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Peculiar Line Opacities and Atmospheric Structure in CP Stars

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Abstract. The effects of elemental abundance anomalies caused by radiative diffusion on the atmospheres of chemically peculiar (CP) stars will be discussed. A brief review of the various types of CP stars and the diffusion process along with the intricacies of radiative acceleration calculations will be given. Recent progress in stellar atmosphere modeling, including the effects of the abundance stratification of the elements due to diffusion on the atmospheric structure, will be presented. The various physical phenomena that need to be included in future generations of atmospheric models of the different types of CP stars, and in particular for magnetic stars, along with the possible applications of these models will be discussed.

1. Introduction

It is more than a century ago (Maury 1897; Cannon 1901) when it was first noticed that some stars' spectra had peculiar line strengths. Some lines were either much stronger or much weaker than in normal stars. This can be interpreted as respectively large overabundances or underabundances, at least in the line forming regions of the stars, of the elements producing these lines.

Several nuclear based theories were suggested in order to explain the abundance anomalies observed in these chemically peculiar (CP) stars. Fowler et al. (1965) suggested that these abundance anomalies were caused by rapid neutron captures. While Brancazio & Cameron (1967) proposed a model in which nuclear reactions at the surface of stars were responsible for the anomalies. However, the observations of a large sample of peculiar A-type stars of Adelman (1973) showed that these nuclear theories could not reproduce the observed anomalies.

Michaud (1970) proposed that diffusion of the elements due to the competition between the momentum transfer to ions during photoexcitation or photoionization and gravitational settling causes the observed abundance anomalies in CP stars. Since the various ions of a given element have varying radiative absorption capacities, the supported abundance in stars is temperature dependant, and thus vertical abundance stratification gradients can occur in hydrodynamically stable stellar regions.

In some type of stars, the atmosphere is believed to be stable enough so that abundance gradients can exist in the optically thin regions. The accumulation or depreciation of the various elements at different atmospheric depths can then modify the atmosphere's structure. Up to now, the vast majority of spectroscopic and photometric studies have employed model atmospheres with homogeneous abundances.

In this paper we will discuss the importance of diffusion on the atmospheric structure of upper main sequence CP stars. First, we will briefly review the various types of CP stars and the basic equations important for the diffusion phenomena. Then, recent progress in atmospheric modeling including the effects of abundance stratification due to diffusion will be presented. Finally, future challenges for the modeling of CP stars will be discussed.

2. CP Stars

Preston (1974) divided the upper main sequence CP stars in four groups. The CP1 group includes the metallic line (Am) stars, the CP2 group contains the magnetic Ap stars, the CP3 group includes the HgMn stars while the CP4 group contains the He-weak stars. Besides having abundance anomalies, all of these stars have low rotational velocities as compared to normal stars of the same effective temperature (T_{eff}). The anomalies depend on T_{eff} but there also exists a large scatter of abundances for a given element for stars of the same CP group with identical T_{eff}. Abundances of magnetic stars also differ from their non-magnetic counterparts.

In this section we will briefly review these different groups of upper main-sequence CP stars in order to distinguish those in which diffusion can be important in their atmosphere. We took the liberty to add the He-strong and ^{3}He stars to the CP4 group which we will call the He-abnormal stars.

2.1. Am Stars

Am (and also Fm) stars (Titus & Morgan 1940) are non-magnetic (Landstreet 1982) main sequence stars with $7000 < T_{\mathrm{eff}} < 10\,000$ K. They possess underabundances of Ca and Sc. As mentioned above, these stars have low rotational velocities (i.e. less than 120 km/s, Abt & Moyd 1973). Since most Am stars are spectroscopic binaries, it is believed that tidal forces cause their low rotational velocities (Abt 1961). It was suggested (Watson 1971; Smith 1971) that the abundance anomalies emanate from diffusion at the base of the hydrogen convection zone. The classical explanation for the occurrence of the AmFm phenomena is that the He convection zones disappear in Am stars because He can sink, due to diffusion, towards the centre since these stars have low rotational velocities and that diffusion can dominate in the regions where the He convection zones once existed. Recently, Abt (2000) showed from statistical arguments, that rotation alone determines whether a star is normal or abnormal (i.e. an Am star). The anomalies observed at the surface are then caused by diffusion at the base of the hydrogen convection zone that remains. At these depths Ca is in the Ar-like ionization stage and is weakly supported by radiative forces thus giving a Ca underabundance at the surface of these stars. Even though abundance anomalies are present in the atmosphere of these stars, convection due to hydrogen ionization should dominate there and no atmospheric abundance gradients should exist.

Evolutionary stellar models of AmFm stars including the diffusion of elements have been constructed by Richer, Michaud, & Turcotte (2000). They found that a convection zone due to the accumulation of iron can appear at a depth where $T \simeq 200\,000$ K. In order to have better agreement between the predicted and observed abundances, turbulence was added to these models. At the depth at which turbulence has to be efficient to obtain satisfactory results, Ca is in the Ne-like configuration so that it settles gravitationally since the radiative acceleration is small for this noble gas configuration. The underabundance of Ca is then caused very differently than in the classical explanation.

2.2. Ap Stars

Ap (and Bp) stars are slowly rotating (i.e. less than 120 km/s, Abt, Chaffee, & Suffolk 1972) main sequence stars with $7000 < T_{\mathrm{eff}} < 15\,000$ K which have large magnetic fields (up to $\simeq 10^4$ G) at their surface (Babcock 1958). The configuration of the magnetic field was first modelled by a dipolar field inclined with respect to the axis of rotation of the star, commonly called the oblique rotator model (Babcock 1949). However the magnetic fields of ApBp stars are much more complex (Landstreet et al. 1989) than this simple model. These magnetic structures seem to lead to abundances patches on the surface of these stars.

Helium is underabundant in Ap stars while the iron peak elements are overabundant (up to +2 dex relative to solar values). The rare earth elements are extremely overabundant (up to +5 dex for Eu). The CP2 class can be divided into two categories: The Ap (SrCrEu) stars with $7000 < T_{\mathrm{eff}} < 10\,000$ K, and the Ap (Si) stars with $10\,000 < T_{\mathrm{eff}} < 15\,000$ K. In this last category Si is overabundant by up to +2 dex while its abundance is less than +1 dex in Ap (SrCrEu) stars. A more complete discussion surrounding the abundances of Ap stars can be found in Ryabchikova (1991) and Cowley (1993).

Abundance stratifications of several elements have been observed in Ap stars (Babel & Lanz 1992; Babel 1994; Wade at al. 2001). A more complete review of abundance stratifications in stars can be found in Ryabchikova, Wade, & LeBlanc (2002). Recently Kochukhov, Bagnulo & Barklem (2002) showed that by increasing the temperature in the line formation regions the core-wing anomaly of hydrogen Balmer lines (Cowley et al. 2001) observed in Ap stars can be reproduced. They suggested that the effect of the stratification of the elements in the atmosphere could cause such a temperature rise. The results from the studies mentioned above strongly support the common belief that strong magnetic fields at least partially inhibit convection and that diffusion can then be important in the atmospheres of Ap stars.

2.3. HgMn Stars

HgMn stars are non-magnetic, slowly rotating ($v \sin i < 100$ km/s, Wolff & Preston 1978) main sequence stars with $10\,000 < T_{\mathrm{eff}} < 15\,000$ K who were first identified as a group by Morgan (1931). These stars have large overabundances of Hg (from +4 to +6 dex) while the overabundance of Mn has a large scatter (from slightly above solar values to approximately 4 dex). The rare earth elements are also strongly overabundant. Helium is generally underabundant. A complete review of the abundances of HgMn stars can be found in Takada-Hidai (1991).

There also exists isotopic anomalies in these stars. For instance, in the star χ Lup (White at al. 1976), almost all of the Hg is in the form of ^{204}Hg while its relative solar abundance is only 7%. Isotopic anomalies of Pt have also been observed (Dworetsky & Vaughan 1973) in these stars. Light-induced drift (Atutov & Shalagin 1988; LeBlanc & Michaud 1993) is suggested as the cause of these isotopic anomalies.

Since HgMn stars are relatively hot and are slowly rotating, their atmosphere should be stabe enough so that diffusion can play an important role there.

2.4. He-abnormal Stars

He-abnormal stars are main-sequence stars that come in a wide variety. The He-weak stars have $14\,000 < T_{\rm eff} < 20\,000$ K and He underabundances by factors from 2 to 15 (Norris 1971). The P-Ga type (or sometimes called phosphorous stars) are non-magnetic stars that have overabundances of P (up to +2 dex) and Ga (up to +5 dex) while the Si and SrTi types are magnetic stars. Some He-weak stars have an abnormally high ^{3}He to ^{4}He ratio. These are called ^{3}He stars.

Another type of He-abnormal stars are magnetic He-rich stars in which the ratio of He/H varies from 0.3 to 10. Since radiation pressure is not sufficient to explain such He overabundances, other mechanisms such as mass loss must come into play (Vauclair 1975).

Recently Sigut, Landstreet, & Shorlin (2000) proposed that in order to explain certain emission lines in the ^{3}He star 3CenA, abundance stratification in the atmosphere must be present. Self-consistent atmosphere models including diffusion are then needed to properly study these stars.

3. Diffusion and Radiative Accelerations

In hydrodynamically stable regions of stars, the diffusion velocity (V_i) of an ion i of a trace element A can be approximated by the following equation (Vauclair & Vauclair 1982; Alecian & Vauclair 1983; Landstreet, Dolez, & Vauclair 1998):

$$V_i \approx D_i(-\nabla \ln C_i + \frac{A_i m_p g_{\rm rad}(A_i)}{kT} - ((A_i - 1) + (A_i - Z_i) f_p) \nabla \ln P), \qquad (1)$$

where D_i is the diffusion coefficient of the ion, C_i its concentration, A_i and Z_i its atomic number and ionic charge, $g_{\rm rad}(A_i)$ its radiative acceleration and f_p is the ionization fraction of HII. The first term in this diffusion equation is related to the diffusion induced by a concentration gradient, while the last three terms represent the effect of the radiative, gravitationnal and electrical forces on the diffusion velocity. The radiative acceleration of the ion i, which is critical for the accurate evaluation of the diffusion velocity, is given by

$$g_{\rm rad}(A_i) = \frac{4\pi}{c} \frac{1}{X(A_i)} \int_0^\infty \kappa_\nu(A_i) H_\nu d\nu, \qquad (2)$$

where H_ν is the Eddington flux, κ_ν is the radiative opacity of the ion and $X(A_i)$ its mass fraction. Since the various elemental species compete for the radiative flux, this equation depends not only on the ion in question but also (through H_ν) on the presence of the other elements.

Several methods have been used to calculate radiative accelerations. The most numerically efficient method is based on parametric equations (Alecian 1985; Alecian 1994; Alecian & LeBlanc 2002) that approximate g_{rad} while reproducing its dependance on the element's concentration (i.e. the saturation effects). However this method has the disadvantage that it cannot take precisely into account the line blending effects and it is also only valid for $\tau >> 1$. Gonzalez et al. (1995) also developed a numerically efficient method to calculate g_{rad}, but this method is also only valid below the atmosphere. In stellar atmospheres, the opacity sampling method (e.g. LeBlanc, Michaud & Richer 2000) is better suited. In this method, equation (2) is numerically integrated at a sufficiently high number of frequency points in order properly sample the lines to obtain a precise g_{rad}. The flux must then be calculated at a each of these frequencies thus increasing computing time. Typically, in the atmosphere the radiative transfer equation will have to be solved at several hundred of thousands of frequency points. This method has the advantage that it can precisely take into account the effect of line blends and thus better take into account the effect of the diffusing elements on each other.

In order to obtain an average g_{rad} on a given element the contributions of its ions must be properly weighted by the ionization fractions and the diffusion coefficients of the ions (see equation 15 of Gonzalez et al. 1995). However the momentum received by a given ion during photoabsorption or photoionization might not be spent in that same ionic state depending on the rate of ionization or recombination. The momentum can then be redistributed to another ionic state (Montmerle & Michaud 1976). This is especially important in the upper atmosphere since the mobility of the neutral species is much larger than in an ionized state. This redistribution effect is hard to evaluate and is the cause of some uncertainty in g_{rad} calculations.

4. Results from Recent Atmospheric Modeling

Up to now the vast majority of atmospheric models have assumed that abundances do not change with depth. As discussed above, in some stars abundance gradients should exist and could then affect the atmospheric structure. In this section we will review recent results of self-consistent stellar atmospheres that were calculated while taking into account abundance gradients caused by diffusion. The first two studies mentioned are for stars outside the main-sequence that, however, possess chemical peculiarities and in which abundance gradients can form in the atmosphere. Finally we will discuss preliminary results of self-consistent atmospheric modeling of Ap stars.

4.1. White Dwarfs

Dreizler & Wolff (1999) calculated self-consistent model atmospheres of white dwarf stars. The structure of the atmosphere was calculated while assuming that the radiative, gravitationnal and electrical forces cancel in the diffusion equation given above for each element at all depths in the atmosphere. Their synthetized spectra better reproduce the EUV spectrum of hydrogen rich (DA spectral type) than the homogeneous models. At $\lambda < 230$ Å, their new models predict the flux depression observed in the DA white dwarf G 191-B2B ($T_{\mathrm{eff}} = 56\,000$ K).

4.2. Blue Horizontal-Branch Stars

Blue (or hot) horizontal-branch (BHB) stars have abundance anomalies at a temperature threshold ($T_{\rm eff} > 11\,000$ K) which is the same temperature at which there is an observed drop in their rotation velocities (Peterson, Rood, & Crocker 1995). Other observational peculiarities such as photometric jumps (Grundahl et al. 1999) and photometric gaps (Ferraro et al. 1998) also occur in BHB stars at the same $T_{\rm eff}$ threshold. These observations strongly support the idea that diffusion becomes efficient in the atmosphere of these stars at this $T_{\rm eff}$ threshold and that these peculiarities can be explained by the abundance anomalies caused by diffusion.

Hui-Bon-Hoa, LeBlanc, & Hauschildt (2000) built self-consistent model atmospheres for BHB stars. Their models were calculated with a modified version of the multi-purpose atmospheric code `PHOENIX` (e.g. Hauschildt, Allard, & Baron 1999). These models were constructed by supposing that the radiative, electrical and gravitational forces cancel for each element. It was found that if diffusion becomes efficient in BHB stars with $T_{\rm eff} > 11\,000$ K, both photometric jumps and gaps are predicted by these new stratified models.

4.3. Ap Stars

Construction of self-consistent model atmospheres of Ap stars is now in progress. As for those of the BHB stars mentioned above, these models are calculated with a modified version of the `PHOENIX` code. Since these models are still in development, it should be noted that the results presented here are preliminary.

Wade et al. (2001) showed that the lines of several elements could be better fitted to observations for Ap stars with an empirical two step abundance stratification (see Fig. 1). In their calculations they did not take into account the back effect of this stratification on the atmosphere. They found that the transition zone between the two steps is at $\log(\tau_{5000}) \approx -0.7$ for the elements considered (Ca, Fe and Cr).

In the first series of self-consistent models calculated we supposed that no convective mixing was present in the atmosphere. The abundance profiles were calculated as in Hui-Bon-Hoa, LeBlanc, & Hauschildt (2000). These profiles do not, for instance, adequately reproduce the observed line profiles of Fe as compared to the two step stratification of Wade at al. (2001). As shown in Fig. 1, the increase of the Fe abundance in the self-consistent model is deeper in the atmosphere than in the two step empirical model. This abundance increase is due to the increase of the Fe I and then the Fe II opacities at $\log(\tau_{5000}) \approx 0$. However these models are successful in better reproducing the observed UV flux excess in β CrB as compared to the flux obtained with homogeneous models (see Fig. 5 of Ryabchikova, Wade, & LeBlanc 2002).

The fact that the transition zone between the two steps found by Wade at al. (2001) for the different elements are very near where convection would begin, suggests that convective mixing could be present in Ap stars. Models were then calculated by supposing a convective mixing zone while supposing that the regions outside this zone are supposed stable (i.e. no overshooting). An abundance plateau (see Fig. 1) is then produced. The height of this plateau depends strongly on the depth of the convective zone because the $g_{\rm rad}$ varies rapidly at the bottom of the mixing zone. We found that only a small shift in

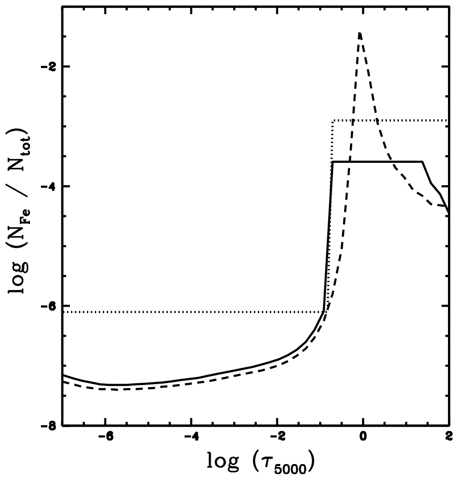

Figure 1. Abundance profile of Fe in a $T_{\rm eff}$ = 7700 K, $\log g$ = 4.0 star. The dotted curve represents the two-step empirical model, the long-dashed curve is for a self-consistent model supposing no convective mixing while the solid curve represents a self-consistent model assuming convective mixing.

the position of the bottom of the convenction zone can grealty affect this height and can bring it close to what is found empirically. Babel (1992) showed that this height is also affected by mass loss. Both these effects could partly explain the scatter of the abundances found in Ap stars with similar $T_{\rm eff}$.

The effects of magnetic fields were not included in the models presented here. Diffusion can be affected when ions diffuse across magnetic field lines (e.g. Hui-Bon-Hoa, Alecian, & Artru 1996). Preliminary calculations including this effect show that it can modifiy the structure in the upper atmosphere and might play a role in the creation of the core-wing anomaly of hydrogen lines. Magnetic fields also affect the $g_{\rm rad}$ through the Zeeman effect (Alecian & Stift 2002). Other effects such as ambipolar diffusion (Babel & Michaud 1991; LeBlanc, Michaud, & Babel 1994) and NLTE effects on $g_{\rm rad}$ (e.g. Hui-Bon-Hoa et al. 2002) could also play a role and should be included in future modeling of Ap stars.

5. Conclusion and discussion

The first generation of 1D model atmospheres including the stratification of the elements due to diffusion have been constructed for several types of stars and have been relatively successful in explaining several observational anomalies. Some of these are still in development while more physical processes are being included. Preliminary results show that self-consistent model atmospheres with convective mixing better reproduced the observed stratification in cool Ap stars than those with no mixing. Even though no velocity fields have been observed in such stars, convection might not be completely inhibited and some slow mixing could be present. The modeling of magnetic stars is particularly complex, and optimally, full 3D models with a temporal treatment of diffusion are needed. However, even these advanced models will suffer from uncertainty relative to the initial conditions and to the interaction of the atmosphere with the interior.

References

Abt, H. A. 1961, ApJS, 6, 37

Abt, H. A. 2000, ApJ, 544, 933

Abt, H. A., Chaffee, F. H., & Suffolk, G. 1972, ApJ, 175, 779

Abt, H. A., & Moyd, K. I. 1973, ApJ, 182, 809

Adelman, S. J. 1973, ApJ, 183, 95

Alecian, G., & Vauclair, S. 1983, Fund. of Cosmic Physics, 8, 369

Alecian, G. 1985, A&A, 145, 275

Alecian, G. 1994, A&A, 289, 885

Alecian, G., & LeBlanc, F. 2002, MNRAS, 332, 891

Alecian, G., & Stift, M. J. 2002, A&A, 387, 271

Atutov, S. N., & Shalagin, A. M. 1988, Soviet Ast. Lett., 14, 284

Babcock, H. W. 1949, Observatory, 69, 191

Babcock, H. W. 1958, ApJS, 3, 141

Babel, J, & Michaud, G. 1991, A&A, 248, 155

Babel, J. 1992, A&A, 258, 449

Babel, J., & Lanz, T. 1992, A&A, 263, 232

Babel, J. 1994, A&A, 283, 189

Brancazio, P. J., & Cameron, A. G. W. 1967, Can. J. of Physics, 45, 3297

Cannon, A. J. 1901, Harvard Ann., 28, 129

Cowley, C. R. 1993, in Peculiar versus Normal Phenomena in A-type and Related Stars, IAU Coll. 138, ed. M.M. Dworetsky, F. Castelli & R. Faraggiana, ASP Conf. Series 44, 18

Cowley, C. R., Hubrig, S., Ryabchikova, T.A., Mathys, G., Piskunov, N., & Mittermayer, P. 2001, A&A, 367, 939

Dreizler, S., & Wolff, B. 1999, A&A, 348, 189

Dworetsky, M. M., & Vaughan, A. H. 1973, ApJ, 181, 811

Ferraro, F. R., Paltrinieri, B., Fusi Pecci, F. Dorman, B., & Rood, R. T. 1998, ApJ, 500, 311

Fowler, W. A., Burbidge, E. M., Burbidge, G. R., & Hoyle, F. 1965, ApJ, 142, 423

Gonzalez, J.-F., LeBlanc, F., Artru, M.-C., & Michaud, G. 1995, A&A, 297, 223

Grundahl, F., Catelan, M., Landsman, W. B., Stetson, P. B., & Andersen, M. I. 1999, ApJ, 524, 242

Hauschildt, P. H., Allard, F., & Baron, E. 1999, ApJ, 512, 377

Hui-Bon-Hoa, A., Alecian, G., & Artru, M.-C. 1996, A&A, 313, 624

Hui-Bon-Hoa, A., LeBlanc, F., & Hauschildt, P. H. 2000, ApJ, 535, L43

Hui-Bon-Hoa, A., LeBlanc, F., Hauschildt, P. H., & Baron, E. 2002, A&A, 381, 197

Kochukhov, O., Bagnulo, S., & Barklem, P. S. 2002, ApJ, 578, L75

Landstreet, J. D. 1982, ApJ, 258, 639

Landstreet, J. D., Barker, P. K., Bohlender, D. A., & Jewison, M. S. 1989, ApJ, 344, 876

Landstreet, J. D., Dolez, N., & Vauclair, S. 1998, A&A, 333, 977

LeBlanc, F., & Michaud, G. 1993, ApJ, 408, 251

LeBlanc, F., Michaud, G., & Babel, J. 1994, ApJ, 431, 388

LeBlanc, F., Michaud, G., & Richer, J. 2000, ApJ, 538, 876

Maury, A. C. 1897, Harvard Ann., 28, 1

Michaud, G. 1970, ApJ, 160, 641

Montmerle, T., & Michaud, G. 1976, ApJS, 31, 489

Morgan, W. W. 1931, ApJ, 73, 104

Norris, J. 1971, ApJS, 23, 213

Peterson, R. C., Rood, R. T., & Crocker, D. A. 1995, ApJ, 453, 214

Preston, G. W. 1974, ARA&A, 12, 257

Richer, J., Michaud, G., & Turcotte, S. 2000, ApJ, 529, 338

Ryabchikova, T. A. 1991, in Evolution of Stars: The Photospheric Abundance Connection, IAU Symp. 145, ed. G. Michaud & A. Tutukov, (Dordrecht: Kluwer), 149

Ryabchikova, T. A., Wade, G. A., LeBlanc, F. 2002, in Modelling of Stellar Atmospheres, IAU Symp. 210, (in press)

Sigut, T. A. A., Landstreet, J. D., & Shorlin, S. L. S. 2000, ApJ, 530, L89

Smith, M. A. 1971, A&A, 11, 325

Takada-Hidai, M. 1991 in Evolution of Stars: The Photospheric Abundance Connection, IAU Symp. 145, ed. G. Michaud & A. Tutukov, (Dordrecht: Kluwer), 137

Titus, J., & Morgan, W. W. 1940, ApJ, 92, 256

Vauclair, S. 1975, A&A, 45, 233

Vauclair, S., & Vauclair, G. 1982, ARA&A, 20, 37

Wade, G. A., Ryabchikova, T. A., Bagnulo, S., & Piskunov, N. 2001, in Magnetic Fields across the Hertzsprung-Russell Diagram, ed. G. Mathys, S. K. Solanki & D. T. Wickramasinghe, ASP Conf. Series 248, 373

Watson, W. D. 1971, A&A, 13, 263

White, R. E., Vaughan, A. H., Preston, G. W., & Swings, J. P. 1976, ApJ, 204, 131

Wolff, S. C., & Preston, G. W. 1978, ApJS, 37, 371