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High frequency versus low frequency oscillations in roAp stars

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Abstract. The frequency range in which roAp stars' pulsations are found is of key importance to the understanding of different aspects of these stars. In this work we will report recent theoretical and observational results concerning some of the oldest open questions associated with roAp stars. In particular, we describe: 1) how recently derived helium profiles resulting from diffusion alone affect the stability of low and high radial order modes in models of roAp stars; 2) how the energy of oscillations with frequencies above the acoustic cut-off frequency is distributed onto magnetic and acoustic components in the magnetically dominated region, and the implications of this distribution to mode reflection; 3) how the theoretically-predicted intermediate frequency roAp stars are being searched for, after the discovery of the first example of this kind, HD 116114, with an oscillation period of 21 minutes.

Key words. Stars:variable – Stars: magnetic – Stars: peculiar

1. Introduction

Some of the oldest open questions concerning rapidly oscillating Ap stars (hereafter roAp stars) are directly related with the frequency range in which the oscillations are observed. Questions like *Why are high radial order modes excited and low radial order modes suppressed in these stars?*, *What mechanism is responsible for the reflection of high frequency oscillations in their outer layer* or *Can roAp stars be found which pulsate in frequencies that are significantly different from the typical frequencies observed in these stars?* have long been debated. Below we report on recent theoretical and observational results concerning the questions enumerated above.

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2. Why are high radial order modes excited and low radial order modes suppressed in roAp stars?

The high radial order oscillations observed in roAp stars are nowadays believed to be driven by the traditional opacity-mechanism acting in the region of hydrogen ionization (Dziembowski & Goode 1996). This driving is in contrast with the driving of the much lower radial order oscillations observed in δ-Scuti stars which, despite being found in a similar region of the HR diagram, are known to have their oscillations excited by the opacity-mechanism acting in the region where helium undergoes its second ionization.

Despite the general believe that the oscillations observed in roAp stars are excited by the opacity-mechanism acting in the region of hydrogen ionization, linear nonadiabatic calculations performed in models of roAp stars only predict high radial order oscillations to be unstable when either a chromosphere is included in the models (Gautschy et al. 1998) or the envelop convection is assumed to be suppressed by the magnetic field (Balmforth et al. 2001; Cunha 2002).

Despite the success of these models in predicting the excitation of the observed oscillations, the latter predict also the excitation of oscillations of much lower radial order, with frequencies similar to the frequencies observed in δ-Scuti stars. Since no low radial order oscillation has ever been observed in roAp stars one is led to suspect that there is still some physics missing in the nonadiabatic models that have been used so far.

Recently Saio (2005) has shown that the direct effect of the magnetic field on pulsations is important to the stabilization of low order modes in roAp stars. Here we report on another important contribution to the stabilization of these modes, related to the helium settling in the envelop of roAp stars.

Theado et al. (2005) have produced helium profiles for the envelop of roAp stars by evolving models from ZAMS, including atomic diffusion and, in some cases, a wind. Envelope convection was also suppressed in their models, whenever a simple criteria for suppression of convection (previously used by Balmforth et al. (2001)) was satisfied. The helium profiles thus derived were included in models of roAp stars used to perform linear nonadiabatic calculations. In figure 1 we show the modes that are found to be excited in two typical models of roAp stars, when different helium profiles are used in the envelop.

The results show that helium settling clearly contributes towards the stabilization of the low order modes in roAp stars. This is not a surprise, since, just as in the case of δ-Scuti stars, it is the opacity mechanism acting in the region of second helium ionization that is the main responsible for the excitation of low order modes in the models of roAp stars. With the settling of helium, the helium content of that region is strongly decreased and, hence, the low order modes are no longer excited.

3. What mechanism is responsible for the reflection of high frequency oscillations in the outer layers of roAp stars?

Some of the oscillations observed in roAp stars have frequencies that are well above the theoretical acoustic cut-off frequency derived in standard models of these stars. This fact has raised the so-called *problem of the cut-off frequency in roAp stars* which has been under debate since pulsations were first discovered in roAp stars. However, to understand the problem of wave reflection in the surface of roAp stars it is necessary to take into account the magnetoacoustic nature of the waves.

In the outer layers of a roAp star the magnetic pressure largely dominates over the gas pressure. In those layers the magnetoacoustic wave decouples into a wave that is essentially acoustic, associated with a displacement that is nearly along the magnetic field direction, and wave that is essentially magnetic, associated with a displacement that is nearly perpendicular to the magnetic field direction (Sousa and Cunha - in preparation). This decoupling results from the difference in the wavenumbers associated with the magnetic and acoustic components. The direction of the displacement associated with each of the components is determined by the direction of the perturbed Lorentz force which, to first order, is perpendicular to the unperturbed magnetic field.

If the frequency of the oscillation is above the acoustic cut-off frequency (which itself depends on the inclination of the magnetic field (Dziembowski & Goode 1996)) the energy associated with the acoustic component in the outer layers of the star will be lost. In Sousa and Cunha (these proceedings) we describe how the fraction of energy lost through acoustic running waves in the atmosphere of roAp stars can be estimated. Still, one interesting question that remains is what happens to the energy that is associated with the magnetic component in the outer layers of the star. The condition that the magnetic field tends to a vacuum field as the density tends to zero assures that in an ideal formulation of the problem the energy associated with the magnetic compo-

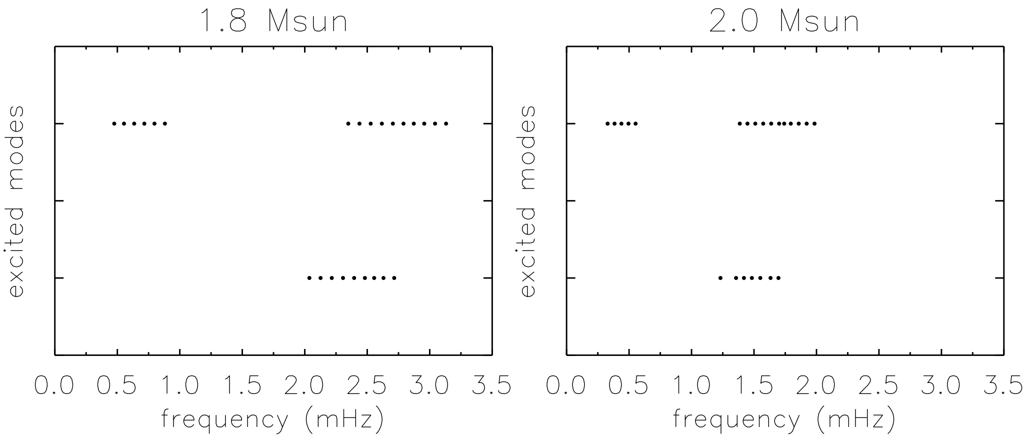

Fig. 1. The figure shows the modes that are predicted to be excited in two models of roAp stars. Left: model with mass $M = 1.8\mathrm{M}_{sun}$, effective temperature $T_{eff} = 8390\mathrm{K}$ and relative luminosity $L/\mathrm{L}_{\mathrm{sun}} = 11.02$. Right: model with mass $M = 2.0\mathrm{M}_{sun}$, effective temperature $T_{eff} = 8390\mathrm{K}$ and relative luminosity $L/\mathrm{L}_{\mathrm{sun}} = 19.35$. In both panels the top symbols show the results obtained when the envelop of the model used has homogeneous chemical composition, while the lower symbols show the results when helium is deficient in the envelop due to gravitational settling.

nent is totally reflected. However, it is important to know how, and where in the atmosphere, such reflection takes place.

Both the acoustic wave in the interior of the star and the magnetic wave associated with the displacement perpendicular do the magnetic field in the outer layers, may be described as sums of two running wave components propagating in opposite directions (see figure 1 of Sousa and Cunha - these proceedings).

In figure 2 we show the ratio between the fluxes carried by the upwardly propagating magnetic component in the outer layers of the star and the upwardly propagating acoustic component in the interior. The frequency of the oscillation used to produced this figure was 4.3 mHz, well above the maximum acoustic cutoff frequency for the simple model considered. The model was composed of an index 3 polytropic interior matched at the surface onto an isothermal atmosphere. The results are shown as function of co-latitude θ for the case of a dipolar magnetic field. The change in co-latitude thus reflects the change in the inclination of the magnetic field, from vertical, at $\cos\theta = 1$, to horizontal, at $\cos\theta = 0$. The calculations were made assuming, at each latitude, a local plane parallel geometry and a magnetic field that is locally uniform (e.g. (Cunha & Gough 2000))

As expected, near the magnetic pole, where the magnetic field is close to vertical, almost none of the energy content of the acoustic wave in the interior is passed onto the magnetic wave in the surface layers. However, as the magnetic field gets more inclined, an increasing fraction of the acoustic energy in the interior is passed, through the coupling that takes place in the region where the magnetic pressure is comparable to the gas pressure, onto the magnetic wave in the outer layers. However, the energy content of the magnetic wave in the outer layers decreases rapidly with hight. In practice this means that most of the energy that is passed onto the magnetic wave ends up being reflected not too far from the surface.

4. Can roAp stars pulsate with periods that are outside the typical range observed?

The oscillations observed in roAp stars have principle periods that are larger than 15 minutes. On the other hand, the smallest periods observed in δ-Scuti stars are close to 30 minutes. Thus, until recently the oscillations ob-

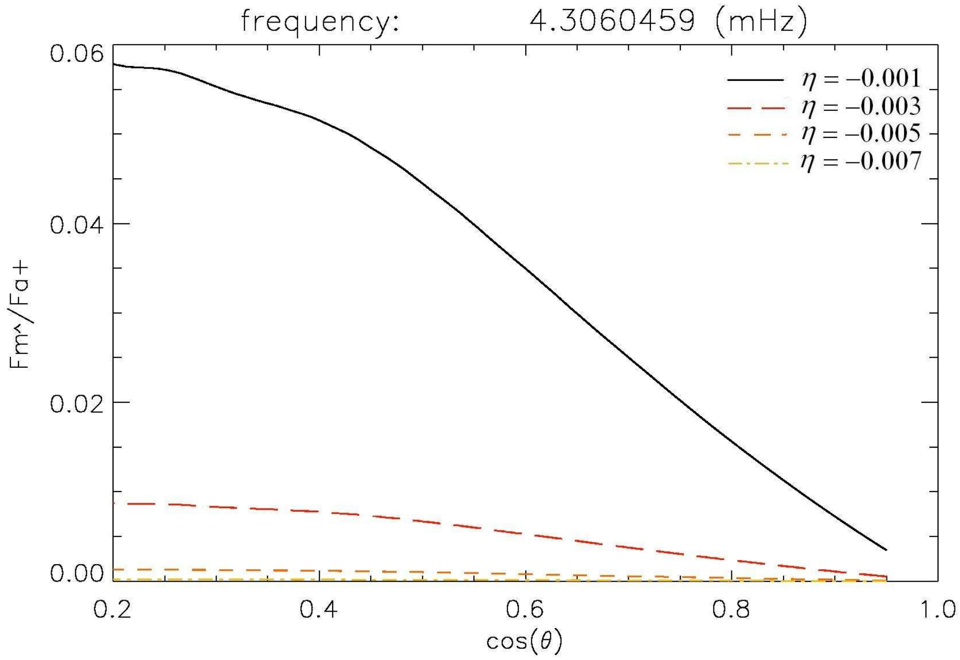

Fig. 2. Ratio between the fluxes F_m^+ and F_a^+ carried, respectively, by the upwardly propagating component of the magnetic wave in the outer layers and the upwardly propagating component of the acoustic wave in the interior (see figure 2 of paper Sousa and Cunha - these proceedings - for details). The different lines show the ratio at different heights in the atmosphere, with η defined as $\eta = 1 - r/R$, where r is the radial coordinate and R the radius of our simple model model.

served in roAp stars and in δ-scuti stars were believed to be separated by a clear gap in the period range. The question of whether this gap was real was however raised by the theoretical instability strip presented in Cunha (2002). According to the latter some cool Ap stars close to terminal age main sequence are expected to pulsate with periods that are between the two limits mentioned above.

The first intermediate-period roAp star, with a principal oscillation period of 21 minutes was found recently (Elkin et. al 2005). Following that discovery a small survey is being carried out by the same team in search for additional roAp stars with periods below the typical observed range. We note, however, that these longer periods still correspond to modes of high radial order.

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