MAGNETIC FIELDS IN SPIRAL ARMS

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Received March 23, 1953

ABSTRACT

In this paper two independent methods are described for estimating the magnetic field in the spiral arm in which we are located. The first method is based on an interpretation of the dispersion (of the order of 10°) in the observed planes of polarization of the light of the distant stars; it leads to an estimate of $H = 7.2 \times 10^{-6}$ gauss. The second method is based on the requirement of equilibrium of the spiral arm with respect to lateral expansion and contraction: it leads to an estimate of $H = 6 \times 10^{-6}$ gauss.

The hypothesis of the existence of a magnetic field in galactic space[1] has received some confirmation by Hiltner's[2] observation of the polarization of the light of the distant stars. It seems plausible that this polarization is due to a magnetic orientation of the interstellar dust particles;[3] for such an orientation would lead to different amounts of absorption of light polarized parallel and perpendicular to the magnetic field and, therefore, to a polarization of the light reaching us. On this interpretation of the interstellar polarization we should expect to observe no polarization in the general direction of the magnetic lines of force and a maximum polarization in a direction normal to the lines of force. And if we interpret from this point of view the maps[4] of the polarization effect as a function of the direction of observation, it appears that the direction of the galactic magnetic field is roughly parallel to the direction of the spiral arm in which we are located. In this paper we shall discuss some further consequences of this interpretation of interstellar polarization, in an attempt to arrive at an estimate of the strength of the interstellar magnetic field.

As we observe distant stars in a direction approximately perpendicular to the spiral arm, it appears that the direction of polarization is only approximately parallel to the arm. There are indeed quite appreciable and apparently irregular fluctuations in the direction of polarization of the distant stars.[4] This would indicate that the magnetic lines of force are not strictly straight and that they may be better described as "wavy" lines. The mean angular deviation of the plane of polarization from the direction of the spiral arm appears to be about $\alpha = 0.2$ radians.[4] There must clearly be a relation between this angle, α, and the strength of the magnetic field, H. For, if the magnetic field were sufficiently strong, the lines of force would be quite straight and α would be very small; on the other hand, if the magnetic field were sufficiently weak, the lines of force would be dragged around in various directions by the turbulent motions of the gas masses in the spiral arm and α would be large. To obtain the general relation between α and H, we proceed as follows:

The velocity of the transverse magneto-hydrodynamic wave is given by

$$V = \frac{H}{\sqrt{(4\pi\rho)}}, \tag{1}$$

[1] E. Fermi, *Phys. Rev.*, **75**, 1169, 1949.

[2] W. A. Hiltner, *Ap. J.*, **109**, 471, 1949.

[3] Of the two theories which have been proposed (L. Spitzer and J. W. Tukey, *Ap. J.*, **114**, 187, 1951, and L. Davis and J. L. Greenstein, *Ap. J.*, **114**, 206, 1951), that by Davis and Greenstein appears to be in better accord with the facts.

[4] W. A. Hiltner, *Ap. J.*, **114**, 241, 1951.

where ρ is the density of the diffused matter. In computing the velocity, V, we should not include in ρ the average density due to the stars, since the stars may be presumed to move across the lines of force without appreciable interaction with them, whereas the diffused matter in the form of both gas and dust has a sufficiently high electrical conductivity to be effectively attached to the magnetic lines of force in such a way that only longitudinal relative displacements are possible.

According to equation (1), the transverse oscillations of a particular line of force can be described by an equation of the form

$$y = a \cos k \left(x - V t \right) , \tag{2}$$

where x is a longitudinal co-ordinate and y represents the lateral displacement. We take the derivatives of y with respect to x and t and obtain

$$y' = -ak \sin k \left(x - Vt \right)$$

and

$$\dot{y} = -akV \sin k \left(x - Vt \right) . \tag{3}$$

From these equations it follows that

$$V^2 \overline{y'^2} = \overline{\dot{y}^2} . \tag{4}$$

The lateral velocity of the lines of force must be equal to the lateral velocity of the turbulent gas. If v denotes the root-mean-square velocity of the turbulent motion, we should have

$$\overline{\dot{y}^2} = \tfrac{1}{3} v^2 . \tag{5}$$

The factor $\frac{1}{3}$ arises from the fact that only one component of the velocity is effective in shifting the lines of force in the y-direction. The quantity y', on the other hand, represents the deviation of the line of force from a straight line projected on the plane of view. Hence,

$$\overline{y'^2} = \alpha^2 . \tag{6}$$

Now, combining equations (1), (4), (5), and (6), we obtain

$$H = \left(\tfrac{4}{3} \pi \rho \right)^{1/2} \frac{v}{\alpha} . \tag{7}$$

In equation (7) we shall substitute the following numerical values, which appear to describe approximately the conditions prevailing in the spiral arm in which we are located:[5]

$$\rho = 2 \times 10^{-24} \text{ gm/cm}^3 , \quad v = 5 \times 10^5 \text{ cm/sec, and } \alpha = 0.2 \text{ radians.} \tag{8}$$

With these values equation (7) gives

$$H = 7.2 \times 10^{-6} \text{ gauss.} \tag{9}$$

An alternative procedure for estimating the intensity of the magnetic field is based on the requirement of equilibrium of the spiral arm with respect to lateral expansion and contraction. As an order of magnitude, we may expect to obtain the condition for this equilibrium by equating the gravitational pressure in the spiral arm to the sum of the material pressure and the pressure due to the magnetic field. In computing the gravita-

[5] For ρ, the estimate of J. H. Oort (cf. *Ap. J.*, **116**, 233, 1952) from observations of the 21-cm line is used; while the value of v adopted is that of A. Blaauw, *B.A.N.*, **11**, 405, 1952.

tional pressure, we should allow for the gravitational force due to all the mass present, i.e., of the stars as well as of the diffused matter. We are interested, however, in computing the gravitational pressure exerted on the diffused matter only. Assuming for simplicity that the spiral arm is a cylinder of radius R with uniform density, one finds for the gravitational pressure:

$$p_{\text{grav}} = \pi G \rho \rho_t R^2 , \tag{10}$$

where G denotes the constant of gravitation, ρ is the density of the diffused matter only, and ρ_t is the total mean density, including the contribution of the stars. The kinetic pressure of the turbulent gas is given by

$$p_{\text{kin}} = \tfrac{1}{3} \rho v^2 \tag{11}$$

while the magnetic pressure is given by

$$p_{\text{mag}} = \frac{H^2}{8\pi} . \tag{12}$$

And for the equilibrium we must have

$$p_{\text{grav}} = p_{\text{kin}} + p_{\text{mag}} . \tag{13}$$

In computing p_{grav} we shall assume a radius of the spiral arm of 250 parsecs or $R = 7.7 \times 10^{20}$ cm. As before, we shall take $\rho = 2 \times 10^{-24}$ gm/cm^3; and for ρ_t we shall assume[6] 6×10^{-24} gm/cm^3. For these values of R, ρ, and ρ_t equation (9) gives $p_{\text{grav}} = 1.5 \times 10^{-12}$ dynes, while p_{kin} computed with the values already given is 0.2×10^{-12} dynes. We attribute the difference to the magnetic pressure. Hence

$$\frac{H^2}{8\pi} = 1.3 \times 10^{-12} , \tag{14}$$

or

$$H = 6 \times 10^{-6} \text{ gauss.} \tag{15}$$

The two independent methods of estimating H therefore agree in giving essentially the same value for the field strength. A field of about 7×10^{-6} gauss indicated by these estimates is ten times smaller than that which Davis and Greenstein[3] have estimated as necessary for producing an adequate orientation of the dust particles to account for the interstellar polarization. If the present estimate of 7×10^{-6} gauss is correct, one should conclude that the mechanism of orientation is somewhat more effective than has been assumed by Davis and Greenstein.

Since this paper was written, our attention has been drawn to the fact that the idea underlying the first of the two methods by which we estimate the magnetic field in the spiral arm is contained in an earlier paper by Leverett Davis, Jr. (*Phys. Rev.*, **81,** 890, 1951). We are sorry that we were not aware of this paper when we wrote ours. However, since with the better estimates of the astronomical parameters now available the value of H derived is a great deal different from Davis' value and since further the value we have derived is in accord with our second independent estimate, we have allowed the paper to stand in its original form.

[6] Cf. J. H. Oort, *Ap. J.*, 116, 233, 1952.