N91-14908

ALIGNMENT MECHANISMS OF PARAMAGNETIC GRAINS REVISITED

M. Seki
College of General Education, Tohoku University
Sendai 980, Japan

ABSTRACT

Taking into account the tight coupling of grain axis with angular momentum due to effective dissipation of rotational energy, we have re-investigated the alignment of spheroidal grains by paramagnetic relaxation. Alignment degree will be significantly improved in diffuse clouds. The inclusions of superparamagnetic (SPM) substances may play a key role in grain alignment in dark clouds as well as in diffuse clouds.

INTRODUCTION

The linear polarization observed in many reddened stars is generally assumed to be produced by alignment of anisotropic grains in the magnetic field. According to Davis and Greenstein (1951, referred to hereafter as "DG"), the angular momentum of a grain J will align with respect to magnetic field B and the principal axis of greatest inertia A tends to line up with J by paramagnetic absorption of the rotational kinetic energy. The magnetic field calculated on the DG theory is much larger than that has been measured. Seki and Hasegawa(1986) reinvestigated the DG mechanism for spheroidal dielectric grains by taking into account the tight coupling of grain axis A with J due to effective dissipation of rotational energy by the internal friction or by the Barnett effect (Purcell 1979). They find that the alignment degree of A with respect to B is distinctly improved.

In some dark clouds, where optical or IR polarizations possibly caused by aligned grains are observed (Vrba et al,1981;Seki and Hasegawa 1987;Hildebrand 1988),the temperatures of the gas and of the dust are so low that alignment by paramagnetic relaxation seems to be difficalt. The "pinwheel" mechanism may be ineffective either,because hydrogen is mainly in molecular form and there exist few UV photons.

Jones and Spitzer(1967) and Mathis(1986) suggest that a part of interstellar grains are superparamagnetic(SPM). In the present paper, we will examine the effect of the imaginary part of magnetic susceptibility χ'' on polarization efficiency of spheroidal grains on the basis of the "improved" DG mechanism.

DEPENDENCE OF POLARIZATION EFFICIENCY ON χ''

We consider a cloud of identical dielectric spheroids spinning in a uniform magnetic field B. The ratio of polarization P(%) to A_V(mag) is a measure of polarization efficiency of the cloud. If P/A_V is not large and the grain size is smaller than the wavelength at V, we may write the polarization efficiency as follows;

$$P/A_V = (P/A_V)_{pf} \cdot Qa \cdot \sin^2 \nu ,$$

where $(P/A_V)_{pf}$ is the polarizing effectiveness for picket-fence alignment, Q_a is the alignment degree of grain axis with respect to magnetic field, and ν is the angle between the line of sight and the direction of magnetic field. Values for $(P/A_V)_{pf}$ are obtained from Rogers and Martin (1978). The alignment parameter is expressed as

$$Q_a = \langle P_2(\cos(A,B)) \rangle ,$$

where angular brackets denote an ensemble average. If the angles (J,B) and (A,J) are uncorrelated, $Q_a = Q_j \cdot Q_x$. Q_j and Q_x are calculated following Seki and Hasegawa (1986) and Purcell and Spitzer (1971).

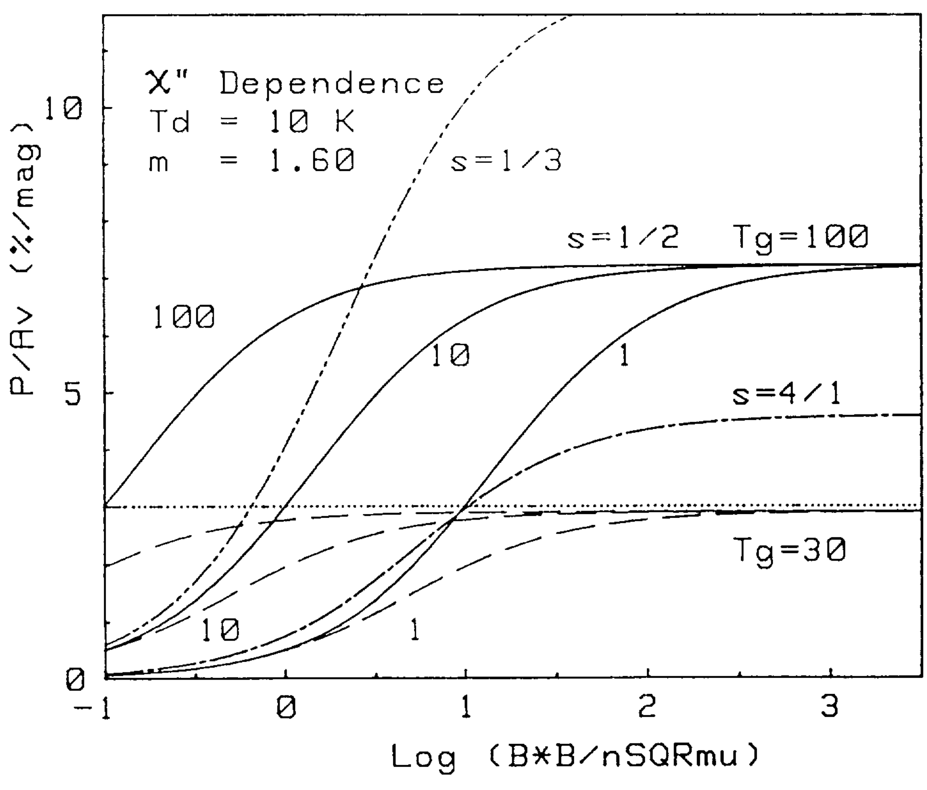

Figure 1. Dependence of P/A_V on the magnetic susceptibility of the grain. The equivalent radius is 0.1μm.

Taking $\nu = 90°$, we show in Figure 1 the polarization efficiency as a function of magnetic field strength for various grain models. The horizontal dotted-line represents the observed efficiency of 3 %/mag. In every case, P/A_V increases monotonously with $B^2/\sqrt{\mu n_g}$ and approaches asymptotically to an upper limit. (μ : the mean molecular weight of the gas; n_g : the number density.) The limiting value depends on the grain's shape (s), the temperatures of the gas (T_g) and of the dust (T_d), and the refractive index (m) via $(P/A_V)_{pf}$.

For $\omega \ll 10^9$ sec^{-1}, $\chi''(\omega)$ is approximately given as

$$\chi'' = 2.5 \cdot 10^{-12}\, k\, \omega / T_d,$$

where k = 1 gives χ'' found in most paramagnetic substances. In order to see the effects of SPM inclusions, we have made calculations of P/A_V by simply changing the value of k. The numeral (1,10,or 100) by each curve in Figure 1 represents the value for k. Evidently, the curve of P/A_V vs B^2/n_g shifts in the horizontal direction by changing the paramagnetic susceptibility coefficient k; that is, k is a factor by which the effect of B^2/n_g on the degree of grain alignment is amplified. The effect of SPM inclusions appears significant for low values of B^2/n_g, say, for $B^2/n_g < 10\ (\mu G)^2/cm^{-3}$. This comes from the fact that Q_j is proportional to the ratio of the magnetic to gas-friction torques δ for a small value of δ, which in turn varies as $(k/(r_{eq} + k) \cdot (B^2/n_g)$, where r_{eq} is the equivalent radius of the grain.

Assuming that B scales as $n_g^{0.5}$ and taking $B \approx 10$ μG at $n_g = 10^2$ cm^{-3} (Heiles,1987; Myers and Goodman, 1988), we get $B^2/n_g \approx 10^0$. Then, it seems from Figure 1 that inclusions of SPM substances with $k \approx 10$ are required for oblate grains with T_d = 10 K and axial ratio 1/2 in diffuse clouds. The temperature of the gas in a dense and quiet cloud may be much lower than that in the environment. As is demonstrated in Figure 1, polarization efficiency by the same grains may be reduced by a factor of about 2 in the gas of T_g = 30 K. However, the reduction factor is not so large at $B^2/n_g \leqq 10^{0.5}$ and the derived efficiency at $B^2/n_g = 10^0$ is 2 %/mag. Evidence for the decrease of polarization efficiency with increasing optical depth has been found in several dark clouds (Vrba et al.,1981; Seki and Hasegawa, 1987). Therefore, the calculated efficiency is not necessarily inconsistent with the observed one.

Table 1 is a summary of our results. Alignment degree of dielectric spheroidal grains will be significantly improved if the tight coupling of grain axis with angular momentum is taken into account. Inclusions of SPM substances may play an important role in grain alignment in dark clouds as well as in diffuse clouds.

REFERENCES

Davis,L.Jr. and Greenstein, J.L.: 1951, Astrophys. J. 114, 206

Heiles, C.: 1987, in "Interstellar Processes" (eds. D.J.Hollenbach and Thronson,Jr.), p. 171.

Hildebrand, R.H.: 1988, Astron. Lett. and Communications, 26, 263.
Jones, R.V. and Spitzer, L.Jr. ; 1967, Astrophys. J. 147, 943.
Mathis, J.S.: 1986, Astrophys. J. 308, 281.
Myers, P.C. and Goodman, A.A.: 1988, Astrophys. J. 326, L27.
Purcell,E.M.: 1979, Astrophys. J. 231, 404.
Purcell, E.M. and Spitzer, L.Jr.: 1971, Astrophys. J. 167, 31.
Rogers, C. and Martin, P.G.: 1978, Astrophys. J. 228, 450.
Seki, M. and Hasegawa, T.I.: 1986, Sci. Rep. Tohoku Univ. 7,135 (=Sendai Astronomiaj Raportoj Nr.307).
Seki, M. and Hasegawa, T.I.: 1987, in "Star Forming Regions" (IAU Symp. 115,eds. M.Peimbert, and J. Jugaku), p. 82.
Vrba, F.J., Coyne, G.V. and Tapia, S.: 1981, Astrophys. J. 243, 489.

Table 1. Magnetic Field Strengths Needed for P/Av = 3 %/mag *)

Alignment	Axial Ratio	χ'' **)	$B^2/\sqrt{\mu} n_g$	B (μG) n_g=10 cm^{-3}	B (μG) 1 cm^{-3}
Classical DG	1 : 2	1	-----	-----	-----
	4 : 1	1	1000	100	30
	4 : 1	10	400	63	20
Improved DG	1 : 2	1	10	10	3
	1 : 2	10	1	3	1
	1 : 2	100	0.1	1	0.3
	4 : 1	1	100	30	10
	4 : 1	10	10	10	3
Tg = 30 K	1 : 2	10	100	30	10 *)
Pin Wheel (PW)	1 : 2	1	1.4	3.7	1.4
	4 : 1	1	6	7.8	2.5

*) For grains with m = 1.6, r_{eq} = 0.1 μm, and Td = 10 K in the gas of μ=1 at Tg = 100 K. Minimum magnetic fields for grains with χ'' = 1 are from Seki and Hasegawa (1986).

**) In units of $2.5 \times 10^{-12}\ \omega / Td$.