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Observations of solar-like oscillations and asteroseismic models including rotation

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Abstract. Since the success of helioseismology, numerous efforts have been made to detect solar-like oscillations on other stars. Thanks to new spectrographs developed for extra-solar planet searches, the accuracy needed to detect such oscillations has recently been achieved. In this paper, we present new asteroseismic measurements obtained with the Coralie and Harps spectrographs as well as new theoretical analyses based on these observations. In particular, we focus on the effects of rotation on the modelling of solar-type stars and on its influence on the determination of fundamental stellar parameters.

Key words. Techniques: radial velocities – Stars: fundamental parameters – Stars: oscillations – Stars: evolution – Stars: rotation

1. Introduction

The solar five-minute oscillations have led to a wealth of information about the internal structure of the Sun. These results stimulated various attempts to detect a similar signal on other solar-like stars by photometric or equivalent width measurements. These past years, the stabilized spectrographs developed for extra-solar planet search achieved accuracies needed for such a detection. While solar-like oscillations have been detected for a handful of solar-type stars, individual p-mode frequencies have only been identified for a few of these stars: α Cen A (Bouchy & Carrier 2002; Bedding et al. 2004), α Cen B (Carrier & Bourban 2003), Procyon A (Martić et al. 2004a; Eggenberger et al. 2004a) and η Bootis (Kjeldsen et al. 1995, 2003; Carrier et al. 2005a). Individual frequencies have also been identified in the giant star ξ Hydrae (Frandsen et al. 2002).

Based on these asteroseismic data, numerous theoretical analyses have been performed in order to determine precise global parameters (see for example Eggenberger et al. 2004b for the α Cen system) and to try to test the effects of overshooting or rotation on the models (see Di Mauro et al. 2003 for η Boo or Eggenberger et al. 2005a for Procyon).

To illustrate the effects of rotation on stellar evolution, we will confront rotating models to new asteroseismic measurements obtained for the G0 IV star η Bootis and the F9 V star β Virginis. Finally, we will briefly discuss the problem of the solar rotation profile.

2. η Bootis

Solar–like oscillations in η Bootis were first detected by Kjeldsen et al. (1995, 2003). We

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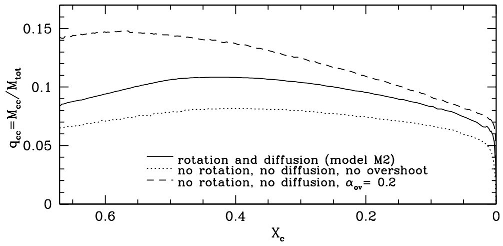

Fig. 1. Ratio of the mass of the convective core to the total mass of the star (q_{cc}) as a function of the central hydrogen abundance (X_c) for three different models of η Bootis with a mass of 1.69 $M_{\odot}$.

also observed this star with the Elodie and Coralie spectrographs and identified 22 individual p–mode frequencies (Carrier et al. 2005a). Based on these seismic data and on non–asteroseismic observational constraints, detailed stellar models were computed using the Geneva evolution code. Note that comprehensive theoretical studies have already been performed for η Bootis by Di Mauro et al. (2003, 2004) and Guenther (2004), but contrary to our analysis, these studies are based on the seismic data of Kjeldsen et al. (2003) and do not include the effects of shellular rotation.

We find that the inclusion of shellular rotation changes the values of the deduced fundamental parameters of η Bootis and in particular its age. Indeed, without rotation an age of 2.39 ± 0.10 Gyr is found, in perfect accordance with the results of Di Mauro et al. (2003) and Guenther (2004), while rotating models predict a larger age of 2.65 ± 0.10 Gyr. This illustrates the fact that, for small initial velocities, rotational effects are found to mimic the effects due to an overshoot of the convective core into the radiative zone. Indeed, the lifetimes of rotating models are enhanced with respect to those of standard models, because mixing feeds the core with fresh hydrogen fuel. As a result, the hydrogen exhaustion in the central region is delayed and the time spent on the main sequence increases. This can be seen in Fig. 1 which shows the ratio of the mass of the convective core to the total mass of the star (q_{cc}) as a function of the central hydrogen abundance (X_c) for a standard model without overshooting, for a standard model with

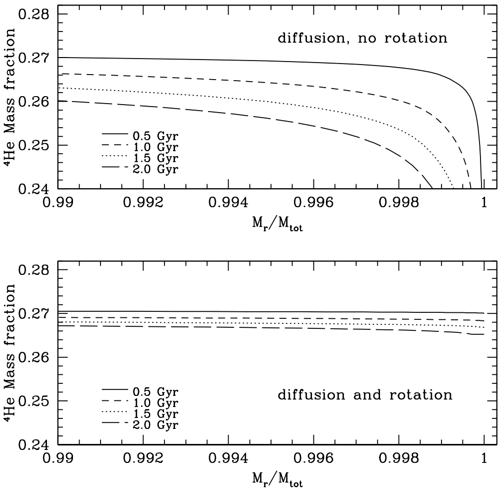

Fig. 2. Helium abundance profile in the external layers of a model of η Bootis at different age during its evolution on the main sequence. The model on top only includes atomic diffusion, while the model on bottom includes atomic diffusion and shellular rotation.

$\alpha_{ov} \equiv d_{ov}/\min[H_p, r_{core}] = 0.2$ and for a model with rotation and atomic diffusion. We see that the rotating model exhibits a larger convective core for a given X_c, i.e. for a given evolutionary stage on the main sequence, than the standard model without overshooting. In the same way the non-rotating model with $\alpha_{ov} = 0.2$ also exhibits larger convective cores on the main sequence than standard models without overshooting. This explains why the inclusion of rotation or overshooting increases the lifetimes of the model on the main sequence and hence the deduced age for η Bootis.

We also note the effects of rotation on the surface abundances. For stars more massive than about 1.4 $M_{\odot}$, it is indeed necessary to introduce a transport mechanism, like rotational mixing, in order to counteract the effect of atomic diffusion in the external layers. When only atomic diffusion is included in a star with a thin convective envelope, helium and heavy elements are drained out of the envelope, resulting in too low surface abundances which are incompatible with observation. This is illustrated in Fig. 2 which shows the helium profile in the external layers of a star at differ-

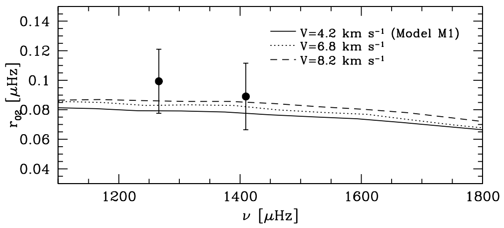

Fig. 3. Ratio of the small to large separations $r_{02} \equiv \delta\nu_{02}/\Delta\nu_{n,\ell=1}$ as a function of frequency for models of β Virginis with the same value of the mean large separation (72.1 μHz) but different surface velocities V. Dots indicate the observed values.

ent age during its evolution on the main sequence for a model including only atomic diffusion and for a model including both shellular rotation and atomic diffusion. Figure 2 shows that rotation induced mixing prevents the helium from being drained out of the convective envelope.

3. β Virginis

Solar–like oscillations in the F9 V star β Virginis were first detected by Martić et al. (2004b). Recently, Carrier et al. (2005b) observed β Virginis with the Coralie and Harps spectrographs and reported the identification of 31 individual frequencies.

We find that two distinct solutions well reproduce all existing asteroseismic and non-asteroseismic observational constraints: a main–sequence model with a mass of $1.28 \pm 0.03\,M_\odot$ and an age $t = 3.24 \pm 0.20$ Gyr, or a model in the post main–sequence phase of evolution with a lower mass of $1.21 \pm 0.02\,M_\odot$ and an age $t = 4.01 \pm 0.30$ Gyr. The small spacings $\delta\nu_{02}$ and the ratio r_{02} between small and large spacings are sensitive to the differences in the structure of the central layers between these two solutions, and can therefore be used to unambiguously determine the evolutionary stage of β Vir. Unfortunately, existing asteroseismic data do not enable such a precise determination.

Changing the rotational velocity of the models results in a change of the structure of the stellar core which influences the p–mode frequencies. Indeed, an increase of the rotational velocity increases the mixing in the central core of the star and hence the values of the small separations. This is illustrated in Fig. 3 which shows the ratio of small to large separations for three models of β Virginis with different surface velocities.

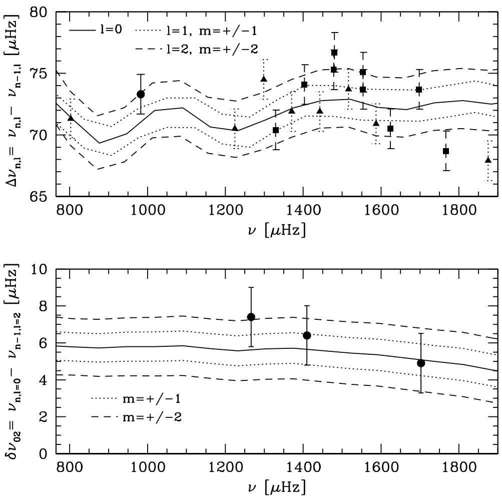

Fig. 4. Dispersion of the large and small spacings expected from rotational splittings for β Virginis. The observed large spacings for the $\ell = 1$ modes are expected to lie between the maximum/minimum values delimited by the $\ell = 1$, $m = \pm 1$ modes. In the same way, the observed large spacings for the $\ell = 2$ modes and the observed small spacings $\delta\nu_{02}$ are expected to lie between the maximum/minimum values delimited by the $\ell = 2$, $m = \pm 2$ modes.

Rotation can also partly explain the large dispersion of the observed large separations and in particular the fact that the dispersion for non–radial modes is found to be larger than for the radial modes. Figure 4 suggests that the scatter of frequencies introduced by the rotational splittings (that cannot be resolved because of the resolution of the time series) can account for the large dispersion of the $\ell = 1$ and $\ell = 2$ modes.

4. The solar rotation profile

Finally, we briefly discuss the problem of the solar rotation profile. Helioseismic observations show that the solar angular velocity is approximately constant down to about $0.2\,R_\odot$,

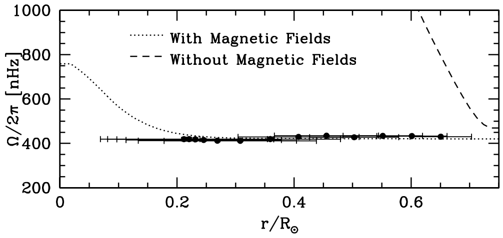

Fig. 5. Rotation profile for a model with rotation only (dashed line) and with both rotation and magnetic field (dotted line) at the age of the Sun. The points with their respective errors bars correspond to the angular velocity in the solar radiative zone deduced from GOLF+MDI and LOWL data (Couvidat et al. 2003).

while models with shellular rotation produce an insufficient internal coupling to ensure solid body rotation. This suggests that another effect intervenes.

There are currently two main possible explanations: internal gravity waves and magnetic fields. As shown by Talon & Charbonnel (2005), internal gravity waves are able to extract angular momentum from the central parts of a solar–type star. We also recently studied the effects of magnetic fields, and in particular of the Tayler–Spruit dynamo (Spruit 2002), on the solar rotation profile. We find that the Tayler–Spruit dynamo can account for the flat rotation profile of the Sun as deduced from helioseismic measurements (Eggenberger et al. 2005b). This is illustrated in Fig. 5 which compares the theoretical rotation profile of models computed with an initial velocity of 50 km s^{-1} to the one deduced from helioseismic measurements.

5. Conclusions

Shellular rotation changes the values of the fundamental stellar parameters and, in particular, significantly increases the age of the star. Asteroseismic observables are also influenced by rotation, but existing seismological data obtained for slow rotating solar-type stars are not accurate enough to reveal these rotational effects. We can hope that, in a near future, solar–like oscillations for stars with larger surface velocities will be observed in order to really study the structural effects of rotation and to directly measure rotational splittings of non–radial p–modes. On the theoretical side, it will be interesting to develop stellar models including a comprehensive treatment of rotation (with angular momentum transport by internal gravity waves) and magnetic fields.

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