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STELLAR SPOTS-HEATING AND COOLING DIAMAGNETICALLY.

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ABSTRACT Diamagnetic effects as heating and cooling mechanisms at stellar surfaces have been ignored in the past. This is due to the misconseption that the effect, when averaged over a velocity distribution, vanishes. We explore here the relevance of the effect to the observed luminosity and color modulations observed in CP stars.

INTRODUCTION: MOTIVATION

There are CP stars exhibiting light and spectral variations. These can be understood in terms of thermal and chemical spots at the surface of a rotating star.
Some difficulties in matching theory with the empirical data, include:
(1) Anti-phase luminosity variations on the two sides of a "null" wavelength have been observed. λ_0 is correlated with stellar temperature, such that it increases with decreasing effective temperature (Leckrone et.al.,1974).
Such observations could be accounted by backwarming: UV spectral line variations of some elements indicate indeed local partial blocking of the UV continuum, and hence warming the underlying layers. As the blocking increases, the UV intensity will diminish, while that in the visible will increase.
There are, however, Ap stars whose light variations cannot be explained by backwarming (e.g. HD 111133 does not exhibit line variation, yet its luminosity does vary (Wolf,1976; Schoeneich, 1981); in HD 215441 light and spectral variations are not agree with backwarming and line-blocking effects (Polosukhina,1992).
In their study, Schoeneich and Staude (1976) have tried to explain the observed different light curves at various wavelengths, for different stars. They have introduced a three parameter family of luminosity models for atmospheres. Their parameters are:
(a) The "cool" temperature of a spot;
(b) The "elevated" temperature above the "cool" spot;
(c) The fraction of the visible disk covered by such spots.
These semiempirical models can be fit to the data, but do not explain the physics of cooling or heating.

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(2) There are indications of CP stars with chromospheres and coronae. Thus, α And and Feige 86 show Si IV, N V and C IV lines (Hack,1981). Shore et al.(1990) observed phase dependent C IV and Si IV profile variations in peculiar stars.

Shore et.al.(1990) explain them in terms of an oblique rotator whose atmosphere is cooler at the magnetic poles and warmer at the magnetic equator. The mechanism behind these thermal differences is not identified. We are thus led to explore a temperature differentiating mechanism in the following sections.

SPEED FILTERS AND DIAMAGNETIC HEAT PUMPS (DMHP)

We first consider the motion of a single charged particle in a non-uniform magnetic field, and the ensuing speed filter when combined with gravity. Subsequently we point out some difficulties encountered in passing to a fluid description, and finally we resolve them by taking the correct averages.

It is well known that a charged particle, moving in a (geometrically) diverging magnetic field, experiences a diamagnetic effect (DME) such that it is being pushed out of regions with large $\mathbf{B}^2$ (field intensity) into regions of low $\mathbf{B}^2$. Fermi (1949,1954) discussed the effect in connection with cosmic ray acceleration. It is also well known that charged particles trapped in the geomagnetic field oscillate between the magnetic poles. The combination of the DME and gravity yields speed filters.

In figure 1 we consider a "floating" charged particle, experiencing both gravity $\mathbf{mg}$ and the Lorentz force $\mathbf{F}_L$. Let the charged particle $(\mathbf{e},\mathbf{m})$ have a velocity $\mathbf{v}_\perp$ orthogonal to the magnetic field lines in a horisontal plane. The magnetic field $\mathbf{B}$ is supposed to (geometrically) diverge so that $\mathbf{B}^2$ decreases with hight. Suppose that $\mathbf{v}_\perp$ has such a magnitude that the vertical component of the Lorentz force exactly balances the weight $\mathbf{mg}$. The charged particle will float at a given hight, without falling down, although collisions are not yet included.

Consider now what happens when the floating particle collides with another particle. If now $\mathbf{v}_\perp$ increases, so does $\mathbf{F}_L$, and the particle will oscillate between two levels, but the average level it finds itself in, is higher compared to the original "floating" level. Conversly, if $\mathbf{v}_\perp$ decreases, we find the particle, on the average, lower.

Collisions thus cause the particles with large $\mathbf{v}_\perp$ to diffuse up, those with low $\mathbf{v}_\perp$ to diffuse down. Looked at this differently, we can state: The competition between gravity (down) and the DME (up) in a plasma with collisions, result in

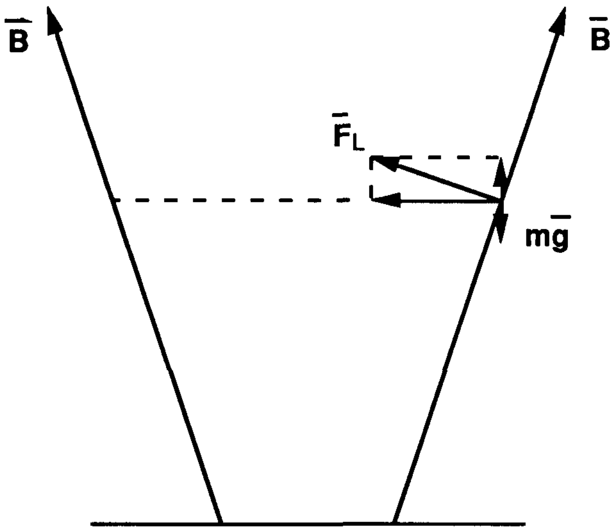

Fig.1. The speed filter. The Lorentz force, $\mathbf{F}_L$, is orthogonal to the local field direction.

a speed filter. From the point of view of statistical mechanics, the speed filter is essentially a heat pump. Heat is being pumped up into the corona; simultaneously the spot below is being cooled. Incidentally, the mechanism, i.e. the heat pump, operates without the need for convection or any kind of waves.

DIFFICULTIES WITH THE FLUID (MHD) DESCRIPTION

Passage from the single particle picture to that of a fluid (i.e. the MHD equations), involves usually the Boltzman equation (Spitzer,1962):

$$\frac{\partial f}{\partial t} + \overline{v} \cdot \nabla_r f + \frac{1}{m} \overline{F} \cdot \nabla_v f = \left(\frac{\partial f}{\partial t}\right)_{coll} \qquad (1)$$

$f(\overline{v},\overline{r},t)$ is the distribution function of the particles. At this level, the description is in terms of microscopic quantities - the single particle's velocity $\overline{v}$, and the force $\overline{F}$ experienced by such a particle.
To obtain the (macroscopic) momentum balance equation, the standard procedure is to multiply equation (1) by $m\overline{v}$, and integrate over velocity space. From the third term in equation (1), one obtains the macroscopic bulk effect of the microscopic Lorentz forces acting on the charged particles:

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$$\langle \overline{F}_L \rangle = e \langle \overline{v} \times \overline{B} \rangle = e \langle \overline{v}_\perp \rangle \times \overline{B} \qquad (2)$$

Here <Q> denotes the average of any quantity Q over velocity space. It is clear that the resultant macroscopic force either vanishes ($\langle \overline{v}_\perp \rangle = 0$), or yields a vector that does not have a component along the local field **B**. Thus the DME vanishes altogether. We now have the peculiar situation, that the diamagnetic effect, always in the same direction (from strong to weak field intensity, along the field), does not appear any more in the MHD description!

RESOLVING THE DIFFICULTIES.

That the DME "goes away" upon averaging in velocity space, is a common misconception, due to wrong averaging. The averaging described in the previous section is essentially an ensemble average. In his work, Gibbs originally suggested to replace dynamic quantities obtained through the correct time averaging, by an ensemble average. The assumption made (and not always explicitely stated) is that both averages ($\langle\ \rangle_{ensemble}$, $\langle\ \rangle_{time}$) yield the same. We show how this fails for the DME. In fig.2 a charged particle is initially at A (time t=0) on the field line indicated with $\hat{n}_0$. As the particle gyrates in the (geometrically) diverging field, the Lorentz force $\mathbf{F}_L$ has a component along $\hat{n}_0$. This is shown for the $\mathbf{F}_L$ when the particle is for example at D.

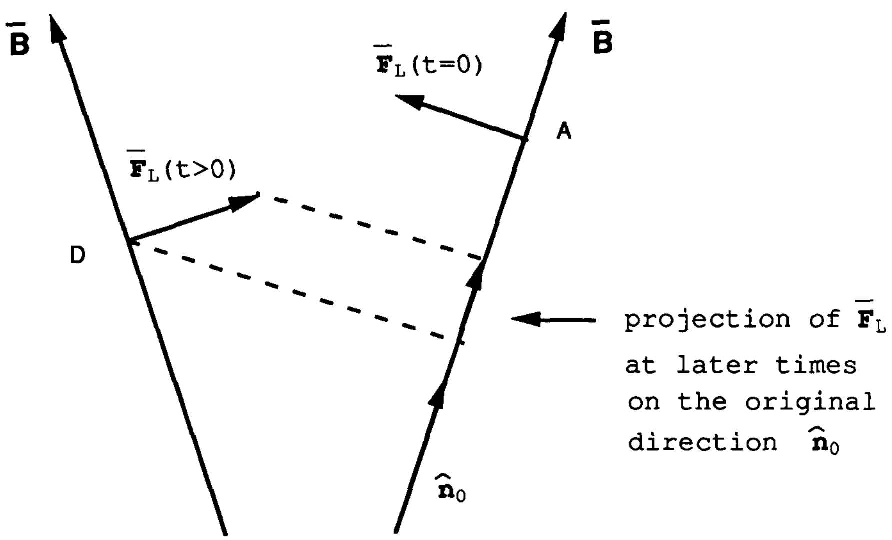

Fig.2. Projecting the Lorentz force at different times on the original direction $\hat{n}_0$.

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We note the following:

(a) The only times that the projection of $\mathbf{F}_L$ on the initial $\hat{\mathbf{n}}_0$ vanishes, is whenever the particle is in the direction $\hat{\mathbf{n}}_0$, specifically at t = 0.

(b) The projection of $\mathbf{F}_L$ on $\hat{\mathbf{n}}_0$, i.e. $\mathbf{F}_L \cdot \hat{\mathbf{n}}_0$, is always positive, irrespective of the sign of **B** or the charge **e**, provided the particle is not in the $\hat{\mathbf{n}}_0$ direction.

It is now clear why the ensemble average fails to represent the (dynamic) DME: The ensemble average is chosen to be made when t=0, just at the moment that $\mathbf{F}_L \cdot \hat{\mathbf{n}}_0 = 0$.

Thus, the ensemble average does not yield a correct description of the diamagnetic effect. The momentum equation (and the heat equation) have to be modified, to incorporate the time average (instead of the ensemble average) of the DME.

CONCLUSION

Since Ap stars, and possibly all CP stars, have magnetic fields, the diamagnetic heat pumps must be operating at their surfaces, causing a modification of the thermal structure of their atmospheres. It will therefore be helpful to have field measurments which can yield field gradients. These are neccessary because the efficiency of the heat pump depends on the rate of geometric divergence of the field structures (i.e. $\nabla(\ln \mathbf{B}^2)$), and also on the plasma density and gravity.

With such data available, one can model cool spots at the CP stellar surface and modify thermal structure with height.

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