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ON INTERSTELLAR GRAIN ALIGNMENT BY A MAGNETIC FIELD

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SUMMARY

The role of the galactic magnetic field in the alignment of interstellar grains believed to cause optical polarization is discussed. The angular momentum of a charged grain is shown to precess about the magnetic field on a timescale less than the relaxation time of most alignment mechanisms, thus introducing the magnetic field as an important factor in many processes other than the Davis–Greenstein mechanism. The different predictions of Davis–Greenstein alignment and alignment combined with precession are presented. Recent direct observational evidence concerning magnetic alignment raises both positive support and contradictions.

1. INTRODUCTION

If the galactic magnetic field is a dominant factor in the alignment of interstellar grains, then a prediction can be made regarding the relative orientation of the observed electric (E) vector of the polarized light and the projection of the magnetic field on the celestial sphere. Such a prediction accompanied the acceptance of the Davis–Greenstein (1951) paramagnetic absorption mechanism, and established optical observations (often used in conjunction with radio observations) as a means of studying the topology of the magnetic field (e.g. Ireland 1961; Hornby 1966; Bingham & Shakeshaft 1967; Mathewson 1968; Seymour 1968). Recently, however, while presenting their alternative alignment proposals, Harwit (1970a,b) and Wickramasinghe (1970) have dismissed the DG mechanism. In view of the potential value of magnetic alignment in probing the magnetic field it seems important to discuss the arguments at greater length. At the same time an additional process through which the magnetic field could be effective is introduced.

It is shown in Section 2 that in the galactic magnetic field the angular momentum of a spinning charged grain precesses around the field direction sufficiently rapidly to be of interest. The effect of this precession in combination with other alignment processes are compared with the DG mechanism. In Section 4 recent observational evidence bearing on magnetic alignment is discussed.

2. PRECESSION OF THE ANGULAR MOMENTUM

In a steady state grains become negatively charged to equalize the effective impact rates of electrons and heavier (slower) positive ions.* For an H II region

* Charging by photoemission of electrons can occur near early-type stars (Mathews 1967).

at temperature T, Spitzer (1968) found that the number of electrons on a grain of radius a cm was given by

$$Z = 1 \cdot 4\ 10^3\, aT \tag{1}$$

when charges of either sign stick and are neutralized with equal probabilities. In an H I region where the electrons come from heavier singly-ionized atoms the charge will be slightly increased, a mean charge of a few electrons being typical for $a \sim 10^{-5}$ cm and $T \sim 100\,°$K. Fluctuations on a timescale short compared to 10^{12} s, the time required for significant precession (equation (6)) are unimportant, and a non-zero average charge of only one electron is sufficient.

Consider an electronic charge e fixed to the surface* of a spinning spherical grain, at a distance $a_\perp$ from the axis of rotation. (A sphere was chosen for simplicity; the average value of $a_\perp{}^2$ is $2/3\ a^2$.) The motion of the charge creates a magnetic moment given by (Goldstein 1964)

$$\mathbf{m} = \frac{e}{2c}\, a_\perp{}^2\, \frac{\mathbf{J}}{I} \tag{2}$$

where $\mathbf{J}$ is the angular momentum, I is the moment of inertia and c is the speed of light. The interaction of $\mathbf{m}$ with the magnetic field $\mathbf{B}$ produces a torque $\mathbf{m} \times \mathbf{B}$ which in turn causes a precession of $\mathbf{J}$ about $\mathbf{B}$. The equation of motion is a form of the Larmor equation

$$\frac{d\mathbf{J}}{dt} = \mathbf{m} \times \mathbf{B} = \mathbf{J} \times \frac{ea^2}{3cI}\, \mathbf{B} \tag{3}$$

from which the angular velocity of precession† is

$$\omega_L = \frac{ea^2B}{3cI}. \tag{4}$$

The time $\tau_L = 3\pi cI/2ea^2B$ for significant precession is to be compared to the relaxation time for processes governing the rotational temperature of the grain. These processes are usually dominated by collisions with neutral hydrogen atoms for which (Jones & Spitzer 1967)

$$\tau_c = \frac{3I}{4na^4(2\pi mkT)^{1/2}} \tag{5}$$

where n is the number density of hydrogen atoms, mass m, and k is Boltzmann's constant. Introducing practical units for a (10^{-5} cm), T (100 °K), B (10^{-6} Gauss), n (10 cm^{-3}), τ (10^{12} s) and grain density ρ (g cm^{-3})

$$\tau_L = 0 \cdot 48\, \frac{\rho a^3}{ZB}$$

$$\tau_c = 3 \cdot 3\, \frac{\rho a}{nT^{1/2}}$$

and

$$\tau_L/\tau_c = 0 \cdot 14\, \frac{nT^{1/2}a^2}{ZB}. \tag{6}$$

* Only the weaker condition that the charge have the same mean angular momentum per unit mass as the grain surface need be satisfied.

† Note the similarity to the gyrofrequency of the helical motion of the charged grain around the field (Spitzer 1968).

Clearly precession must be an important phenomenon. A qualitative discussion of its effects on alignment mechanisms is presented below.

3. PRECESSION COMBINED WITH ALIGNMENT MECHANISMS

Jones & Spitzer (1967) have shown that the steady state distribution of a grain's rotational angular momentum may be characterized by a rotational temperature that can in principle be calculated from the diffusion coefficients in the Fokker–Planck equation describing the rotation. Alignment of the angular momentum relative to some direction in space occurs only when the rotational temperatures along perpendicular axes are different; a necessary but not sufficient condition is that the diffusion coefficients are not the same for all axes. These axes are chosen convenient to the alignment process (e.g. in the direction of the magnetic field, or in the galactic plane), and a quantitative measure of the angular momentum alignment for spheres can be calculated, dependent on the difference between the rotational temperatures.

The precession described above couples with any alignment process by mixing the diffusion coefficients perpendicular to the field direction. Consequently the magnetic field becomes an axis of symmetry in the angular momentum distribution.* If there is a maximum in angular momentum along the field direction, the alignment is similar to the usual† DG alignment; a minimum, on the other hand, indicates alignment opposite to DG. Thus alternative processes including precession can either reinforce or compete against the DG mechanism. It is important to note that in either case there can be no polarization along the field direction, since it is an axis of symmetry.

As an example let T_B be the rotational temperature for an axis in the direction of a magnetic field in the galactic plane, and let $T_\parallel$ and $T_\perp$ be the temperatures for axes in the plane perpendicular to the field, parallel and perpendicular to the galactic plane respectively. Consider next any PL mechanism,‡ intended to give $T_B = T_\parallel > T_\perp$. The introduction of the magnetic field through precession has the important effect of making $T_\parallel$ and $T_\perp$ equal. At the same time the difference between $T_\perp$ and T_B is decreased, thus reducing the degree of alignment in these PL mechanisms with precession. If the galactic magnetic field were simply parallel to the plane it would not be possible to distinguish between the DG and PPL mechanisms on the basis of the direction of alignment. Of course the mechanisms will differ in the degree of alignment possible, and also, because of size dependence, in the wavelength dependence of polarization.

As a second example, consider a magnetic field perpendicular to the plane. In this case the PL mechanisms are not affected by precession since the rotational temperatures along axes in the plane are all the same (T_p). However $T_p > T_B$, in contrast to $T_p < T_B$ if DG alignment dominates. Such simple examples provide a useful basis for examining optical polarization data for evidence of the magnetic field.

* Precession is of no consequence when the magnetic field is already an axis of symmetry, as previously shown for the Davis–Greenstein (1951) mechanism.

† Gas temperature greater than grain temperature (Jones & Spitzer 1967).

‡ For the purposes of illustration, a PL mechanism is one which produces a maximum in angular momentum equally along all axes in the galactic plane. This embodies the common qualitative feature of the Harwit (1970a) and Wickramasinghe (1970) proposals.

4. OBSERVATIONS OF THE MAGNETIC FIELD

(i) *Field strength*

The strength of the magnetic field, estimated and measured to be at least one microgauss, should not limit magnetic influence through precession. However precession is only a part of the alignment process, to be combined with some suitably strong additional mechanism. To its advantage, precession can easily (and should) be introduced in the treatment of a large variety of alignment processes, for example the PL mechanisms already mentioned, or others yet to be conceived.

On the other hand, in the DG mechanism the magnetic field directly causes alignment through paramagnetic absorption. From his Monte Carlo results Purcell (1968) finds

$$B > 7 \cdot 5\,(na)^{1/2} \tag{7}$$

when the ratio of grain to gas temperature is greater than 0·1 and $T \sim 100\,^{\circ}\mathrm{K}$ (practical units as for equation (6)). Thus a stronger field is probably required for DG alignment than for precession.* It is possible, though more difficult to accept, that the grains are ferro-magnetic or super-paramagnetic, in which case a field of a microgauss or less would be sufficient (Jones & Spitzer 1967).

However for paramagnetic grains the problem of field strength is critical. There remain uncertainties about what grain size a (dependent on the grain material) and what hydrogen density n are correct for the polarizing grains. Compounded with this are difficulties first in measuring the magnetic field strength and, subsequently, deciding whether the value obtained suitably describes those regions where the magnetic field is allegedly affecting the polarizing grains. Average values of only a few microgauss have been found using pulsar dispersion and rotation measures (Woltjer 1970). Similar low values are often found from Zeeman splitting measurements (Verschuur 1969), but nevertheless fields as high as 20 μG have been detected (in the Perseus arm in the direction of Cas A). Other less direct evidence (e.g. Burbidge 1969) does not yet present a clear picture. It is possible that the field is strong enough for DG alignment to be important (at least in localized regions), but this cannot be made definite until the larger problem of the magnetic field strength is understood.

(ii) *Field direction*

To make use of observations of the position angles of optical E vectors it is first necessary to know how the direction of the E vector is related to the space alignment of angular momentum for a sphere just discussed. The angular momentum of a spheroid with the same rotational temperature for all axes is aligned along the grain axis with the highest moment of inertia, since angular momentum is proportional to $I^{1/2}$. An alignment process therefore results in aligning the axis with the largest moment of inertia along the space direction with the largest rotational temperature. Since the direction of the E vector is that in which the time-averaged grain profile has the least dimension, E vectors lie along the projection of the space direction of highest rotational temperture. The influence of the magnetic field on the angular momentum has been discussed previously.

* Purcell & Spitzer (1971) conclude on the basis of further Monte Carlo calculations that B must exceed 10 μ for alignment by paramagnetic absorption.

Quantitative results are more difficult to obtain, but some have been calculated by Purcell (1968) using a Monte Carlo technique.* Such computations are useful in estimating what degree of angular momentum alignment for spheres (where analytical methods are available) corresponds to a certain percentage of polarization by aligned grains of anisotropic shape.

There have been many investigations of the polarization of stars at low galactic latitudes. In graphs showing the longitude dependence of the dispersion of position angle, Hiltner (1956) and Klare & Neckel (1970) have found maxima at $l \sim 80°$ and $260°$. The directions of minimum polarization are $l \sim 50°$ and $230°$ (Serkowski 1962). The rough correspondence of these directions with tangents to the local spiral arm as outlined by optical tracers (Sharpless 1956) suggests that the aligning force could be associated with the spiral arm. More recently radio measurements of the polarized background synchrotron radiation and observations of the Faraday rotation of extragalactic radio sources have indicated a large scale magnetic field associated with the local spiral arm (Bingham & Shakeshaft 1967; Berge & Seielstad 1967; Seymour 1968). This evidence is consistent with magnetic alignment (DG or precession) but is not convincing.

Much interest has been shown in small scale features such as dark lanes, nebular streamers and fine filamentary structures, where E vectors are found to lie predominantly along the length (Hall 1958; Elvius & Hall 1966). If a magnetic field is important to the alignment then it must lie along the filaments, a reasonable but otherwise unsupported hypothesis.

Direct, unambiguous evidence is desirable. In the discussion below, independent knowledge of the field topology is derived from observations of the polarized radio background; the intrinsic radio polarization vectors are perpendicular to the magnetic field. Though limited to certain regions of the sky and to relatively nearby magnetic fields (a few hundred parsecs), this method is of considerable value. For comparison to the radio magnetic field (rmf) it is convenient to use the detailed maps of E vectors compiled by Mathewson & Ford (1970), which, for high latitude stars as well, show position angles, percentage polarization and the development of polarization with distance. From these maps it is clear that in addition to regions of general alignment parallel to the galactic plane, there are prominent regions where the opposite is true, or there is a large scatter. There is nevertheless some regularity; Mathewson (1968) has even found flow patterns to fit the observations. It is worth stressing that, contrary to recent statements, there is not everywhere general alignment parallel to the galactic plane. In some ways this is fortunate since the lack of overall alignment with the plane provides the opportunities for distinguishing between different proposed alignment mechanisms.

Least interesting are the polarized regions where the rmf and E vectors are both parallel to the galactic plane; while consistent with magnetic alignment, they admit the alternative of any non-magnetic alignment process with symmetry in the galactic plane (a PL mechanism). Several such regions exist, e.g. $l \sim 150°$, $b \sim 10°$ (Fig. 1 of Mathewson 1968).

When the rmf is inclined to the galactic plane, this ambiguity can be resolved. For example in the large region around $l \sim 200°$, $b \sim 0°$ studied by Bingham & Shakeshaft (1967) the rmf is inclined at about $25°$ to the galactic plane, as are the E vectors. Furthermore, optical and radio estimates of the distance agree and the average inclination of the E vectors decreases for more distant stars

* See also Purcell & Spitzer (1971).

($\sim$2 kpc). Several similar regions exist, five in the range $l \sim 320°$ to $0°$, $b \sim -50°$ to $60°$ (Mathewson 1968). Here then is strong evidence that the magnetic field is important to the alignment mechanism. Unfortunately there is not a clear choice between the two types of magnetic alignment envisaged, DG and precession (PPL).

The most interesting but in practice also the most puzzling regions have either the rmf or the *E* vectors perpendicular (highly inclined) to the galactic plane. A striking case of the latter stands out from $l \sim 10°$, $b \sim 60°$ to $l \sim 50°$, $b \sim -60°$, where the *E* vectors closely follow the ridge of the galactic continuum emission (Mathewson 1968). First it should be noted that PL mechanisms, intended to produce *E* vector alignment parallel to the galactic plane cannot explain this large feature without major modification. How does the DG fare? Early studies of the polarization of continuum radiation in other regions have suggested that the rmf runs parallel to the length of ridges and spurs. Applied to the continuum measurements of the present radio feature, this trend provided agreement with the DG mechanism (Mathewson 1968). Direct polarization measurements above $b = 40°$ gave further support (Bingham 1967). However recent observations of the North Polar Spur (Spoelstra 1971) have spoiled this simple picture. Above $b = 40°$, the rmf runs nearly perpendicular to the plane, confirming Bingham's results. But below $b = 40°$, the derived rmf is often parallel to the galactic plane. It is remarkable that here the magnetic field appears to be perpendicular to the ridge. The direction of the *E* vectors of course contradicts the DG prediction. Although there is no apparent compelling reason to retain the DG mechanism here, these results could obviously be explained if the radio and optical polarization arise in different volumes of space. On the other hand, the significance of the alignment of the *E* vectors along the feature at all latitudes might be understood in terms of a non-magnetic mechanism; this possibility certainly detracts from the evidence for DG alignment above $b = 40°$. Further observations are warranted to clarify the ambiguities of this interesting region.

The opposite problem is encountered around $l \sim 150°$, $b \sim -50°$ (the Cetus Arc), where the *E* vectors are nearly parallel to the plane but the rmf is steeply inclined (Mathewson 1968). In confirming these results Spoelstra (unpublished work) has found the lower latitude extensions equally puzzling. The evidence again is contradictory to the DG alignment, but there remains, as yet, the ambiguity.

These examples were intended to illustrate one way the predictions of magnetic alignment can be directly checked. Many more regions could still be studied. Where *E* vectors are nearly perpendicular to the galactic plane in regions of continuum emission, radio polarization observations could be attempted (around $l \sim 270°$, $b \sim 20°$; $l \sim 310°$, $b \sim 30°$; $l \sim 45°$; $b \sim -40°$; $l \sim 80°$, $b \sim -30°$ to name a few). In addition optical observations might be extended, notably away from the galactic plane in the Northern Hemisphere. It is often essential to establish what volume of space is contributing to the polarization.

5. CONCLUSIONS

The magnetic field can influence the alignment of interstellar grains not only through the Davis–Greenstein mechanism, but also by causing a precession of the angular momentum of charged grains. The latter does not require as strong a magnetic field, but it is dependent on an additional alignment process. Using the polarized radio background to derive the field direction, direct evidence for magnetic alignment has been sought. Positive support was found in several regions where the inclination to the galactic plane was relatively low ($<30°$). But in regions with high inclination there is negative as well as positive evidence for DG alignment. In view of the ambiguities that have arisen so far, the important question of the acceptance of DG alignment to map the magnetic field cannot yet be considered to be answered satisfactorily. It is hoped that the concept of magnetic alignment as extended in this paper will be entertained in the future as new observations concerning both the magnetic field and the alignment of interstellar grains become available.

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