# MAGNETIC ALIGNMENT THEORY AND THE INTERPRETATION OF POLARIZATION

Pierre Cugnon
Observatoire Royal de Belgique

## ABSTRACT

This paper presents some reflexions about the theory of magnetic spinning alignment. It is shown that a classical enhanced thermal Davis and Greenstein mechanism may be considered as a limiting case of Purcell's suprathermal spinning alignment theory when the number of active sites on a given grain becomes very important and/or for very short-lived suprathermal sites.

This result is applied to the interstellar medium and some problems in which it may be important are briefly discussed, with special attention to local implications.

## INTRODUCTION

It has been shown by some authors (see for example Purcell and Spitzer 1971; Cugnon 1971, 1983; Greenberg 1978) that Davis and Greenstein thermal alignment mechanism (TSA) failed by about one order of magnitude to explain the required degree of alignment when "standard" interstellar conditions were assumed.

That is the reason why Purcell (1975, 1979) proposed an alternative D-G mechanism, in which the grains, driven to "suprathermal" rotational velocities by some constant torque, were thus much more easily aligned by paramagnetic relaxation. This theory appears now to account correctly for the polarization observations (Johnson, 1982; Aannestad and Greenberg, 1983), although there remain some uncertainties in the formulation of the theory and in the values of the parameters (effect of dissipative torques, re-surfacing time, number of active sites). Spitzer and McGlynn (1979) made a very detailed analysis of the problem of disalignment due to grain re-surfacing and concluded that "long-lived" spin-up was necessary to account for grain alignment in Purcell's mechanism.

In his paper of 1979, Purcell pointed out that the rotational temperature of the grain could be quite different from the gas temperature, and should in fact be calculated taking into account all the possible excitation mechanisms acting on a grain provided that excitation occurs randomly with a characteristic time shorter than the collisional damping time. This leads to a rotational temperature $T_{eff}$ which can be quite higher than the commonly used gas temperature, and induces a somewhat more efficient alignment mechanism, we shall call "enhanced thermal alignment" mechanism (ETSA). On the other hand, if the excitation is not random and takes place systematically at a few peculiar sites of long duration, we are in the case of Purcell's suprathermal spinning alignment (SSA).

It appears then that ETSA and SSA respectively refer to extreme opposite cases of rotational excitation. The theoretical analysis which follows briefly developes this point and examines the role of some parameters in the transition from SSA to ETSA. The third section will then be devoted to some interstellar implications of the obtained results.



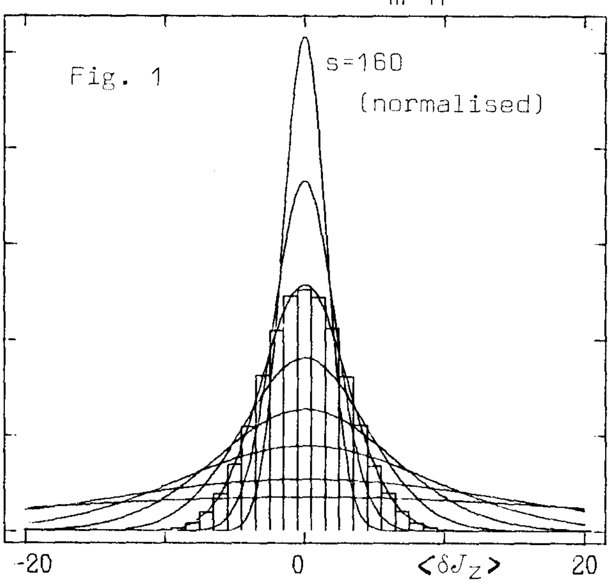
https://doi.org/10.1017/S0252921100098456 Published online by Cambridge University Press

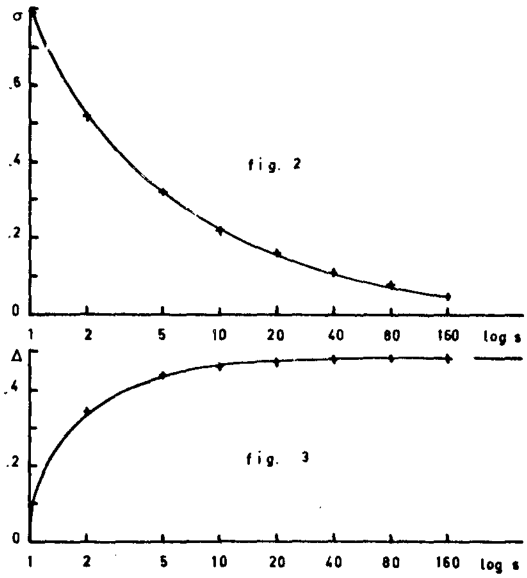
## THEORETICAL DISCUSSION

The starting idea of this analysis was to apply Purcell's theory to spheroidal particles. The impossibility of inducing any suprathermal torque along the symmetry axis for such grains (an essential condition for SSA) was avoided assuming that each active site had a preferential direction of molecular ejection, allowing then for a tangential impulsive force. The point is subject to discussion, but this is out of the frame of this short paper.

The grain surface of a 2:1 prolate spheroid was then divided into 10000 equivalent elements among which a fixed number ($s$) of active sites with their ejection direction were randomly selected. We then computed the mean and mean square of the impulsive angular momentum variation corresponding to a great number (50000 and 100000) of such configurations with the same $s$, also randomly generated. The histogram of fig. 1 shows, for $s$=40, the deduced distribution of the grains with respect to $\langle \delta J_z \rangle$ in units of $a(E_m m_H)^{1/2}/20$, where $a$ is the transverse radius, $E_m$ the part of the recombination energy converted to kinetic energy. This distribution is fairly well described by a gaussian curve; this is confirmed by 7 other runs, with $1<s<160$, for which only the adjusted curve is plotted.

Two quantities are then derived from each distribution (the outer brackets denoting the average on the configurations) : the dispersion $\sigma=(2\langle\langle \delta J_z\rangle^2\rangle)^{1/2}$ of the gaussian approximately equal to $.7\,a\,s^{-1/2}(E_m m_H)^{1/2}$ (fig 2), and the mean fluctuation $\Delta=(\langle\langle \delta J_z^2\rangle-\langle \delta J_z\rangle^2\rangle)^{1/2}$ (fig 3), fast increasing from zero ($s$=1) to an asymptotic value of $.4883\,a\{2(E_m m_H)^{1/2}\}$, which is derived from an analytical expression.




In a situation where the collisional damping time $t_c$ is short with respect to the re-surfacing time $t_s$ (ideal suprathermal case), the acceleration produced by the mean resulting torque $n_m \langle \delta J_z \rangle$, where $n_m$ is the number of hydrogen molecules leaving the grain surface per time unit, will be damped after a time of the order of $t_c$ and will induce a stationary mean angular momentum of $n_m t_c \langle \delta J_z \rangle$ around which the grains will be gaussian distributed (micro-distribution), because of the different thermal excitation processes (Purcell, 1979), among which the most important one is generally related to the fluctuation $\Delta$ defined above. We shall also define a "macro-distribution" which is the gaussian distribution of the stationary values of $\langle J_z \rangle$, whose dispersion is equal to $n_m t_c \sigma$. It must be emphasized that if a temperature can be associated with the micro-distribution, this is not the case with the macro-distribution as long as exchanges of grains between "cells" of the angular momenta space are impossible. It may be confirmed, using a simple one-dimentional F-P equation, that the stationary situation is well the state described above whith the dispersion of the micro-distribution equal to $(n_m t_c)^{1/2}\Delta$. The comparison between both dispersions provides in our "ideal" case a way of measuring the efficiency of SSA versus ETSA. We then define $g = n_m t_c \sigma/\{(n_m t_c)^{1/2}\Delta\} = (n_m t_c)^{1/2}(\sigma/\Delta)$. With the above expressions for $\sigma$ and $\Delta$ and using Cugnon's formulation, we obtain, for a 2:1 prolate spheroid, $g \simeq 2\{(fM)/(s\,m_H)\}^{1/2}$ where $M$ is the mass of the grain and $f$ the fraction of incoming hydrogen atoms which leaves the grain as molecules. When assuming realistic intervals of variation for the parameters, i.e. $10^8 \lesssim M/m_H \lesssim 10^{10}$, $10 \lesssim s \lesssim 1000$, $1 \lesssim f \lesssim 1$, we obtain $10^2 \lesssim g \lesssim 10^5$, so that if we associate a "pseudo-temperature" with the macro-dispersion, it will be generally quite higher than the rotational temperature $T_{eff}$ defined by Purcell. This makes ETSA generally impossible under our ideal assumption. However, re-surfacing can occur much more frequently. The other extreme limit corresponds to $t_s \ll t_c$, at which a grain then suffers a great number of mean impulsive torques gaussian distributed (fig 1). The resulting net torque vanishes, allowing then for ETSA. For intermediate cases, this torque will not vanish, but will be statiscally reduced compared with the torque computed for the ideal case, the amplitude of this reduction depending on the number $q$ of complete re-surfacing. The resulting macro-dispersion for $\langle J_z \rangle$ will also decrease with increasing $q$. A very rough approach consists of saying that $q$ resurfacing correspond to multiply the number of emitting sites by a factor $q$, so that $g$ becomes $2\{(fM)/(qsm_H)\}^{1/2}$. If this is not too bad, the conditions in which ETSA becomes operative ($g \sim 1$) are certainly peculiar but not too exotic. The next section will examine some consequences of this provisional conclusion.

## POLARIZATION AND INTERSTELLAR PHYSICAL PARAMETERS

It is well-known that for thermal D-G mechanism the magnetic field intensity can be calculated using a theoretical expression of the degree of alignment, this quantity being itself deduced from the observed ratio of polarization to extinction. A formula has been proposed for this purpose by Cugnon (1983), which takes into account asymptotical calculation combined with the main results obtained in this domain (Purcell and Spitzer 1971; Cugnon 1971; Greenberg 1978). Unfortunately the formulation of SSA is not so firmly established because of uncertainties in the role of some parameters; furthermore, it is still difficult to predict the final state of orientation for prolate grains. The situation naturally appears still more complicated for intermediate cases between SSA and ETSA. Consequently, very few can be said about the field strenght when SSA is working except that it is lower than the field required to achieve ETSA.

It has been shown above that SSA overcomes ETSA in most interstellar situation so that estimating the magnetic field using formulations of classical D-G alignment appears now subject to criticism. From this point of view, we shall now examine rapidly the case of two nearby regions which have been studied in details by Coyne et al. (1979)(I) and Vrba et al. (1981)(II). It appears that in case (I), the observed densities and temperatures are not far from the diffuse ISM values. The $\lambda_{max}$ distribution is also similar to-, though broader than the general ISM curve. Because of this similitude, we assume, like Johnson (1982), that long-lived active sites make SSA efficient in this region, so that the magnetic field may be quite smaller than the value of 200 μG proposed by the authors. On the other hand, in the dark cloud of R Coronae Australis (II), the distribution of grain sizes seems to permit local situations where frequent re-surfacing by accretion may occur. It is then possible that in certain regions of this cloud, the ETSA formulation can be used in order to obtain the magnetic field intensity. Using Cugnon's expression of Rayleigh reduction factor and the values of the physical parameters taken from Vrba et al., we obtained, for the same elongation of .2, a value of the field of about 100 μG, thus very close to the value found by the authors (classical TSA, $T_{rot} = T_{gas}$). However, if ETSA is assumed with $300 < T_{eff} < 500$ K (this is not critical), and elongations around .4, the field is reduced by a factor 2. Furthermore, under slightly thus reasonable different assumptions on gas and grain temperatures and densities, grain size and elongation, a factor 3 between extreme estimations of the field may exist, i.e. from 40 to 120 μG in this particular case. However, such a situation would be present quite generally in the few regions where ETSA may be supposed to act, despite the fact of a well-established theoretical formulation.

Let us now have a look on the temperatures and densities which can play a role in the different spinning alignment processes. In classical TSA, the ratio of two temperatures $\xi = T_{gra}/T_{rot}$, where $(T_{gas}+T_{gra})/2 \leq T_{rot} \leq T_{gas}$, depending on the type of collisions, plays a fundamental role; $\xi=1$ implies no polarization and one could expect for $\xi>1$ an inversion of the polarization. This point is important in clouds where $T_{gra}$ is approaching $T_{gas}$ (Johnson 1982). The role of the gas density is also fundamental, for the collisional damping time increases with decreasing gas densities; this could made the alignment easier in regions poor in gas where the occasional presence of important quantities of dust is expected. This conclusion also holds for ETSA. In this case, however, the temperature ratio $\xi=T_{gra}/T_{eff}$ is much smaller than for TSA so that it can be put equal to zero in most cases. For SSA also, the grain temperature appears not to be a relevant parameter. In this late case, one should also expect that higher gas densities could make the alignment more difficult. However, the ratio of the re-surfacing time by accretion to $t_c$ appears to be quite independant of gas densities and temperatures, but very sensitive to depletion (Greenberg 1978, 1983).

This rapid survey shows the importance of collected results from independant sources, and how this collection can help to decide between one or another mode of magnetic alignment. However, a point to point comparison appears to be necessary, implying a relatively important number of stars behind the dusty region studied, a good angular resolution of the measurements, and a rather unimportant column density of dust in front of it. These conditions are best fulfilled in the local ISM; the two regions quoted above are good examples of this conclusion.

REFERENCES.

Aannestad P.A., Greenberg J.M. 1983, Ap. J. 272, 551.
Coyne G.V., Tapia S., Vrba F.J., 1979, Astr. J. 84, 356.
Cugnon P., 1971, Astr. Ap. 12, 398.
Cugnon P., 1983, Astr. Ap. 120, 156.
Greenberg J.M., 1978, in *Cosmic Dust* ed. J.A.M. McDonnell, (New-York, Wiley), p. 187.
Johnson P.E., 1982, Nature 295, 371.
Purcell E.M., 1975, in *The Dusty Universe* ed. G.B. Field & A.G.W. Cameron, (New-York, Neal Watson), p. 155
Purcell E.M., 1979, Ap. J. 231, 404.
Purcell E.M., Spitzer L., 1971, Ap. J. 167, 31.
Spitzer L., McGlynn T.A., 1979, Ap. J. 231, 417.
Vrba F.J., Coyne G.V., Tapia S., 1981, Ap. J. 243, 489.



https://doi.org/10.1017/S0252921100098456 Published online by Cambridge University Press