DIFFUSION PROCESSES AND CHEMICAL PECULIARITIES IN MAGNETIC STARS

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ABSTRACT. This review tries to expose some essential aspects of our current understanding of diffusion processes in magnetic CP stars. Many problems remain to be explained due to the fact that the presence of strong magnetic fields increases the number of free parameters in "diffusion models". More observational constraints are needed before one can attempt modelling every aspects of magnetic CP stars.

1. SOME GENERALITIES CONCERNING DIFFUSION OF ELEMENTS AND MAGNETIC CP STARS

Many papers, since the initial work of Michaud (1970), have exposed how elements may diffuse in stars (see the review papers by Michaud, 1980, Vauclair, Vauclair, 1982, and Alecian, Vauclair, 1983). In this section we shall try to show very briefly, why diffusion appears to be a powerful mechanism in explaining Chemically peculiar (CP) stars even if many problems remain to be solved.

1.1 How diffusion answers the global constraints deduced from the observations

From the whole set of informations given by the observations, one may work out a list of global minimum constraints which must be satisfied by any theoretical model for magnetic CP stars. We list them as follows:

(i) the anomalies affect the outer layers of the CP stars;
(ii) the anomalies must appear in a much smaller time than the stellar life time on the Main Sequence;
(iii) the phenomenon occurs in a well defined interval of T_{eff};
(iv) in this interval, there are several categories of CP depending on T_{eff};
(v) the peculiarities of magnetic CP are different from non-magnetic CP , for the same T_{eff};
(vi) in each category, there is an important diversity of abundance

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peculiarities from star to star.

The diffusion processes are considered to be efficient in CP stars, because these constraints are satisfied respectively as follows:

(i) diffusion is efficient in the outer layers (more than in deeper layers);
(ii) diffusion may build anomalies in times smaller than 10^4 years in stable atmospheres;
(iii) the effects of diffusion are destroyed if macroscopic motions are too strong. For instance, strong turbulence, convection or meridional circulation mix the stellar material and chemical differentiation cannot be established. On the other hand,strong mass losses carry away the atmospheric material faster than diffusion builds stratifications. Now, mixing and mass loss seem too be minimum in the range of T_{eff} where CP stars are found;
(iv) diffusion is very sensitive to T_{eff} and log g (through the radiative acceleration g^{rad} and the hydrodynamical situation which prevails), therefore, different abundance anomalies are obtained according to the spectral type;
(v) diffusion is very sensitive to the magnetic field in the atmosphere (above $\tau_{5000} \simeq 10^{-1}$);
(vi) All the parameters needed to describe completely a given star and which are important in how diffusion occurs, are not accurately known (essentially hydrodynamical ones). On the other hand, diffusion is a time dependent process: a given star may have several phases of peculiarities.

In the following sections of the present review, we shall put emphasis on two of these last points: magnetic field and time-dependent diffusion.

We do not consider that any other process than diffusion must be excluded in explaining the CP phenomenon, but all the processes which have been invoked till now, have appeared to be inadequate (see the comments of Bonsack, 1981). As for an example, the accretion process (which certainly exits more or less) cannot be considered as an alternative with respect to diffusion (Michaud, 1976): if mixing motions are too strong for diffusion, they are also too strong for accretion. And, for stable outer layers, the accreted material must diffuse as well as the original one. In this case, diffusion is much more efficient than accretion and well correlated with T_{eff} while accretion is not. Finally, accretion appears to be a secondary effect compared to diffusion.

1.2 A possible scenario for magnetic Ap stars.

According to the theoretical works on diffusion in CP stars during the last fifteen years, a possible scenario is given in figure 1. This scenario explains how a star may become an Ap star. Of course this scenario is very schematic and more sophisticated ones could be imagined.

The arrival on the main sequence is probably associated with some braking

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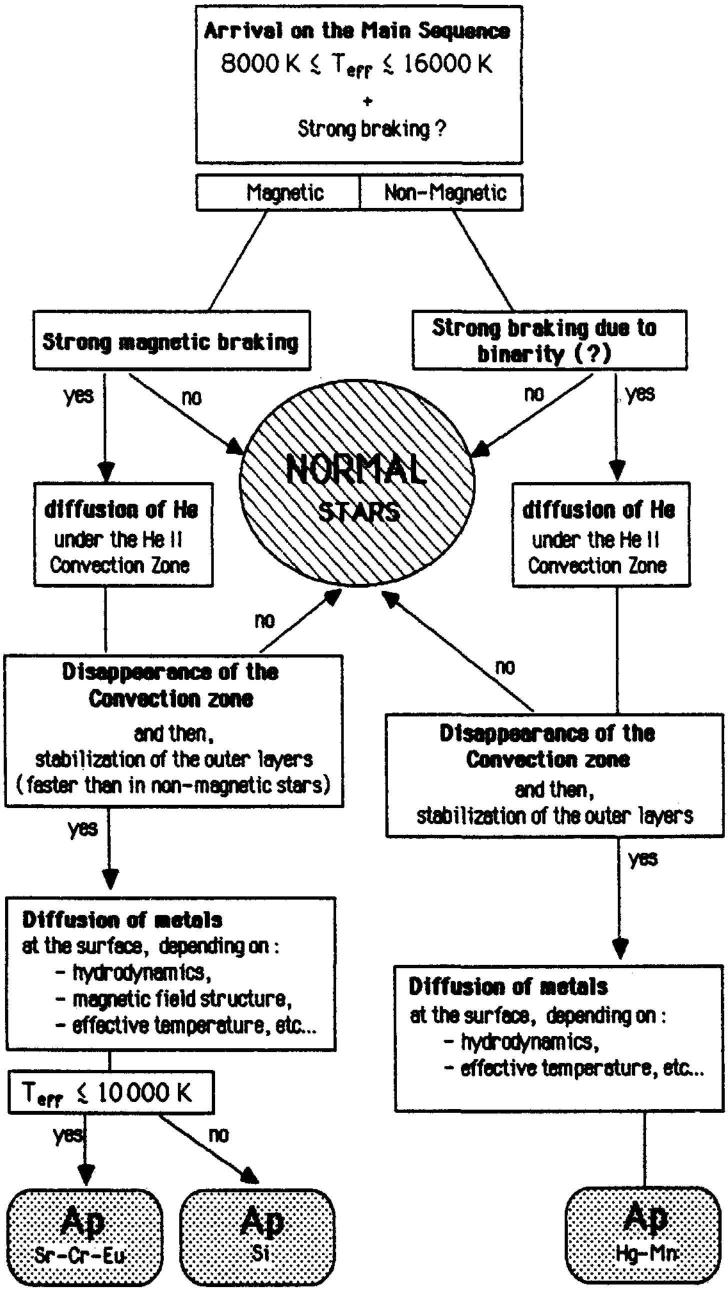

Figure 1
A possible scenario for Ap stars

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mechanism which will help the star to be more stable than others having the same mass. This former step is rather badly known, but once the mixing processes occurring at the bottom of He II ionization-convection-zone, are practically smoothed out, helium may settle down by diffusion. When helium becomes underabundant in the outer envelope this leads to the disappearance of the convection zone and then, to the stabilization of atmospheric mixing motions. After that, efficient diffusion processes can start in the atmosphere, the detailed behavior depending on hydrodynamics, magnetic field structure and intensity, and also, on the effective temperature.

This scenario is almost the same for magnetic (Sr-Cr-Eu; Si) and non-magnetic (Hg-Mn) Ap stars except for the braking mechanisms. The rotational velocity is probably reduced by the magnetic field for magnetic stars and by something like tidal effects in the case of binaries for the non-magnetic stars. On the other hand, the presence of a strong magnetic field stabilizes the atmosphere before the He settling is complete. In that case, diffusion may go on in the atmosphere, shortly after the arrival on the Main Sequence and therefore, peculiarities appear faster than in non-magnetic Ap stars. This explains why the ratio of the number of magnetic Ap stars vs non-magnetic, is higher in young clusters (Michaud, 1981).

2. DIFFUSION IN PRESENCE OF A MAGNETIC FIELD

When magnetic field is present, the diffusion velocity may be written as follows:

$$v_{Di} = \frac{D_i}{1 + \omega_i^2 t_i^2} \left[\ldots + \frac{m_i}{kT} (g_i^{rad} - g) + \ldots \right] , \quad (1)$$

with $\omega_i = \dfrac{ZeH}{m_i c}$,

and :

$$v_D \simeq \frac{\sum_i N_i v_{Di}}{\sum_i N_i} , \quad (2)$$

$i = 0, 1, 2, \ldots$

where D_i is the diffusion coefficient of the ion i, m_i its mass, g_i^{rad} the radiative acceleration, g the gravity, t_i the collision time, ω_i the gyro-frequency, Z e the ion charge, H the intensity of the horizontal component of the magnetic field, k, T and c are respectively the Boltzman constant, the local temperature and the light velocity. The velocity v_D (expression (2)) is a ponderated mean value which approximates, in the case of horizontal or zero magnetic field, or high densities (optically thick medium), the

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average velocity of the whole element (see the detailed study by Montmerle and Michaud (1976)).

In expression (1), we have only shown the terms which are the most important ones in usual cases, for more complete expressions see the review paper by Alecian and Vauclair (1983). As shown in expression (1) horizontal magnetic field affects diffusion through $\omega_i^2 t_i^2$ term: for zero magnetic field, neutral atoms, or high densities (which implies very small t_i) this term cancels out.

In CP stars, the presence of magnetic field may have important consequences on how diffusion occurs for some elements. Silicon provides a typical example of such a case. This element is often found overabundant in magnetic stars (about 10 to 10^2 with respect to solar abundance) while it is found normal or slightly overabundant in non-magnetic stars (Hg-Mn). This behavior has been first explained by Vauclair et al (1979) and studied after in more details by Alecian and Vauclair (1981). In the case of zero magnetic field (or when magnetic field lines are vertical), silicon is very weakly supported by the radiation field: Si II and Si III settle down while Si I goes toward the surface, the mean velocity v_D is slightly positive (element moves upward) and a weak overabundance (a factor 10) may be obtained at the stellar surface. Now, if there is a strong horizontal magnetic field (stronger than 5000 Gauss), the downward motion of the ions is impeded above $\tau_{5000} \simeq 10^{-1}$, and there, the negative contribution of the ions becomes weaker in v_D. This leads to higher overabundances (about a factor 10 to 10^2 can be obtained by diffusion in the atmosphere).

Other elements may also have special behavior in the presence of magnetic field. For instance boron, which has a strong positive v_D, can be overabundant only if there is a magnetic field (Borsenberger et al, 1981). Generally speaking, the less an element is abundant with respect to hydrogen the more it is pushed up by the radiation field, the detailed behavior depending on its atomic properties. Elements like boron, which are strongly pushed through the stellar outer layers by the radiation field, will reach the surface whether the star is magnetic or not, and then strong horizontal magnetic lines will force them to accumulate high in the atmosphere, before they leave the star.

Some other elements may also accumulate in the "line forming" region before reaching the place where magnetic field can trap them. In that case, these elements must show the same kind of overabundances than in non magnetic stars.

Actually, the situation is much more complex in real cases, since the magnetic field lines may have various angles with respect to the horizontal and in this case, the mean diffusion velocity $\mathbf{v}_D$ is no more vertical but it is the sum of a vertical and horizontal component (cf. Alecian and Vauclair, 1981). In spite of these difficulties, some predictions are possible. For instance Vauclair et al (1979) and, Alecian and Vauclair (1981) have predicted that silicon is preferentially overabundant at places where the magnetic lines are horizontal. However, horizontal diffusion (horizontal component of $\mathbf{v}_D$) may change this feature (Mégessier, 1984), we shall discuss that problem in the next section.

All these studies have been made in the framework of the "oblique rotator model": the diffusion processes in the magnetic field, will produce patches and rings according to the geometry of magnetic lines. Michaud et al (1981) have studied this in detail.

3. TIME-DEPENDENT DIFFUSION

Expression (1) allows the computation of the diffusion velocity at a given place in the medium and for a given concentration of the considered element. Starting from an homogeneous concentration of that element throughout the star, diffusion may create abundance stratifications if mixing motions are not too strong. These stratifications may be interpreted as abundance anomalies by the spectroscopists, as far as the line forming region is concerned. Strictly speaking, the detailed computation giving a qualitative and quantitative description of these stratifications, is required in order to make any theoretical prediction on what kind of abundance peculiarities may be observed.

Abundance stratifications are obtained by solving the continuity equation:

$$\partial_t N + \boldsymbol{\nabla}.(N\mathbf{v}) = 0 \ , \qquad (3)$$

where:

$$N = N(\mathbf{r},t) \ , \qquad (4)$$

and :

$$\mathbf{v} = \mathbf{v}_D(N(\mathbf{r},t),\mathbf{r}) + [\ \mathbf{V}\ ] \ , \qquad (5)$$

where V represents some eventual hydrodynamical velocity like a stellar wind for instance (turbulence must be included in v_D (Vauclair et al, 1978)). Actually, equation (3) is a time-dependent non-linear partial differential equation which must be solved numerically.

3.1 Vertical stratification

Even in the case of magnetic Ap, a star has essentially a spherical symmetry and the gradients involved in $\mathbf{v}_D$ are essentially vertical. Therefore, diffusion in stars may be assumed to be a vertical one-dimensional process. However, this simplification is far from enough for solving easily equation (3). Fortunately, in many cases a "zero order" approximation allows a rough estimate of the overabundances that can be expected at the stellar surface. This approximation consists in comparing the radiative acceleration g^{rad} to gravity g throughout the star, and in assuming that equation (3) will reach a stationary solution with $N = N^*$ such as $g^{rad} = g$ everywhere in the star. Now, due to the non-linearities in equation (3), the existence of such a stable stationary solution is not certain.

This problem has been recently studied by Alecian and Grappin (1984) who considered the time-dependent diffusion of one ion in stellar envelopes. They have shown that stable solutions like $N \simeq N^*$ are possible in optically thick regions, but also abundance stratifications may go through transient states very different from the stationary solution before reaching it (in the case of zero mass loss). If such transient states affect upper optically thin regions, this may produce ups and downs of observable abundances during the stellar lifetime. On the other hand, these authors have also speculated on a possible unstable scenario in building abundance stratifications in outer optically thin stellar regions. If such transients states or unstable stratifications occur in Ap stars atmospheres, this means that there may be several phases of peculiarities for some elements in a given star. This can explain the wide diversity of abundance anomalies observed in magnetic and non-magnetic Ap stars because a given star may go through different phases of peculiarity.

3.2 Horizontal diffusion

We have shown in section 2 that, due to the presence of magnetic field, an horizontal component of the diffusion velocity shows up. Generally, the effect of this drift velocity is negligible comparing to the vertical process. But one can suppose that, when the vertical stratification approaches stationarity (with formation of rings and patches), horizontal diffusion must be taken into account. On another way, as pointed out by Michaud et al (1981), a slight turbulence may add also an horizontal component to the diffusion velocity in the case of horizontal concentration gradients. So in this case rings and patches become wider with time.

A quantitative study of horizontal diffusion has been made for silicon by Mégessier (1984). Using the radiative acceleration of Alecian and Vauclair (1981), Mégessier has computed the drift velocity of silicon assuming a dipolar configuration of the magnetic field. She has found that, after silicon accumulates in a ring at the magnetic equator (horizontal field lines), silicon migrates toward the magnetic pole and then, sinks (see her communication to this colloquium for some new observational results). Such a process will take about 10^8 years to be achieved (to be compared with 10^4 years for the vertical process). Now, long times as 10^8 years raise the problem of the permanence of the magnetic structures at the surface of Ap stars. Indeed, observational confirmation of silicon horizontal diffusion would imply that the magnetic structures remain unchanged during about 10^8 years (whereas the diffusion time of surface magnetic lines is precisely of the order of 10^8 years for structures having a size equal to the stellar radius).

4. SOME IMPORTANT PROBLEMS CONCERNING MAGNETIC CP STARS AND RELATED TO THE DIFFUSION PROCESSES

4.1 Rapid variations of cool Ap stars

The discovery by Kurtz (1982) of rapid variations (in the frequency range of 4 to 15 minutes) in cool Ap stars, brings a new qualitative knowledge about these stars. According to him, these variations seem to be linked to the presence of strong magnetic field; but why only few high overtone modes are excited and how they are related to the magnetic field was not understood.

Very recently, Dolez et al (1985) have considered the problem of the rapid variations in Ap stars in the framework of the diffusion processes. They have found that the helium stratification due to the combined effect of diffusion and a local mass loss at the magnetic pole, favours the existence of the oscillations found by Kurtz.

4.2 The possible existence of corona

There is not, at the present time, any observational evidence of corona around CP stars. The X-ray observations are near the detection limit (Golub et al, 1983) and cannot be considered as reliable.

The detection of corona around CP might pose a problem as far as its existence would imply some violent atmospheric activities which prevent any chemical separation in the photosphere. Recently, Havnes and Goertz (1984) have made a theoretical study on magnetospheres of early-type CP. According to this study (the first one in this subject), the heating of an eventual corona, would be achieved by the interaction of mass loss with magnetic field and rotation.

4.3 The radiative accelerations

The calculation of accurate radiative accelerations is very important in carrying out computations on diffusion. Several problems make this task difficult. For instance, many efficient atomic transitions absorb photons in UV, where the radiation flux is badly known. On the other hand, until now, these computations have neglected the Zeeman splitting which can increase the radiative accelerations up to a factor two in some cases (Borsenberger et al, 1981). Note that this last effect may act in optically thick regions, i.e. before the $\omega_i^2 t_i^2$ term becomes efficient in equation (1).

4.4 The observational constraints

For the moment the observational constraints are not strong enough to decide what is the real aspect of the magnetic Ap stars' surface. The measurement of magnetic field in the lines of some elements would be helpful: for instance to decide if silicon is accumulated in rings rather than spots (Michaud et al, 1981). Of course, this information might also be obtained by the mapping methods using accurate analysis of spectral line variations (see Khokhlova, this colloquium), however, the lack of uniqueness in the results of these methods (mainly due to the observational uncertainties), preclude for the moment the drawing of firm conclusion on the shape of the surface inhomogeneities.

Precise data on the line profiles and curves of growth should give also useful informations about vertical stratifications (Borsenberger et al 1981, Alecian, 1982).

5. A TIME-DEPENDENT CONCLUSION

Much more observational data for individual stars (mainly on magnetic fields), more constraints are needed before undertaking further detailed theoretical investigations on diffusion processes in the case of magnetic CP stars, because the existence of strong magnetic fields adds too many free parameters.

The general features of magnetic CP stars are well understood if one accepts that diffusion can act in the outer stellar regions. However the detailed features remain to be explained. Models for individual magnetic stars will be probably built up next to the ones for non-magnetic Hg-Mn stars which have more simple properties and for which a parameter-free model can apply.

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