PARTICLE TRANSPORT AND SURFACE ABUNDANCE INHOMOGENEITIES

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Abstract. The various mechanisms leading to the appearance of horizontal inhomogeneities at the surface of ApBp stars are critically reviewed. The effect of magnetic fields is essential but is it more to control locally, on the surface, the appearance of anomalies that are caused by the vertical transport of particles, or is it to create directly the horizontal inhomogeneities by horizontal transport? The time scales for horizontal and vertical transport will be discussed in this context.
The processes discussed include: **a)** ambipolar diffusion of protons and hydrogen in the presence of magnetic fields; **b)** the guiding of diffusion by magnetic fields; **c)** the horizontal component of radiative accelerations; **d)** mass loss; **e)** light induced drift.

1. Introduction

In this paper, will be briefly reviewed some of the processes that are believed to play a role in leading to the observed surface variations of magnetic Ap stars. The large abundance and magnetic field variations over their surface (Wolff 1983, Landstreet 1991) are well modeled by an oblique rotator. Both these variations and the presence of the magnetic field are bound to affect the analysis. First the effect of the magnetic field on the structure of the atmosphere will be discussed. Then how the magnetic field may affect the concentration of abundances on the surface and how this can lead to the appearance of patches. Finally we will also mention how mass loss may play a role by varying over the surface presumably because of the topology of the magnetic field.

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2. Stratification

The diffusion models predict stratificatication of many elements in the atmosphere of peculiar stars. The models used to calculate horizontal separation also lead to vertical stratification. Observational evidence in its favor is starting to appear. Babel (1992, 1994) has discussed convincing evidence in favor of the stratification of Ca in magnetic stars. Smith (1995a, 1995b) has shown that the profiles of resonance GaIII lines are anomalous but can be explained if one assumes the stratification predicted by the diffusion calculations of Alecian and Artru (1987). These effects are however more difficult to analyze than those of horizontal stratification that will be the main subject of this paper.

3. Length and time scales

It is useful to keep in mind an evaluation of the distances that elements must cross in order to create the observed variations and the time this is expected to take through diffusion processes.

Vertically, to create anomalies by a factor of 10, one may need to carry elements over 3 scale heights. At T=20 000 K and $\log g$=4, this gives approximately 10^9 cm. Horizontally, one needs to carry elements over 1/10 to 1/5 of the stellar circumference for inhomogeneities to appear as they do when the star rotates, or approximately 10^{11} cm.

Vertically the time scale is mainly determined by the diffusion driven by radiative acceleration. It takes about 10^4 yr for ionized elements such as MnIII (Fig. 7 of Michaud *et al.* 1976) and it can be as rapid as 10^2 yr for less abundant elements whose radiative acceleration is larger.

Horizontally, the time scale for an abundance inhomogeneity to diffuse:

$$\frac{\partial c}{\partial t} = D_T \frac{\partial^2 c}{\partial x^2} \tag{1}$$

was shown by Michaud (1980) to imply that turbulence was small enough to permit vertical transport assuming that the abundance spots remained at the same position on the surface of the star for a large fraction of the stellar life. For $D_T \sim 10^8\,\mathrm{cm^2/s}$ it takes 10^8 yr to cover a significant fraction of the star surface. If there is no turbulence, it takes 10^{13} yr (for $D_{12} \sim 10^3\,\mathrm{cm^2/s}$). The horizontal component of the radiative acceleration (see below and Fig. 7 of Babel and Michaud 1991a) can lead to a time scale of 10^8 yr for the horizontal transport over 10^{11} cm.

The difference in time scales for the vertical and horizontal transport leads one (in particular Alecian, private communication) to doubt the importance of the horizontal contribution. The magnetic field configuration must be virtually permanent over the surface for the spots to be created by horizontal transport while those spots that can be created by vertical transport could be created in only a small fraction of that time. These could appear even if the surface were stable for periods of only some 10^4–10^5 yr instead of the 10^8 yr required for the horizontal transport.

4. Structure of the atmosphere and surface magnetic fields

Magnetic Ap stars are usually analyzed using nonmagnetic spherically symmetric stellar models. LeBlanc, Michaud and Babel (1995, hereafter LMB) studied one effect of magnetic fields which can be modeled with no arbitrariness but has been omitted up to now in Ap star modeling.

In the atmospheres of A type stars hydrogen is partially ionized, and ambipolar diffusion may play a role (Babel & Michaud 1991b, hereafter BM91, and Michaud & Babel 1991) if the magnetic field suppresses the mixing due to convection. To understand the nature of ambipolar diffusion in the hydrogen ionization region of A type stars one must consider the collision rates of importance for hydrogen. The largest rate is the proton-proton rate, while the charge exchange rate between protons and neutral hydrogen atoms is the second largest one (see Fig. 1 of BM91). The neutral hydrogen-proton momentum exchange rate is much smaller. One may then view the neutral hydrogen state as merely a temporary state: hydrogen is thermalized only in the proton state. While in the neutral state, hydrogen atoms travel a distance which is inversely proportional to the charge exchange rate. In the presence of an ionization gradient there is a difference between the upgoing and downgoing flux of neutral hydrogen atoms and a drift velocity appears. Protons also have a drift velocity but in the direction opposite to that of neutrals. This phenomenon is called the ambipolar diffusion of hydrogen.

In the presence of a magnetic field, the proton diffusion velocity is diminished perpendicular to the field lines while neutral hydrogen is unhampered by the magnetic field. In order for the net proton-hydrogen flux to cancel, there must be a change in the hydrostatic equilibrium. A Lorentz force then has to be included in the hydrostatic equilibrium equation and an atmosphere with a strong horizontal magnetic field is considerably different from its nonmagnetic counterpart. LeBlanc, Michaud and Babel (1994; following BM91) obtained atmospheric models that incorporate these magnetic effects. They assumed that convection is inhibited by the magnetic field and that the magnetic field is constant and horizontal. Since magnetic fields of most Ap stars have strong dipole components (Landstreet 1991) which have nearly horizontal field lines over a large fraction of the surface, the calculations for constant horizontal fields give an indication of the potential importance of the phenomenon and allow to develop observational tests.

Physical processes similar to those considered by LMB were studied by

Peterson & Theys (1981) for B type stars, but they calculated no detailed atmospheric models. Stepien (1978) studied the global effect of a distorted dipole field on the structure of the atmosphere. His results depend strongly on the unknown variation of the field inside the star. Carpenter (1985) did similar calculations and included the Zeeman effect in the opacity calculations. The interaction between ambipolar diffusion and the magnetic field was included in none of those models.

LMB show that the Lorentz force increases effective gravity in the hydrogen ionization region and thus modifies the structure of magnetic atmospheres. In a $T_{\rm eff} = 10\,000$ K star, effective gravity is up to seven times greater than gravity in the presence of a 5 kG horizontal field in the hydrogen ionization zone. The pressure gradient is proportionately increased in the ionization region of these magnetic Ap stars. The effect is present in stars with $T_{\rm eff}$ up to at least 12 000 K but the effect decreases as $T_{\rm eff}$ is further increased and hydrogen is completely ionized in the atmosphere.

Balmer lines are broadened in these magnetic atmospheres leading to a variation of 0.01 mag in the β index in the $T_{\rm eff} = 10\,000$ and 12 000 K models. This is smaller than the variation of 0.02 mag with rotational period typically observed in Ap stars. This still might play a role in explaining the β variations of stars like 56 Ari and CU Vir. Observed metallicity gradients and magnetic field configurations could also play a role. The effect on Balmer lines in the $T_{\rm eff} = 8\,500$ K model is considerably reduced, since the ionization zone occurs at too large an optical depth for the pressure gradient increase to affect observations.

5. The guiding of diffusion by magnetic fields

5.1. ONE STATE OF IONIZATION

If an element is only in one state of ionization, diffusion is guided into a preferred direction by the difficulty for charged particles to cross magnetic field lines. Across magnetic field lines, diffusion is reduced by a factor (Chapman and Cowling 1970):

$$\frac{1}{(1+\omega_i^2\tau_c^2)}, \qquad \text{where} \qquad \omega_i\tau_c = 1.7\ 10^4\,\frac{BT^{1.5}}{N_pZ} \tag{2}$$

All quantities are in the CGS system. This expression has however not been found to be a very accurate description of the particle transport across magnetic field lines in fusion devices and a semi-empirical formula, the Bohm formula, is used in that field (see for instance Laing 1981). In some fusion devices the Chapman and Cowling formula appears to be closer to reality. It may be that the correction is related to the particular geometry of fusion devices and would not apply in astrophysics. A better understanding of this phenomenon is however required.

5.2. TWO STATES OF IONIZATION

When an element is in the neutral and the first ionized states, the guiding by an oblique magnetic field applies only while it is in the ionized state. An atom diffuses vertically when it is neutral but obliquely when it is ionized. There consequently appears an horizontal component to the diffusion velocity that is a function of the ionization as well as of the product $\omega_i\tau_c$. The ionization time scale would also be involved if it is smaller than τ_c. The factor given by Eq. (2) varies as a function of B and Z, so that it depends on the local magnetic field and on the state of ionization. It also depends on T and $T_{\rm eff}$ through the degree of ionization and the ionization time scale. The factor in Eq. (2) is smallest for small Z, so that the first state of ionization is normally the one that follows magnetic field lines closest. If an element is pushed upward in the first state of ionization but settles gravitationally in the second, it migrates horizontally most in the first state of ionization and so towards the region where the field lines are horizontal. The equations may be found in Mégessier (1984) or in Babel and Michaud (1991a).

This effect also leads to an amplification (or a reduction) of vertical accelerations where the magnetic field is horizontal (Vauclair *et al.* 1979). Since the velocity in the first state of ionization is the one that is most reduced, there will be an amplification of the movement in either the neutral or the second state of ionization. The effect is largest for the neutral state but is also significant for the second state of ionization ($Z = 2$) *vs* the first one ($Z = 1$) as the downward velocity ($Z = 2$) could be up to four times less reduced than the upward one ($Z = 1$). This has no effect for gravity which is the same for all states of ionization. But see § 4 for a discussion of ambipolar diffusion.

6. Horizontal radiative accelerations

When a magnetic field is present, radiative transfer is modified in two ways:

1. The spectral lines can be desaturated by Zeeman splitting.
2. The azimuthal symmetry is destroyed by a non-vertical magnetic field.

To study these effects, it is then necessary to consider three absorption coefficients κ_p, κ_l and κ_r, corresponding respectively to the parallel, left and right handed circular oscillators of the classical theory (see Babel and Michaud 1991b for details).

The absorption turns out to depend on the angle between the propagation direction and the magnetic field and this leads to the existence of an horizontal component to the radiative acceleration. The absorption is minimum in the direction of the magnetic field and has a maximum at a large angle from the field, so that an horizontal radiative acceleration appears which is always directed away from the region where the magnetic field is horizontal. The horizontal radiative acceleration however remains relatively small compared to the vertical one. It is at most 2 to 4 % of the vertical component, the value depending on saturation and on multiplet properties. This leads to an horizontal velocity that depends on the local angle between the magnetic field and the vertical.

The magnetic field also leads to an amplification of the vertical radiative acceleration. This depends on the angle between the magnetic field and the vertical so that it varies on the surface of the star. It is shown on Fig. 3 of Babel and Michaud (1991a) for a few cases of interest. It never exceeds a factor of 2.3 for a given line. The largest amplification is for an horizontal magnetic field.

7. Mass loss

Magnetic fields can lead to surface abundance inhomogeneities by affecting mass loss rates (Michaud 1986). Where the magnetic field is horizontal, plasma cannot leave the atmosphere so easily as where field lines are vertical. Since the magnetic pressure is larger than the gas pressure in the atmosphere of A and B stars, it can dominate the structure of the wind. There exists no detailed model of winds in the presence of magnetic fields applicable to A stars. However one may assume that winds may be similar to the magnetic free case where field lines are vertical, but much smaller where they are horizontal.

Recently Babel (1995) has obtained hydrodynamical solutions of radiatively driven winds at the surface of A stars. He solved the multifluid hydrodynamical equations in the presence of radiative acceleration. Metals can have radiative accelerations large enough for them to leave the star but Babel showed that such a wind could not drag hydrogen. The maximum flux that can leave the star does not transfer enough momentum to hydrogen to drag it along in a $T_{\rm eff} = 10\,000\,{\rm K}$ star. There can then only be chemically differentiated winds at the surface of A stars. Some metals (but not all) leave and which leave depends on the radiative acceleration in and somewhat above the atmospheric regions. The maximum mass loss rate possible is of the order of $10^{-16}\,{\rm M}_\odot\,{\rm yr}^{-1}$ for normal A stars but $10^{-17}\,{\rm M}_\odot\,{\rm yr}^{-1}$ for Ap stars. Given that this is the mass loss rate of metals only, it is of the same order as Michaud and Charland (1986) found necessary to explain the abundance anomalies at the surface of AmFm stars.

Fakir (1985) discussed differentiated mass loss at the surface of peculiar stars but he had not obtained multicomponent hydrodynamical solutions.

Since ionized species cannot cross magnetic field lines, mass loss is expected to vary over the surface with the topology of the magnetic field and to be chemically differentiated, leading to horizontal abundance variations over the surface.

8. Light induced drift

The light induced drift velocity (Atutov and Shalagin 1988) is the result of collisional effects. It arises when the radiation field is anisotropic within the profile of at least one Doppler broadened line of an element, so that more atoms are excited in one half of the profile than in the other. Assume, for example, that the photon density is larger on the blue side of the wing, that is when the atom goes away from the star. Since the width is mostly due to Doppler broadening, there are more excited atoms moving away from the star than in the opposite direction. The collisional cross section is larger for atoms in the excited than in the ground state because of the larger effective radius in the excited state, so that there are more collisions for atoms moving in the direction which has the most excited atoms. This imbalance induces a drift velocity in the direction with the least excited atoms (toward the star centre in this case). The LID velocity is much smaller for ionized than for neutral elements since the Coulomb collision cross section is not expected to be much larger in the excited than in the ground state. The LID velocity competes with the diffusion velocity. For ionized elements in ionized hydrogen, diffusion appears to dominate (LeBlanc and Michaud 1993). LID may then be neglected in most cases. However when hydrogen is neutral as in some magnetic star outer atmospheres, the situation might be expected to be different. According to the discussion in § 3 of LeBlanc and Michaud (1993) the effect remains small because reasonable evaluations of cross sections suggest little difference between the ground and excited states. One should then consider LID as a possible contributor to spots only for elements that are themselves neutral in the atmospheres of Ap stars, such as He, Ne or O.

9. Conclusion

One may compare the efficiency of the various processes mentioned above for creating surface inhomogeneities. The horizontal component of the magnetic field acts both to reduce mass loss and to modify the direction of diffusion. In reducing mass loss, it can lead to inhomogeneities on the surface on time scales of 10^4–10^5 yr. In guiding elements, the effect depends on the state of ionization and would so lead to concentrations in different parts of the surface for different elements (Michaud, Mégessier, Charland 1981; BM91b) but on time scales of 10^8 yr or so. If the wind is differentiated (Babel 1995), it leads to surface abundance anomalies where it occurs while an undifferentiated wind would normally reduce anomalies (Michaud *et al.* 1983). The horizontal radiative acceleration acts on a factor of 10 shorter time scale than the guiding by the magnetic field but on a factor of 100 longer time scale than mass loss. It is however premature to exclude any of those processes.

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