# Diffusion in nonmagnetic stars and COROT

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## ABSTRACT

New developments in the modeling of nonmagnetic nonrotating A stars have had a major impact on our understanding of the formation of abundance anomalies in these stars. The great sensitivity of the pulsational properties as well as of the observable chemical composition to the internal mixing processes in chemically peculiar stars make these objects potentially important tools to investigate the depth and nature of that mixing. Some possible implications for the seismology of A and B stars are discussed in light of what the COROT mission could contribute to the study of these stars and of the importance of these objects in the overall success of a mission such as COROT.

## 1. Introduction

New models of elemental diffusion in main-sequence stars have changed the paradigm for the formation of chemical peculiarities in nonmagnetic nonrotating A stars, i. e., the Am stars (Richer et al. 2000). The models use tables of monochromatic spectra for 21 individual elements (H through Ni, with the exception of F, Sc, V, and Co) to compute in a consistent fashion the diffusion of the elements, including accurate radiative forces, and its impact on opacities. They permit the study of diffusion of all the important elements in stellar structure not only in chemically peculiar stars, but also in chemically normal A stars in which deviations from the adopted solar composition can have an effect on predictions of their pulsational properties.

The effect of diffusion in A stars and its impact on the excitation of pulsations or on other facets of their seismology have been made in the past. Unfortunately, those efforts were limited to the study of the evolution of hydrogen, helium, and occasionally some other trace elements such as lithium. It is well known from observations that significant abundance anomalies occur in heavy elements which play a major role in the stellar structure through the opacities. Realistic models of stars in which the chemical composition differ substantially from the solar "standard" can only be achieved with the use of the aforementioned monochromatic opacities. Since helium is the dominant element in the seismology of A stars, the results of previous models can be expected to reproduce the most important (lowest order) effects of diffusion

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on pulsations of A stars. In chemically normal A stars, diffusion will have a much subtler effect on their pulsational properties, which are outside of the context of the theoretical work described here. An insight in those effects was shown by Guzik (1992) who found some possible influence on light curves.

We will hereafter describe the newest theoretical results on the formation and evolution of Am stars and discuss the insight it gives for some other types of stars. The pulsational properties of stars with and without diffusion will then be discussed in the context of the COROT mission.

## 2. Diffusion in A and B stars

Diffusion is expected to be an important process in slowly rotating stars ranging from hot F stars to cool B stars. A-type stars are particularly interesting because many competing processes, such as diffusion, rotation, magnetism, mass-loss, and convection are of the right order of magnitude to produce a wide range of surface chemical compositions depending on their relative importance.

In cool B stars, the abundance peculiarities are thought to be the results of simpler physics. In current models, only rotation and mass-loss are expected to compete with diffusion in the evolution of the superficial chemical composition.

### *2.1. Results for models of nonrotating A stars*

The new models for Am stars have been described in Richer et al. (2000) (see also Turcotte et al. 1998 for results for cooler F stars). We will briefly review them here but the reader should refer to the full paper for all the details.

In early F and hotter stars iron-peak elements are driven outwards by the radiative pressure while light elements (e. g., He, C, N, O, or Ne) sink towards the center. In anterior models in which only He settling was considered, the models for Am stars featured a very shallow surface convection devoid of helium. These models never produced abundance patterns in quantitative agreement with those observed in actual Am stars. Including the evolution of the abundances of iron-peak elements changes this scenario completely.

Figure 1 shows radiative accelerations ($g_{\rm rad}$) for iron-peak elements compared to the gravitational acceleration ($g$) in a model of a 1.9 $M_\odot$ A star. Their radiative acceleration is stronger than gravity to a substantial depth in the models, resulting in the predicted formation of superficial overabundances at the surface or in the outer envelope depending on how mixing behaves. An important feature of their $g_{\rm rad}$ profile is the slight dip at a temperature close to 200,000 K. Diffusion velocities decrease in that region, resulting in an accumulation of iron-peak elements. As these elements dominate the opacity at that temperature, the opacity increases as well. Given enough time a convective instability will occur which will continue growing as more iron-peak elements accumulate in this narrow convection zone.

The time scales necessary for the convection zone to appear vary with the stellar mass. The time scales are smaller for more massive stars because the temperature at which it occurs is closer to the surface in terms of mass and radius. The time scales are of the order of 150 to 200 Myr in the model of a 1.45 $M_\odot$ star, and only a few Myr for more massive B stars (3-4 $M_\odot$). In A stars (1.6 to 2.5 $M_\odot$), one can expect it to form in a few tens Myrs.

The major assumption made in the models, which is borne out with comparisons with observational data so far, is that this iron convection zone is linked to the other convection zones occurring at lower temperature in A stars. The entire envelope from the base of the iron convection zone to the photosphere is therefore assumed to be fully mixed from the moment of the formation of the instability onward. A specific physical model for this linkage has not yet been put forth.

However, it is not necessary that the deep mixing be caused by convection. All this assumption implies is that there is a *minimum* depth for the superficial mixing which is defined by the base of the iron convection zone. This iron convection zone would only form if the mixing in the star was weak enough to permit the formation of large abundance anomalies. In fact, the iron convection zone never forms in the models which best reproduce the Am stars. The deep mixing might be the result of angular momentum transport in the star for example (Talon & Zahn 1997).

This deep mixing assumption yields the correct abundance patterns in specific stars of known age. A quantitative agreement can be obtained in most cases by adjusting the depth of the mixing. The surface abundances therefore become an observational test for mixing mechanisms in these stars. Examples of abundance profiles and of surface abundance patterns for a model of an Am star with different assumed mixing profiles are shown in Figs. 2 and 3 respectively. The strongest constraint on diffusion in Am stars is the underabundances of Ca and Sc and the overabundances of iron-peak elements. For those features to develop, the difference between gravity and the radiative forces at the base of the mixed zone for these elements must have the right signs ($g_{\rm rad}({\rm Ca}) < g, g_{\rm rad}({\rm Fe}) > g$). The inspection of Fig. 1 shows that both the old and the new models can yield the right conditions for that to occur. Indeed, the old model with a mixing ending at $\log T \approx 4.5$ and the new with mixing until $\log T \approx 5.5$ both predict underabundances of Ca which are impossible in other cases. Theoretical and observational evidence rather point to the newer models.

Some questions pertaining to these models are still unanswered. The models include no mass-loss but it is expected to occur in these stars. No mass-loss has been observed yet so it is quite small, but even small mass-loss will have an effect on the evolution of surface anomalies in these stars.

### 2.2. *Results for models of nonrotating cool B stars*

Chemically peculiar B stars, known as HgMn stars, feature strong abundance anomalies from several tens up to $10^6$ for certain elements. Large differences are observed from star to star, much more so than in Am stars. A major difference between A and B stars is the stability of the most superficial regions of B stars, in contrast to A stars in which the outer regions are convective. This allows for the separation of the elements to occur in the atmosphere of B stars, allowing such large abundance anomalies. On the other hand,

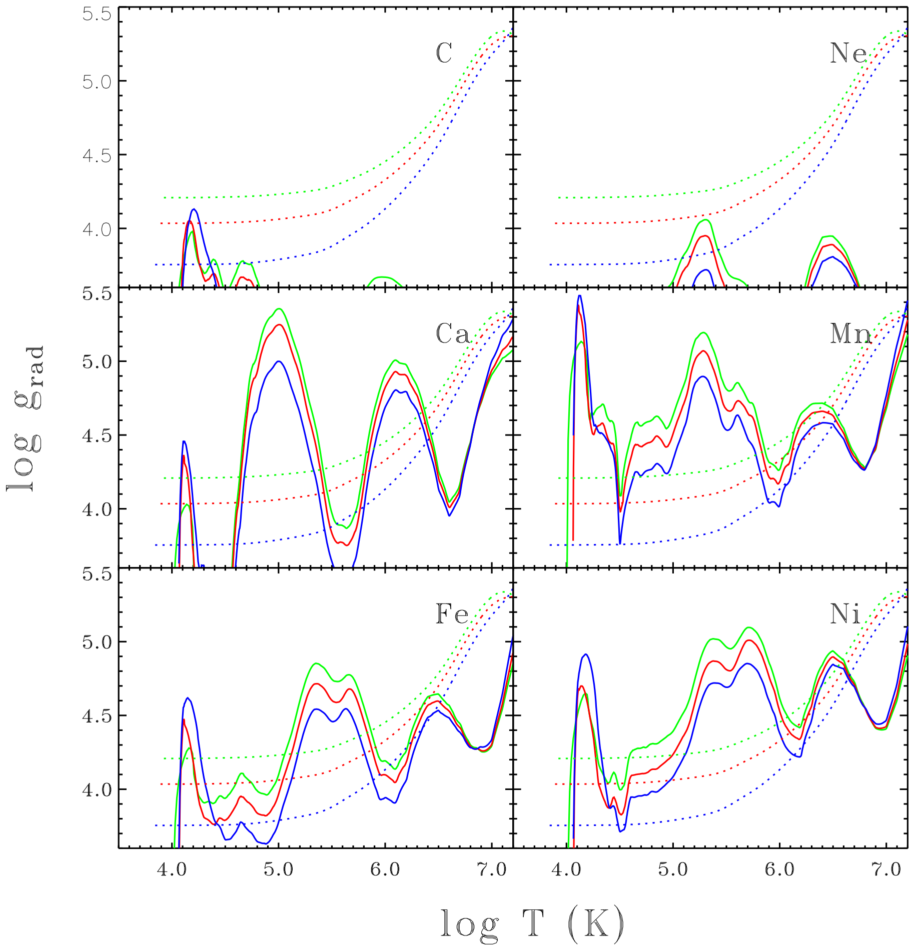


Fig. 1.— The logarithm of the radiative accelerations of selected elements in a model of a 1.90 $M_\odot$ A-type star at three different ages (100, 300, and 670 Myr), in function of the logarithm of the temperature in the star. The gravity for those ages are plotted as dotted curves. When $g_{\rm rad}$ is larger than $g$ (continuous line above the dotted line) the elements are pushed towards the surface (to the left).

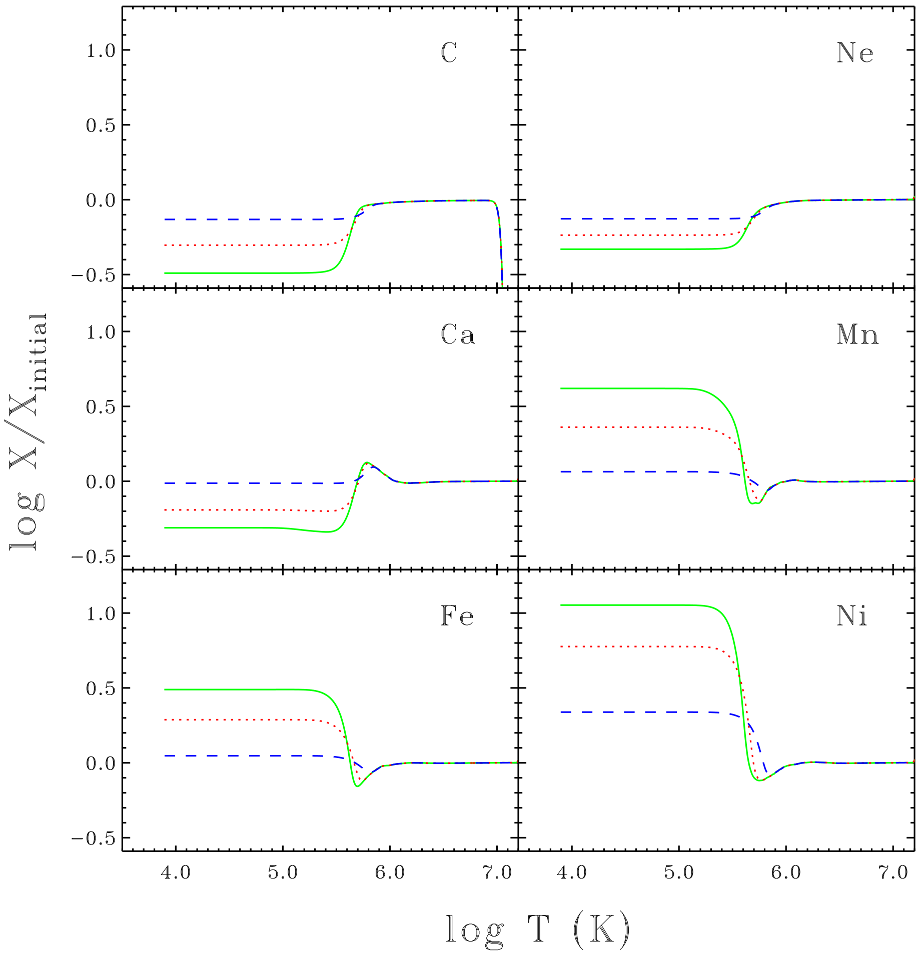


Fig. 2.— Abundance profiles relative to the initial (homogeneous) abundances of the elements identified in the upper right-hand corner of each panel, in models of a 1.90 $M_{\odot}$ star at 670 Myr. Different mixing profiles are assumed in the three models shown. Deeper mixing lead to smaller predicted abundance change (vs. initial content).

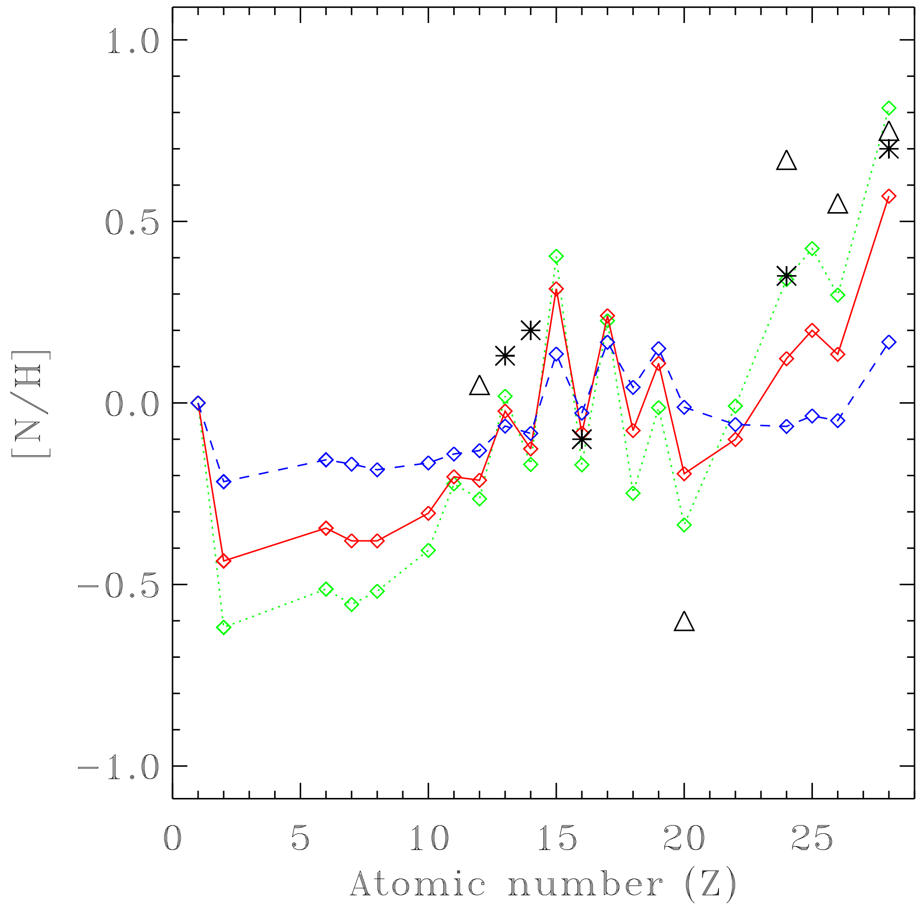


Fig. 3.— Superficial abundances of HD 73045 in the Præsepe cluster with respect to the atomic numbers of all the species modeled. The observed abundances shown are: triangles are from Hui-Bon-Hoa & Alecian (1998) and asterisks are from Burkhart & Coupry (1998). The models shown, roughly at the age and effective temperature of the star, span a wide range of mixing depths and are not optimized to fit the observational data. The flatter curve is a model with deep mixing, and the two other models have progressively shallower mixing. All three assumed mixing profiles extend the fully mixed region below the base of the iron convection zone, if it was allowed to form. See Richer et al. (2000) for actual fits of models to data.

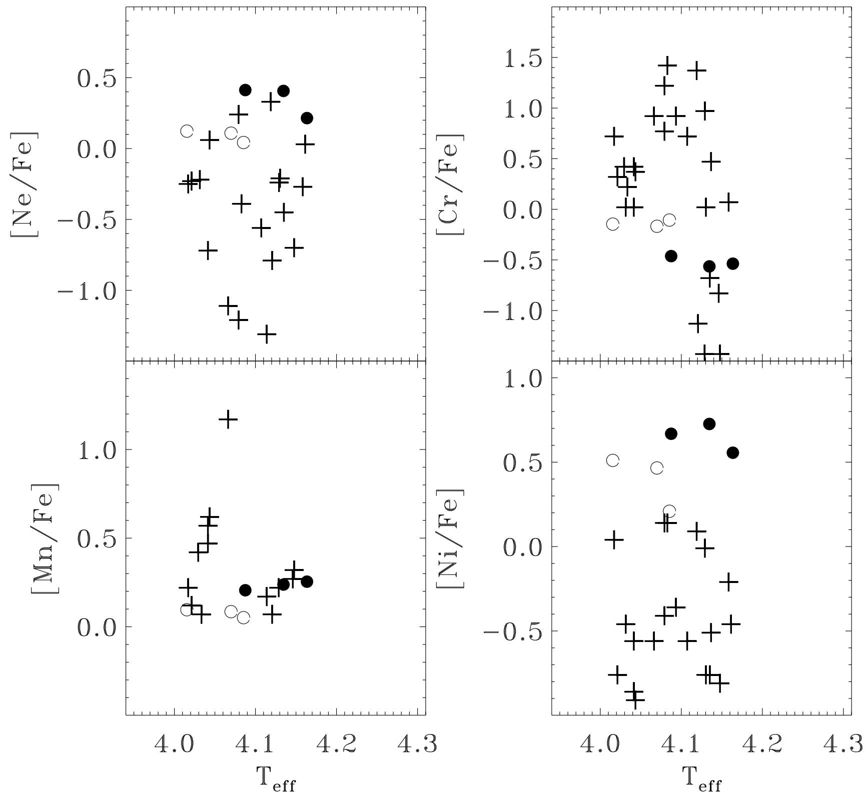


Fig. 4.— Superficial abundance ratios of selected elements with respect to Fe in B stars compared to predictions from models of 3 $M_{\odot}$ (open circles) and 4 $M_{\odot}$ (filled circles). The observed abundances are from Smith & Dworetsky (1993) for all elements except Ne for which they are from Dworetsky & Budaj (2000).

diffusion in the interior should follow the same scenario in both stellar classes. This would be expected to have important consequences for pulsations in these stars, which we will touch upon in the next section.

Current models cannot predict accurately how abundances evolve at the surface. The OPAL data on which we rely are not suitable to calculate radiative acceleration at low temperatures because the spectral lines become too narrow, i. e., the coarseness of the frequency grid does not allow a good sampling of the spectral lines (Richer et al. 1998). Other models tackle the problem of diffusion in the atmosphere directly by using appropriate data to calculate radiative accelerations (see for example Proffitt et al. 1999). If we nonetheless go forward with the same assumption than in the A stars, i. e., that the star is mixed from the base of the iron convection zone to the surface, then the anomalies predicted are within the envelope of observed abundances but cannot reproduce the large gamut of chemical composition observed (see Fig. 4).

## 3. Diffusion and asteroseismology

### *3.1. A stars*

In the models described above, the comparatively large depth of the mixing ensures that some helium remains in the driving region for pulsations in the classical instability strip. This contrasts with older models in which no helium was left to drive pulsations unless mass-loss was assumed or it was assumed that the star was evolved enough so that helium would be dredged-up from the deep interior where it would have previously settled.

The pulsational behavior of the models for nonrotating A stars have been described in Turcotte et al. (2000). In the new models, the Am stars would retain enough helium in the outer region to enable pulsation to occur in the later stages of their main-sequence life if the mixing is deep enough. All models with diffusion show a strong damping of higher frequency modes. As only high frequency modes are excited in young stars, young Am stars are stable. Am stars become marginally unstable once the star has evolved enough so that the fundamental radial mode is overstable. The evolved models of Am stars have overall characteristics coherent with old metallic pulsating A stars. The stars are still young enough that no dredge-up of helium has occurred.

The blue edge of the instability strip is a sensitive tool to evaluate the depth of mixing. It tests the level of depletion of helium in the stars. The modes for which the blue edge of their instability strip is most affected are the higher order modes. In the case of very shallow or weak mixing where helium can barely sustain pulsations, then only very red stars or stars evolved off the main-sequence will be variable. This should leave a visible signature in the distribution of variable metallic A stars in the instability strip.

### *3.2. B stars*

The important difference between pulsations in A and B stars as far as diffusion is concerned is in the elements which are responsible for the excitation of the instabilities. In B stars, helium plays little role as the pulsations are excited by the heavy elements in the so-called metal opacity bump at around 200,000 K. This is exactly the region in which the iron-peak elements are expected to accumulate. The effect of diffusion in B stars would not be to prevent pulsations (as in A-type stars) but rather to contribute to a larger excitation. This is contradicted by observations.

HgMn stars have never been found to be variable except in a few cases which are attributed to rotating spots (monoperiodic variability with periods of several days). Chemically normal stars of the same mass and evolutionary status can be variable, they are part of the Slowly Pulsating B stars (SPB) class of variable stars. Models of HgMn stars are not reliable enough to permit the study of this problem at this juncture. The situation is likely to change in the near future with the large effort being put in the calculations of diffusion in the atmospheres and in the interiors of such stars.

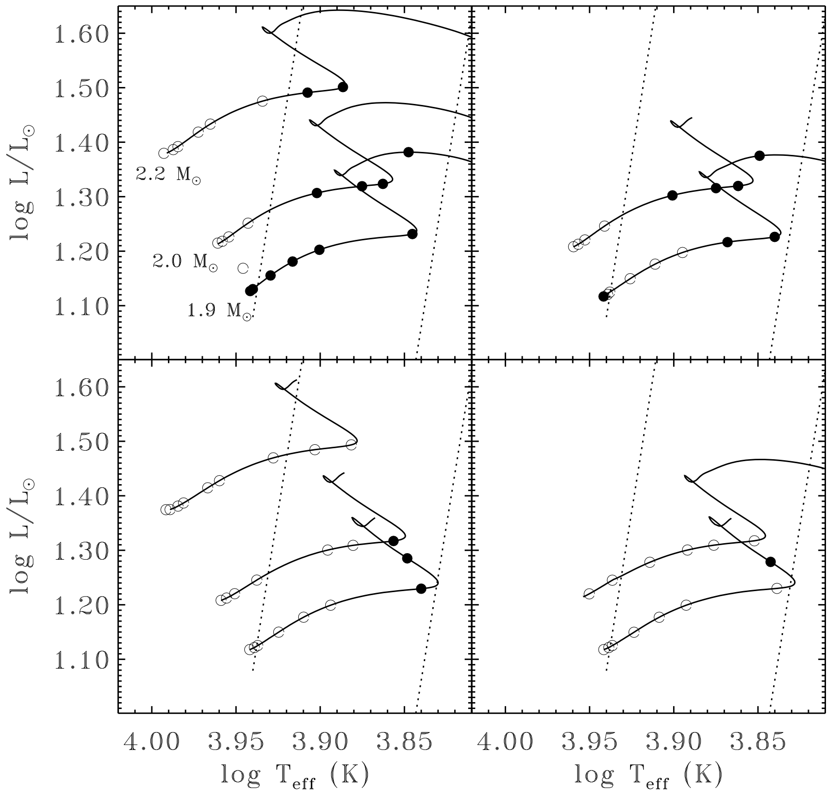


Fig. 5.— Estimates of the instability strip for stars assuming different mixing. Starting from the upper-left and going clockwise the four panels show models for which: no diffusion was included; diffusion with deep mixing was assumed; diffusion with shallow mixing; and diffusion with intermediate mixing. The models which reproduce the surface abundances of Am stars are typically between the shallow and intermediate mixing. Models for which at least one mode was found to be overstable are shown as filled circles, the models shown by open circles are stable. As indicated, models of 1.9, 2 and 2.2 $M_\odot$ were calculated. The dotted lines show the approximate boundaries of the classical instability strip.

## 4. Diffusion and the COROT mission

The fundamental question to ask now is what does diffusion and pulsations in chemically peculiar stars bring to the COROT mission.

We have shown that abundances and pulsations in A-type stars can be strongly affected by diffusion. In solar-type stars, its effect is more subtle but can be important, as has been shown in helioseismology. It is clear that the effects of diffusion on the models of the COROT targets should be considered because of the structural effects it can have. Certainly, in the case of pulsating stars, in view of the difficulties encountered so far in constructing seismic models of $\delta$ Scuti stars (Guzik et al. 2000 for an example), few physical processes can safely be neglected *a priori* in asteroseismology.

The case for the inclusion of chemically peculiar stars in the COROT programme may be difficult to make because of the limited numbers of targets allowed. Nonetheless, the expected physical insight to be gained by their study argues in their favor.

We argue that metallic A stars may provide a more sensitive measure of internal dynamics than normal stars because there is no evident diagnostics of mixing mechanism in these A stars. The prospect of extracting rotational information directly from data inversion is bleak. Although the depth of the convection should be possible to estimate, the usual signature of mixing in the deep interior might be difficult to read.

In Am stars however, the characteristics of the instability strip contains direct information about the abundance of helium in the superficial regions which constrains the depth of the mixing. As the amplitudes of the pulsations are severely reduced by diffusion the high-precision photometry from space offers substantial advantages to ground-based observations.

As far as HgMn stars are concerned, variability has already been excluded at the 5 to 10 mmag level, only space-based observations is likely to permit the detection of pulsations, if they occur. If they are not detected, it then places very strong constraints on either the evolution of the abundances in the interior, or on pulsational properties of these stars, with respect to binarity, magnetism, or other processes. In the event that only rotational variability can be confirmed or detected it would also be an interesting result as the strength of magnetic fields in these stars is still an open question.

There are observing opportunities for both Am and HgMn stars in the COROT programme. The observations of Am and HgMn stars would make use of the seismo field only, since for Am stars the expected periods are similar to those of $\delta$ Sctuti stars, and for HgMn stars, which periods could be as long as a day, we lack spectroscopic data at the magnitudes suitable for the exo field. Table 1 shows how many stars of each class are within the constraints in either field which have been discussed so far. The constraints adopted for the selection are $5.5 < m_{\rm V} < 9$ (design limits for the seismo field), $\pm 10^o$ in RA for each scenario, and $|\delta| < 15^o$.

Although the main programme should be centered on the best candidates for asteroseismology, i. e., solar-type stars and classical $\delta$ Scuti stars, the investigation of the pulsational properties of chemically peculiar stars promises to yield precious complementary information on the dynamics of stellar interiors.

| types | Scenario 1 | Scenario 2 |
|---|---|---|
| Am | 58 | 37 |
| Ap | 27 | 21 |
| HgMn | 8 | 8 |

Table 1: Number of potential targets in either COROT scenarios from the list of chemically peculiar stars compiled by Renson et al. (1991).

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## REFERENCES

Burkhart C., Coupry M.-F., 1998, A&A 338, 1073

Dworetsky M. M., Budaj J., 2000, MNRAS 318, 1264

Guzik J., 1992, in New perspectives on stellar pulsation and pulsating variable stars. IAU Coll. 139, Cambridge: Cambridge University Press, eds J. M. Nemec and J. M. Matthews, 243

Guzik J., Bradley P. A., Templeton M. R., 2000, in Delta Scuti and related Stars, ASP. Conf. Ser. 210, San Francisco:Astronomy Society of the Pacific, eds M. Breger and M. H. Montgomery, 247

Hui-Bon-Hoa A., Alecian G., 1998, A&A 332, 224

Proffitt C. R., Brage T., Leckrone D. S., Wahlgren G. M., Brandt J. C., Sansonetti C. J., Reader J., Johansson S. G., 1999, ApJ 512, 942

Renson P., Gerbaldi M., Catalano F. A., 1991, A&AS 89, 429

Richer J., Michaud G., Rogers F. J., Iglesias C. A., Turcotte S., LeBlanc F., 1998, ApJ 492, 833

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

Smith K. C., Dworetsky M. M., 1993, A&A 274, 335

Talon S., Zahn J.-P., 1997, A&A, 317, 749

Turcotte S., Richer J., Michaud G., 1998, ApJ 504, 559

Turcotte S., Richer J., Michaud G., Christensen-Dalsgaard J., 2000, A&A 360, 603