magnetosphere provides a natural interpretation of the asymmetry in the radio halo parameters on opposite sides of the galactic equator. Observations at northern latitudes are known to indicate a flatter radio halo than at southern latitudes.[1] In fact, since the accretion regime may deviate from spherical symmetry by several tens of percent, we may expect the magnetosphere to have an asymmetry of the same order. The magnetosphere will be more firmly "pressed down" in the direction toward which the Galaxy is moving than in the antapex direction, leading to a corresponding anisotropy in the radio emission. This effect would provide an opportunity for measuring the magnitude and direction of the Galaxy's velocity relative to the intergalactic gas.

4. WARP OF THE GAS-DUST LAYER IN THE GALAXY

Radio observations of neutral hydrogen have established that the gas disk of the Galaxy is bent relative to the galactic equator, and the deflection of the gas layer is symmetric about the galactic center on both sides.[8,9] In a recent note[10] we have interpreted this warp as a precession of the gas disk due to the torque resulting from the accretion of intergalactic gas by the Galaxy.

The torque applied to the disk is regarded as being of order

$$M\approx\alpha\pi\rho v_0^2R_d^3. \tag{3}$$

Here ρ denotes the density of the accreting gas near the galactic disk, v_0 is the velocity at which the Galaxy is moving relative to the intergalactic gas, R_d is the characteristic radius of the galactic disk, and $\alpha < 1$ is an anisotropy coefficient. In order for the observed precession to develop the degree of anisotropy ought to reach several tens of percent (that is, $\alpha \approx 0.1$–0.3) and the accreting gas should have a density $\rho \gtrsim 10^{-29}$ g/cm^3, which is consistent with the model we have adopted for the magnetosphere. We have remarked[10] that in principle the magnetic field of the Galaxy could be responsible for producing the torque. Let us now make this suggestion more precise.

As Zhigulev and Romishevskii have shown,[11] if diamagnetic plasma flows asymmetrically around a dipole then the magnetosphere of the dipole will be subjected to a torque given, to order of magnitude, by the expression (3). In the event the magnetic field of the Galaxy has a quasimultipole global structure, then asymmetric accretion will evidently generate a torque applied to the magnetosphere. Since the magnetic field in the disk is frozen into the gas, the torque that develops will be distributed throughout the disk and will induce a differential precession in it. One can show that the precession period of a ring at distance R out from the center will be given by

$$P(R)\approx\frac{\sigma(R)\,\omega(R)\,R}{\alpha\rho v_0^2}. \tag{4}$$

Here $\sigma(R)$, $\omega(R)$ represent the surface density and angular rotational velocity of the ring layer. Since the quantity $\sigma(R)R$ remains approximately constant in the disk and even diminishes at the periphery, the precession will be more significant at the edge than at the center.

6. SUBSEQUENT ACCRETION OF INTERGALACTIC GAS FROM THE MAGNETOSPHERE

Let us consider the rate at which perturbations in the magnetosphere will grow due to Rayleigh–Taylor (RT) instability. In our case the growth increment for RT instability may be written in the form

$$\Gamma\approx\left(\frac{2\pi g_{\rm eff}}{\lambda}\right)^{1/2},\qquad g_{\rm eff}=\frac{\partial\Phi(Z)}{\partial Z}+\frac{1}{\rho}\frac{\partial}{\partial Z}\left(\frac{B_m^2}{8\pi}\right), \tag{5}$$

where λ is the scale of perturbation and $\Phi(Z)$ represents the gravitational potential of the Galaxy. The magnetic field B_m near the magnetosphere has a nearly homogeneous structure: the power-law decline of the undeformed galactic magnetic field will be partially compensated by the accreting plasma "pressing down" on the magnetic lines of force. Setting

$$\frac{\partial}{\partial Z}\frac{B_m^2}{8\pi}\approx 0,\qquad \frac{\partial\Phi(Z)}{\partial Z}\approx 100\ (\text{km/sec})^2/\text{kpc},$$

we find that perturbations of scale λ will have a characteristic growth time

$$\tau_{RT}\approx 10^7\,\lambda_1^{1/2}\,\text{yr}. \tag{6}$$

Here λ_1 is measured in parsecs.

The diameter λ of the clumps into which accreting plasma passing through the magnetosphere should fragment evidently ought to be such that $\tau_{RT} < \tau_{ff}$, where τ_{ff} is the characteristic time of free fall from the magnetosphere. Hence if we set $\tau_{ff} \approx 10^8$ yr we find that the clouds of accreting plasma will have a maximum size $\lambda < \lambda_{max} \approx 100$ pc.

On the other hand, at scales shorter than the mean free path the gas-dynamical treatment is not appropriate. For a temperature $T_5 = 0.5$–1 and a density $\rho_m \approx 2\cdot 10^{-29}$ g/cm^3 the mean free path $l \approx 2$–10 pc; hence RT instability should cause the growth of perturbations having a wavelength $\lambda \approx 100$ pc. The clouds should be cigar-shaped. The length of the cigars will evidently be determined by the maximum characteristic size of the regularity in the magnetic field along the magnetosphere boundary (of the order of several kiloparsecs). The mass of the clouds may reach 50 $M_\odot$.

If the gas in the magnetosphere has a temperature $T_5 \gtrsim 3$, the gas-dynamical treatment would be inapplicable at scales $\lambda \approx 100$ pc. In this event gas could accumulate in the magnetosphere over a period of order $(3$–$5)\cdot 10^8$ yr, and after this length of time perturbations could grow with a scale $\lambda \approx 1$–2 kpc. The mass of the clouds would then reach $10^3\ M_\odot$. Such clouds of ionized hydrogen, acquiring a velocity of 200–300 km/sec near the gas disk, might be able to instigate the formation of high-latitude clouds of neutral hydrogen.

7. CONCLUSIONS

Figure 2 portrays the form that the magnetosphere of the Galaxy might have if the circumstances discussed above are taken into account. We have here neglected the contribution of galactic gas pressure on the magnetosphere boundary. This simplification is legitimate in terms of our proposed model if its density and temperature satisfy