Time-dependent diffusion in A-stars

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Abstract. Each time diffusion of elements is invoked in explaining abundance anomalies in a star, this supposes implicitly that a stratification process is in progress somewhere in that star. This means also, that the element abundances can still be evolving according to the star's age and fundamental parameters. Moreover, it has been shown that the superficial abundances may have complex temporal behavior. This should be detectable through new observations. In some cases, it may be already apparent in available data.
The building up of the elements' stratification is a very difficult process to study. This is due to the existence of strong non-linearities in the time-dependent equations, which must be solved numerically. We will discuss some works that tackle this problem for Ap and Am stars, and we will present some results concerning mostly Am stars. Future desirable improvements in these studies will be considered.

Key words: microscopic diffusion – CP stars – stratification processes

1. Diffusion in CP stars

1.1. The observational facts

Here, we shall consider mainly the three well-known groups of Chemically Peculiar stars on the main-sequence of the HR diagram: FmAm, HgMn (non-magnetic Ap or weak magnetic field), and magnetic Ap stars. They show clearly abundance anomalies of metals with respect to solar abundances. These anomalies extend from factors of about 2 to 10 (in Am stars) and up to some 10^6 (in Ap stars).

Many abundance determinations have been done for a large number of Ap and Bp stars, covering a large sample of effective temperatures, for a large number of heavy elements. One of the most striking aspects of the observational results is the rather wide scatter of abundances determined in these stars for a given element (see for instance Takada-Hidai 1990). This scatter is partly due to errors in the abundance determinations and to inaccuracies in the effective temperatures determinations, but not only. Despite this scatter, a clear correlation with respect to the effective temperature is well established for some elements like Mn (see for instance Smith and Dworetsky, 1993).

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1.2. The diffusion model

It is generally accepted that diffusion processes of elements provide the best explanation for CP stars anomalies. Of course, microscopic diffusion interacts with other processes in stars, such as large scale motions (convection, turbulence, wind) and it cannot be considered alone: the anomalies are the result of a complex stratification process involving all these motions.

The diffusion model was first proposed by G. Michaud (1970), it is based on two basic findings: on the one hand, the abundance anomalies are related to atmospheric parameters like effective temperature and gravity, on another hand, there is a clear correlation between the superficial abundance anomalies and the radiative accelerations (one of the main terms involved in the diffusion velocity) in stellar external layers. The radiative accelerations are different according to the elements and they depend on atmospheric parameters. The anomalies which are found on main-sequence stars are not found among evolved stars, and this suggests that they are confined mostly to external layers. Moreover, in the HR diagram, the CP stars are located where the stars' outer convection zone is supposed to be the smallest. All of these arguments (with some others which are not discussed here) give a consistent outline for the diffusion model: when the stars evolve, the external layers are mixed with deeper ones and the abundance stratifications are lost.

In the diffusion model, the common property of the CP's is the weakness of the superficial helium abundance (due to helium gravitational settling). This helium underabundance is supposed to lead to the decrease (Am stars) or the disappearance (HgMn and magnetic Ap stars) of the superficial convection zone. Then, diffusion can occur in layers where stratification time scales are much shorter than in normal stars.

2. Stratification processes

Diffusion is basically a time-dependent process. To determine what abundances can be observed at the stellar surface one needs to compute the stratification process which requires solving of the following continuity equation (valid for test particles only, not for helium):

$$\partial_t n + \nabla_r \left(\sum_i n_i \mathbf{V}_{ip} + n\mathbf{V}_M \right) = 0 \tag{1}$$

Where n is the number density of the considered element (and n_i for ions), $\mathbf{V}_M$ is a bulk velocity (stellar wind for instance) and $\mathbf{V}_{ip}$ is the velocity of ions with respect to protons.

The continuity equation must be solved numerically because it is strongly non-linear with respect to n (see the study by Alecian and Grappin, 1984, Alecian, 1986). The diffusion velocity V_{ip} depends on n_i through the radiative acceleration $g_i^{rad}(n_i(r,t),r)$.

This equation is difficult to solve even in the stellar interior (optically thick, in this case the radiative acceleration is easier to compute) partly because the diffusion time scale at the bottom (downward boundary) is very different from the one at the top. On another hand, for Am stars, the characteristic time of the stratification process in deep layers (below the outer convection zones) is often of the same order of magnitude than the time needed to the star's structure to evolve significantly and then, a detailed computation should take into account the changes of the internal structure.

2.1. Optically thick case

Several works have been done and are in progress to study the stratification process in A stars. They are based on different approximations.

For Am stars, Alecian (1996) has solved numerically the continuity equation in the following form (the non-linearities are kept):

$$\partial_t C \;+\; \left[V_M - \langle D\rangle \nabla \ln\left(N_p \langle D\rangle\right)\right] \nabla C \;-\; \langle D\rangle \nabla^2 C \;+\; \frac{1}{N_p}\nabla\left(N_p \sum_i C_i v_{ip}\right) = 0 \tag{2}$$

C is the element concentration, v_{ip} is the diffusion velocity of ions due to radiative acceleration and gravity. He has used an approximate formula for the radiative acceleration which is mainly valid for test particles. On another hand, he has neglected the effects of star's evolution on the main sequence and the feedback of element stratification on the stellar model. He has applied his method on calcium diffusion in Am stars (Fig. 1).

These computations have shown that, according to some values of the mass-loss rate and thickness of the superficial mixing zone, Ca could be overabundant in early phases of stratification (see the comparison with observations by Hui Bon Hoa, this meeting).

Another kind of method has recently been developed by Seaton (1997). He has proposed a semi-numerical method based on a linearization of the continuity equation assuming $\mathbf{V}_M = 0$. His method has the advantage to use very accurate radiative acceleration computations but the drawback is that his method cannot be generalized to any element and to any star.

The group of Montreal (Michaud and collaborators, Turcotte et al, 1998) has undertaken a very impressive task of computing the stratification process in a fully consistent way. The aim is to model the star, its evolution and structure, with detailed opacities (using OPAL tables). The radiative acceleration is computed in details for many elements and at each time step, taking into account the changes of the detailed opacities due to abundance stratification of all these elements at a time. The continuity equation is solved numerically. Presently, as in the previous method, $\mathbf{V}_M = 0$, but this time on numerical grounds. This

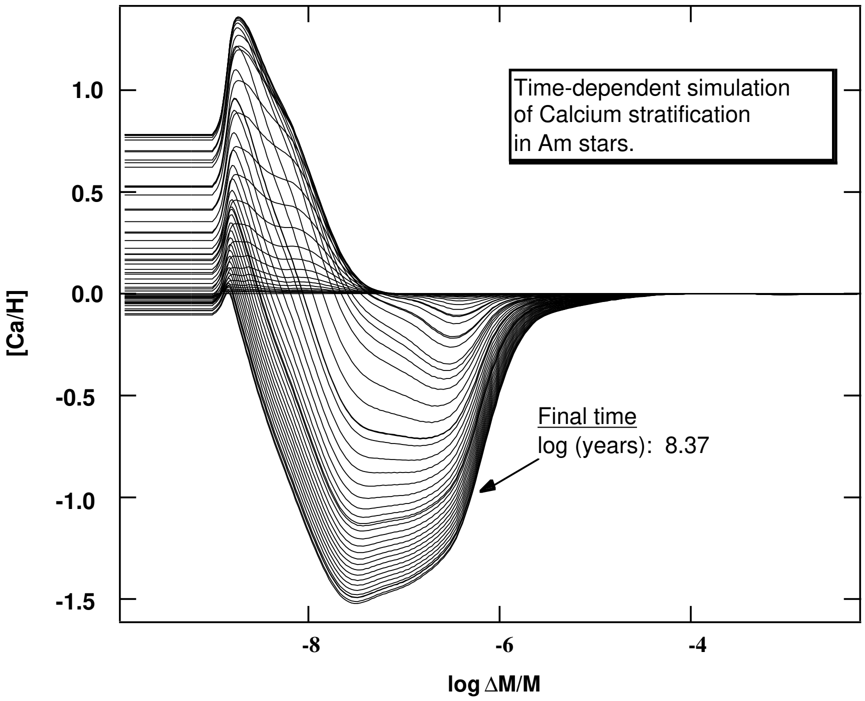

Figure 1. The logarithm of calcium abundance is plotted versus the logarithm of the mass fraction above the point of interest. At time $t = 0$, calcium is homogeneous and solar, the curves represent the abundance at successive time steps. The final time corresponds to log (years) = 8.37.

approach is certainly the most promising one, even if it is very heavy to carry out.

2.2. Optically thin case

In the optically thin case (for Ap stars), the situation is much more problematic because radiation transfer, which can no more be solved locally, make the calculations too huge to be carried out (at the moment): the continuity equation is coupled to the equation of the radiation transfer. Some attempts have been done in the past to solve these coupled equations, but they were rather inaccurate (Alecian and Vauclair 1981, for silicon in Ap stars).

Fortunately, interesting results can be obtained without the need to solve the continuity equation. This is the case, for example, for manganese by Alecian and Michaud (1981): the diffusion model allows them to predict the maximum overabundance that can be observed in HgMn stars versus the effective temperature. This prediction is based on a quasi “ zero order ” approximation (see below), and has been confirmed by the observations of Smith and Dwortesky (1993).

Generally, the stratification in Ap stars atmospheres is studied with some strong approximations. For instance, the " zero order " approximation consists in solving $g^{rad}(n_{equilib.}) = g$ which supposes that the final concentration throughout the medium, is such that the diffusion velocity is zero everywhere (for instance, Alecian and Artru 1988, for gallium). A better approximation is to look for a steady state solution $\nabla_r n_{st}\,(\mathbf{V}_D + \mathbf{V}_M) = 0$ (Babel, 1992). One problem is that one cannot be sure that $n_{equilib.}$ and n_{st} are solutions of the continuity equation coupled with the transfert equation. Another problem is to know what happens at the upper boundary (Babel, 1992), above the photosphere. For instance, are the elements free to leave the atmosphere (role of magnetic field, turbulence, etc.)?

Despite these difficulties, we may try to have some guesses about the behavior of element stratifications in stellar photosphere (see also Alecian and Grappin, 1984). In Fig 2, we present a mental picture of what kind of stratification process could occur in the photosphere of an Ap star. Each window shows the same section of the photosphere at four successive stages (t1 to t4). The upper part of the atmosphere is denoted by τ=0 (optical depth), the bottom (τ=1) is the point where the medium becomes optically thick.

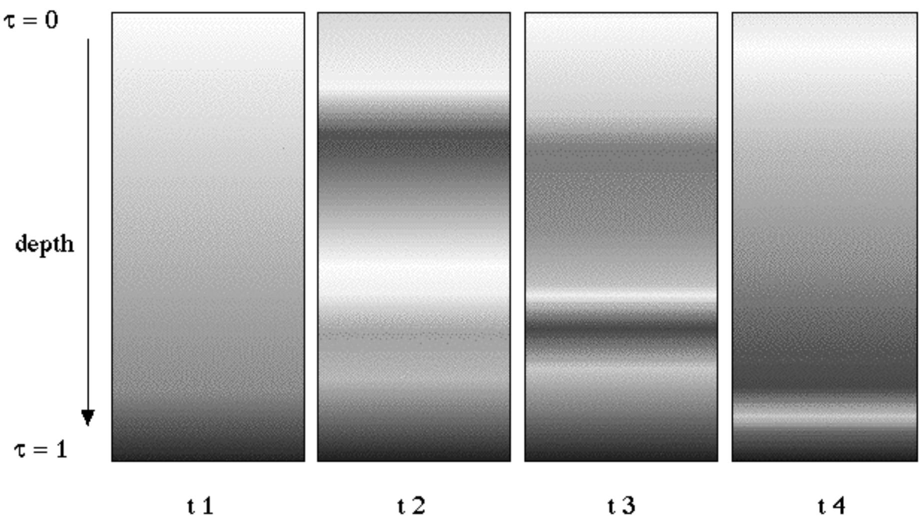

Figure 2. This is a mental picture of what kind of stratification process could occur in the photosphere of an Ap star (see text). Gray level is darker when the particle density of the considered element is higher.

Let us consider an element A (different from hydrogen and helium) and assume that its atomic properties are well fitted to this mental experiment. At time t1, concentration of A is assumed homogeneous throughout the atmosphere (the decrease of the gray level represents the decrease of mass density assuming hydrostatic equilibrium). At time t2, diffusion of A leads to form a cloud in the upper atmosphere (remember that diffusion time-scale is shorter when proton density is smaller, then this cloud should appear first). This cloud is mainly supported by the photons coming from τ=1. Now, if another cloud of element A forms (at time t3) below the first one, this second cloud may act as a shield for photons supporting the upper cloud. Then, the upper cloud is no more supported and falls. This scenario shows how stratifications built up by diffusion could be unstable in Ap stars atmospheres. The time scale of such an instability phenomenon should be of the order of the diffusion time-scales in stellar atmospheres, i.e. around 10 to 10^3 years. No hydrodynamics is involved in this scenario. If this scenario was confirmed by further theoretical studies (they are presently in progress), it may contribute in explaining the scatter observed in Ap stars' abundances.

We have shown that, at the moment, several works have been done to study the time-dependent diffusion in stellar envelopes. Some of them are rather accurate but neglect hydrodynamics and are very heavy to carry out. Another one is less accurate, but takes stellar mass-loss into account, and this is more realistic.

Self-consistent modelling, which will determine the evolution on the main-sequence of an Am star (including all known processes), is within the scope of the next few years. However, the studies on the stratification processes in Ap stars' atmospheres are still embryonic.

In the long run, the goal would be to perform a fully self-consistent modelling (including hydrodynamics) of the envelope together with the atmosphere. This seems to be the only way to answer all the questions raised by observations.

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