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THE MAGNETIC FIELD REVERSAL AS A COROLLARY TO A MECHANISM OF THE ORIGIN OF SPIRAL STRUCTURE

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ABSTRACT

A brief review is given of a theory advanced previously by the author to account for the origin and development of spiral arms in a galaxy. It is shown that a corollary of the theory may explain (a) The position of the spiral arms alternately up and down the average galactic plane (b) The change of sense of the general magnetic field while crossing the galactic plane and (c) The monotonical widening of the neutral hydrogen layer towards the edges of the Galaxy.

SUMARIO

En el presente trabajo se ha dado un breve resumen de una teoría, propuesta hace algunos años, para explicar el origen y el desarrollo de los brazos espirales en una galaxia. Se ha demostrado, luego, que un corolario de esta teoría puede explicar tres resultados observacionales, aparentemente independientes uno del otro. Estos son:

(a) La posición de los brazos espirales, consecutivos, arriba y abajo del plano galáctico medio.

(b) El cambio del sentido del campo magnético al cruzar el plano galáctico y,

(c) El ensanchamiento monotónico de la capa del hidrógeno neutro al alejarse del centro de la Galaxia.

Introduction

Magnetic fields are believed to prevade our Galaxy; many lines of evidence point to their presence. Here we shall be concerned only with the field close to the galactic plane. Polarization of the light of distant stars, on the basis of the Davis-Greenstein mechanism invokes the existence of magnetic lines of force directed roughly along spiral arms without specifying, however, the *sense* of the field. Fortunately the Faraday rotation, which synchrotron radiation undergoes while traversing a magnetic field, gives the possibility to determine the sense of the field.

Highly interesting results have come to light lately by the combined study of direction and sense of magnetic field in our Galaxy. It is true that detailed analysis has revealed structure on a small scale at least in the vicinity of the Sun, yet there is enough evidence to expect that permeating the small scale structure large scale characteristics of the magnetic field can be traced in the spiral arms. It appears that the observed reversal of the magnetic field while crossing the galactic plane, discovered some years ago, is also a large scale characteristic of the field. It is thus logical to expect that this and other large scale magnetic phenomena should be incorporated in the problem of the interpretation of spiral structure.

The aim of the present report is to show that the reversal of the field, emerges as a *corollary* to a mechanism advanced earlier by this author in an attempt to explain the origin and maintenance of spiral arms. The theory proposed makes use of the funneling property of magnetic lines of force. Circumstances leading to this theory and some aspects of it are published already (Pişmiş 1959, 1960, 1963, Huang and Pişmiş 1960). Thus it appears that the large scale problems of spiral structure as well as the field reversal can be satisfactorily accounted for by the theory which we outline below.

Description of the Mechanism for the Origin of Spiral Arms

In an already existing galaxy of Pop. II stars (similar to an E galaxy) we postulate that there still exists an organized gaseous remnant, a subsystem, concentric with the galaxy. This gaseous subsystem possesses, and is held together by, a magnetic field of poloidal nature. As a rough, first approximation, it is assumed that a dipole may represent such a magnetic field. The dipole is taken to be located centrally where the *direction of the poles is perpendicular to the axis of rotation of* the spheroid and therefore also perpendicular to the axis of the galaxy as a whole. Such an orientation of the dipole is quite unorthodox, and herein lies the novelty of our approach.

Our gaseous subsystem, say a spheroid, rotates as a rigid body with constant velocity throughout, at any given instant. This assumption is justified due to the circumstance that the conductivity of interstellar matter may be taken as infinite so that the field is frozen into the matter. No distortion of the dipole field need be feared, as no differential motions are allowed within our model of the gaseous subsystem at this stage.

Now, it is plausible to expect that such a spheroid will, in the course of time, suffer a gradual contraction. In the process of this contraction the magnetic field will carry along the matter in the spheroid. The only regions from where matter may escape, leaking out of the shrinking spheroid, are those of the two magnetic poles. The escaping mass will, thus, *not be carried along* with the main gaseous body; it will stay behind and through the difference of its speed of rotation, with respect to the spheroid, will delineate spiral arms. The mass may also be liberated with a velocity relative to the center of the spheroid which means that it may be ejected. But we shall not discuss here this case.

It is shown earlier that by postulating the existence of such a rotating and shrinking gaseous bulge, with a magnetic field as envisaged, a galaxy will produce and maintain spiral arms during a reasonably long time. Application of this mechanism to M 31, using its rotation curve has shown that this galaxy would have produced and maintained a spiral pattern with 1.5 turns in 3×10^9 years (Pişmiş 1963).

A Corollary to the Mechanism

We have assumed so far that the dipole which represents the magnetic field of the gaseous bulge is perpendicular to the axis of rotation of the galaxy as a whole; expressed otherwise, that the dipole lies within the plane of symmetry. Now consider the case when the dipole is not exactly in the plane of symmetry but is very slightly inclinedto it, say, by a small angle ε.

We now examine the consequences of thisslight inclination of the dipole. In this case the pattern produced by the leakage or ejection from one polar region will evidently not be coplanar with that produced by the other polar region. Each will be a space curve, the projection of which on the plane of symmetry of the galaxy is a spiral. To fix ideas let us take this projection to be a logarithmic spiral. Let the arm produced by leakage from the positive pole have inclination $+ \varepsilon$ in the positive z direction. The spiral produced by this pole will always stay above the plane of symmetry of the galaxy. It will then be represented by the following parametric equation:

$$\tilde{\omega} = a \, exp \; (b\theta) \quad ; z = c\tilde{\omega}$$

where the constant c has the value:

$$c = arctg\varepsilon$$

Likewise the arm produced by the leakage from the opposite pole will have its equation as:

$$\tilde{\omega} = a \, exp \; (b\theta + \pi); \; z = -c\tilde{\omega}$$

It is clear, from the inspection of the equations, that the spiral figure formed by the leakage (or ejection) from the poles will be traced on the surface engendered by the line of the poles as

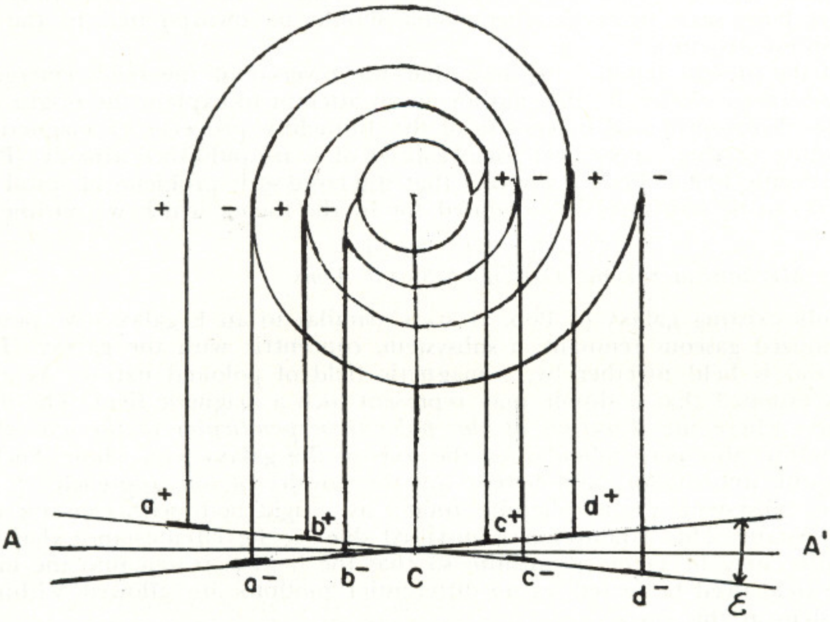

Fig.—*Schematic representation of a spiral galaxy where the arms are engendered as described in the text. The upper one is the galaxy seen along its axis of symmetry; the lower one is a projection of the same galaxy on the meridional plane. The segments a+,....,d+ indicate, on the meridional plane, the projection of the spiral arms, leaving the positive pole, while a−,...,d− are projections due to the negative pole of the magnetic field. The first set of segments lies on the conic surface engendered by the negative pole. The circle with center C is the shrinking bulge where the dipole field is located. AA' is the projection of the plane of symmetry of the galaxy as a whole.*

a generatrix. This surface will have the shape of two very open cones of which the common axis coincides with the rotation axis of the galaxy. With our arbitrary choice of the positive pole at positive z the magnetic field above the plane of symmetry will be positive while the field will be of the opposite sign below the plane. With respect to this plane one arm will be slightly above and the next one slightly below the plane, and the magnetic field in two consecutive arms will be of opposite sign.

The upper part of Figure 1 shows schematically the pattern of two intertwined spirals in the plane of symmetry. These spirals are produced, respectively, by the positive and negative polar regions of the rotating and shrinking bulge which now occupies the central circular form. The spirals are the projections of helicoidal space curves lying on the conical surface with vertex angle $\pi-2\varepsilon$. The projection of the spiral pattern on a plane passing through the axis of rotation of the galaxy (meridional plane) is also shown in that figure.

It is clear that the direction of the magnetic field will be along the spiral pattern; moreover it will have the same sign on one side of the plane AA' and will change sign while crossing AA'. The figure is drawn such that the magnetic field is positive above the plane and negative below it.

Observational Facts Supporting the Corollary

Three observational facts obtained quite independently of one another and apparently unrelated to one another (unaccounted for satisfactorily so far) find a natural explanation in this corollary. We shall discuss these three facts in what follows.

1.—*The magnetic field changes sign while crossing the galactic plane.* This property detected some years ago has been supported by subsequent observations. For example, a discussion of the rotation measures of 37 extragalactic radio sources by Morris and Berge (1964) clearly indicates that the lines of force are oriented along the spiral features in the Galaxy and that the field changes sign when the line of sight crosses the galactic plane. A recent detailed discussion by Bingham and Shakeshaft (1967) gives support to this conclusion. The magnetic field configuration displays a great deal of local irregularity yet the general trend that the lines of force above and below the galactic plane are oppositely directed seems to persist. A detailed discussion of the observational data giving the field reversal will not be attempted here. Such a discussion would require a reliable knowledge of the position of the Sun with respect to the spiral arms.

2.—*Spiral arms are located alternately up and down the average galactic plane.* This is one of the many results anticipated from the Maryland-Green Bank (Westerhout, 1967) high resolution survey of the 21 cm neutral hydrogen line between $b = + 10°$ and $b = - 10°$ and at galactic longitudes 16° to 230° (A. P. Henderson, 1967).* There are considerable fluctuations in the z – position of the spiral features but the net tendency is that the mean of the hydrogen profiles alternates from z positive to z negative as one goes from one spiral arm to the next. It should be emphasized, however, that this trend is just above the noise level and therefore its reality should be accepted with caution.

3.—*The thickness of the neutral hydrogen layer increases as the distance to the galactic center increases.* That in the inner parts of the Galaxy the neutral hydrogen layer is narrow was already known (Rougoor and Oort, 1960, Kerr, 1964). The most recent results in this line are, again, derived from the Maryland-Green Bank survey. It is concluded (Henderson, 1967) that the thickness of the hydrogen layer varies monotonically: it is around 250 pcs at the position of the Sun and increases to 500 pcs at the edge of the Galaxy.

It is well known that spiral features are only general trends marked by a succession of condensations. There is thus a great deal of irregularity in these features. Taking into account the natural width of the arms and their irregularities it is not difficult to see that the combined width of the two sets of intertwined spirals (see the edge-on representation in Fig. 1) may appear as a widening of the layer of neutral hydrogen toward the edge of the Galaxy. This widening can be clearly seen from expressions (1) and (2) where the distance between the two sets of arms is given by:

$$d = 2\,z = 2\,c\tilde{\omega}$$

Thus d increases proportionally to $\tilde{\omega}$.

If this is indeed the case the constant c and hence the angle ε can be estimated in two ways: (a) by the observed width of the hydrogen layer and (b) by the distance z of the spiral arms from the average plane. The two sets of data are independently obtained form the Maryland-Green Bank survey referred to several times. The width of the hydrogen layer is given as 250 pc at the distance of the Sun from the center (10 kpc). The angle ε is, then, $\approx 45'$. To apply the method (b) we have estimated the average z of the inner spiral arm next to the Sun as 100 pcs; the corresponding ε is,

* I am indebted to Dr. Westerhout for kindly providing me with the unpublished thesis of A. P. Hendersen.

therefore, $\approx 40'$. Considering the averaged out values for the thickness of the layer and of the z distance of the spiral arm, the agreement between the two values of ε is rather satisfactory.

Extrapolation of these results to other galaxies would lead us to expect that in some galaxies spiral arms are alternately above and below the average symmetry plane by a small angle, which may vary from one system to another and that the thickness of the layer of neutral hydrogen increases towards the edges of the Galaxy. The only systems where such an effect may be detected are those seen edge-on. But no variations of this kind are reported so far. This is not surprising at all since, if the effect existed, the light of the disk and the nuclear bulge would entirely dominate it on ordinary photographs. There is, though, the possibility that by the application of special photographic techniques on nearly edge-on spirals such an effect may be investigated. A study of the 21-cm radiation of particularly edge-on galaxies with high resolution may be much more rewarding in the detection of the pecularities of the hydrogen layer and of the spiral arms. Some nearby edge-on galaxies like NGC 891, NGC 4565 if studied with a resolution of 8″-10″ might yield the information sought for.

We have shown, in the present *phenomenological* treatment, that our mechanism for the production of spiral arms may possibly explain three phenomena in our Galaxy, apparently quite independent of one other and for which no satisfactory explanation is given till now.

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