ABUNDANCE STRATIFICATION IN THE OUTER LAYERS OF MAIN-SEQUENCE STARS

G. Alecian

A short review on diffusion processes in atmospheres of stars is given. The diffusion model and its application for interpretation of spectral features of Am and Ap stars are described schematically. The building of abundance stratification and the case of calcium in Am stars are described briefly.

1. Abundance anomalies observed in Main Sequence stars. Strong abundances anomalies (more than ten times solar values) may be found among the Main Sequence A and F stars. These stars are the so-called chemically peculiar stars (CP). Although the existence of anomalies has been known for many decades, their origin is understood only since the pioneering work of Michaud (1970).

There are mainly 5 groups of CP stars on the Main Sequence (the detected over- and underabundances are written with respect to the sun):

FmAm

\( T_{\text{eff}} = 7500-9500 \)
Overabundances: iron peak elements (about a factor of 10)
Underabundances: Sc, Ca (about ×0.1)
Peculiarities: all are binaries, slow rotation (\( v \cdot \sin i < 100 \text{ km/s} \))

Ap (Sr-Cr-Eu)

\( T_{\text{eff}} = 8000-12,000 \)
Overabundances: iron peak elements (about \( \times 10^2 \)), rare earths (up to \( \times 10^5 \))
Underabundances: Ti (about \( \times 0.01 \))
Peculiarities: slow rotation, magnetic field, spectroscopic variability

Ap (Si)

\( T_{\text{eff}} = 9500-16,000 \)
Overabundances: iron peak elements (about \( \times 10^2 \)), rare earths (up to \( \times 10^2 \))
Underabundances: He, Ti (about \( \times 0.01 \))
Peculiarities: slow rotation, strong magnetic field, spectroscopic variability.

Ap (HgMn)

\( T_{\text{eff}} = 9500-16,000 \)
Overabundances: iron peak elements (about \( \times 10^2 \)), Mn, Hg, Xe (up to \( \times 10^5 \))
Underabundances: He
Peculiarities: slow rotation, binarity frequency higher than normal, no detection of magnetic field.

He

\( T_{\text{eff}} = 14,000-30,000 \)
Overabundances: He3 (Teff (15,000-21,000)), He (\( \times 10 \), Teff (21,000-30,000))
Underabundances: He (\( \times 0.01 \), Teff (15,000-21,000))
Peculiarities: magnetic field, spectroscopic variability.


294 0571-7256/95/3804-0294$12.50 ©1996 Plenum Publishing Corporation
For more details the reader may refer to, for instance, review papers by Boyarchuk and Savanov (1986), Cayrel et al (1991), and Takada-Hidai (1990).

2. The diffusion model. Various theories have been proposed during the sixties to explain the CP phenomenon. They were unsuccessful except in diffusion theory.

Very schematically, a star may be considered as composed by successive layers where different processes occur according to the local physical conditions. Matter is generally mixed by macroscopic motions as convection, turbulence, and large scale circulations. However, some layers may be quiet. In these layers, chemical separation (or microscopic diffusion) can occur efficiently, providing that diffusion time scales are shorter than mixing time scales (the first ones fall approximately from some years to $10^6$ years according the CP group). Diffusion is mainly due to the competition of two forces: one due to gravity, the other one due to absorption of photons.

Microscopic diffusion is a physical process always active in stars, the problem being to know when it produces detectable effects. It is clearly inefficient in the majority of Main Sequence stars where convective motions are important and which show abundances close to solar ones.

For CP stars, the diffusion model was first proposed by G. Michaud (1970); it is supported by several basic statements:

The abundance anomalies are related to atmospheric parameters (effective temperature, magnetic field).

There is a clear correlation between the superficial abundance anomalies and the radiative accelerations in the quiet zone.

The CP's are stars where mixing motions may be slower than in any other Main Sequence stars: slow rotation ($v \sin i < 100$ km/s), shallow superficial convection zone, undetectable mass-loss rate, and/or strong magnetic field (which may help to stabilize turbulent motions), see Vauclair and Vauclair (1979).

There are no evolved stars (outside the Main Sequence) with the same anomalies. This proves that anomalies are located in the outer layers during the Main Sequence life time, and then, these layers are mixed with deep "normal" ones when convection develops as the stars evolve.

We shall now detail the model for Am and Ap stars (for the sake of conciseness, we do not consider here the case of He stars). Note that the diffusion process may be effective in some evolved stars (Horizontal Branch stars, White Dwarfs) but this is out the scope of the present review.

2.1 Am stars. The classical scenario for FmAm stars is the following (see Michaud, 1986). Normal F and A stars have two superficial convection zones due to hydrogen and helium ionization. These two zones are generally very close to each other and may be considered to form one unique thick zone. If the star has low rotational velocity (due for instance to tidal effects in binary systems), large scale circulation below the convection zone is weak enough for helium to settle down by diffusion (the balance between gravity and radiative acceleration is in favor of gravity for this element). The time needed for helium settling is smaller than the lifetime on the main sequence (Charbonneau and Michaud, 1988). Helium leaves the external layers and the convection zone due to helium progressively disappears as the He abundance decreases in the envelope. The star remains with a shallow superficial convection zone due to hydrogen ionization and then microscopic diffusion may act for metals, just below (in the radiative zone), with short time scales (the time scales decrease with decreasing mass-density). Detectable effects are produced at the stellar surface: due to mixing in this shallow convective zone, the superficial abundances reflect the abundances at the upper boundary of the stable radiative zone where stratifications take place.

2.2 Ap stars. For Ap stars, the classical scenario is the same as for FmAm stars except that due to their higher effective temperature, the remaining superficial hydrogen convection zone is very thin or nonexistent. Therefore, diffusion processes occur in the atmosphere where time-scales are much shorter and diffusion much more efficient. The abundance anomalies of metals are much stronger than in FmAm stars and appear faster.

In case of a strong horizontal component of the magnetic field, the vertical motions of ions are strongly smoothed down and then diffusion can produce horizontal inhomogeneities. This explains the spectroscopic variabilities of magnetic Ap stars and their correlation with the rotational period.

3. Radiative acceleration. Radiative acceleration (which acts against gravity) is due to photoabsorption of ions. Momentum is transferred from the radiation field to ions, according to their atomic properties. Since these properties are