The Ages of Stars
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Stellar ages from asteroseismology: a few examples

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Abstract. Asteroseismology is a powerful tool to derive stellar ages, masses, gravities, radii, etc. Precise determinations of these parameters need deep analyses for each individual stars. Approximate theories are not efficient enough. Here I present results for two stars, μ Arae and ι Hor, which have both been observed during eight nights with the HARPS spectrograph in La Silla. I also show that important constraints can be obtained on core overshooting using the same techniques.

Keywords. stars: atmospheres, interiors, fundamental parameters, oscillations, techniques: spectroscopic

1. Introduction

Asteroseismology can give much more precise values of the stellar parameters, including age, mass, radius, stellar gravity, effective temperature, metallicity, helium abundance value, than any other means. However such precise determinations need deep seismic analyses of individual stars, and cannot be obtained with approximate theories only.

The stellar oscillations have to be observed during a sufficiently long time, typically eight nights with the HARPS spectrograph, to allow precise comparisons with models. The Fourier analysis leads to frequency determinations and to mode identification, as discussed in Bouchy *et al.* 2005.

Meanwhile various evolutionary tracks are computed, using different input parameters (mass, chemical composition, presence or not of overshooting, etc.). The oscillation frequencies of the models are computed and compared with the observed ones. In this framework, departures from the "asymptotic" theory give fundamental information on the stellar parameters and internal structure.

For a given set of abundances (metallicity and helium value), only one model may reproduce the observed frequencies in a satisfying way (Soriano *et al.* 2007, Vauclair *et al.* 2008). We thus obtain a series of "best models" according to the abundance values. An important general result is that the various models obtained in this way have similar ages, gravities and radii. The other parameters are then constrained with the help of the spectroscopic observational boxes.

Asteroseismology can also give information about the internal structure of the stars, and more specifically about the regions where the sound velocity changes rapidly. This happens in various transitions layers, like the limits of convective regions, or layers with strong helium gradients. The transition layers in the stellar internal regions may be characterized using the "small separations", defined as $\delta\nu_{n,\ell} = \nu_{n-1} - \nu_{n-1,\ell+2}$ (Roxburgh & Vorontsov 1994).

In a previous paper dedicated to the study of the exoplanet-host star HD 52265 (Soriano *et al.* 2007), we showed that in some cases the small separations, which should be positive in first approximation, could become negative. We explained how this special behaviour was related to the presence of either a convective core or a helium core with abrupt frontiers, resulting from the presence of a convective core in the past history of the star.

I discuss below the examples of the stars μ Arae and ι Horologii

2. The case of μ Arae

The exoplanet-host star μ Arae (HD160691) is a G5V star with a visual magnitude $V = 5.1$ (SIMBAD Astronomical data base). The Hipparcos parallax was initially derived as $\pi = 65.5 \pm 0.8$ mas (Perryman *et al.* 1997). This was used in the paper Bazot *et al.* (2005) which first derived the stellar parameters of this star from seismology. More recently, a new analysis was carried out by Van Leeuwen (2007), who gives $\pi = 64.48 \pm 0.31$ mas. In a forthcoming paper (Soriano & Vauclair, 2009), this new value is used to obtain an absolute magnitude of $M_V = 4.20 \pm 0.04$ and a luminosity $\log(L/L_\odot) = 0.25 \pm 0.03$, lower than the previously derived one.

Spectroscopic observations by various authors gave five different effective temperatures and metallicities (see references in Bazot *et al.* 2005). The ages obtained for this star from chromospheric index vary between 1.45 Gyr (Rocha Pinto & Maciel 1998) and 6.41 Gyr (Donahue 1998)

This star was observed for seismology in August 2004 with HARPS. At that time, two planets were known. The observations aimed for seismology lead to the discovery of a third planet, μ Ara d, with period 9.5 days (santos *et al.* 2004). More recently, evidence for a fourth planet has been discovered (Pepe *et al.* 2007).

The HARPS seismic observations allowed to identify 43 oscillation modes of degrees $l = 0$ to $l = 3$ (Bouchy *et al.* 2005). In Figure 1, they are presented in the form of an echelle diagram and compared with one of our models. The best seismic fits lead to a mass of $1.10 \pm 0.01\ M_\odot$, effective temperatures between $T_{eff} = 5620$ and 5750 K, gravities between $\log g = 4.211$ and 4.215, and ages between 6 and 8 Gyr. The age of 1.45 Gyr given by Rocha Pinto & Maciel 1998 is definitively excluded. The values obtained from seismology, are much more precise than those obtained from spectroscopy alone, for masses, gravities and radii.

Computations of models including overshooting (modelled as an extension of the convective core) have also been done in (Soriano & Vauclair, 2009) for μ Arae. We showed how core mixing can be constraint from seismic observations. In this star, mixing by overshooting or any other means at the core limit cannot have an extent of more than 0.005 times the pressure scale height.

3. The case of ι Horologii

The case of the exoplanet-host star ι Hor (HD17051) has recently been discussed in detail in Laymand & Vauclair (2007) and Vauclair *et al.* 2008. Three different groups have given different stellar parameters for this star: Gonzalez *et al.* 2001, Santos *et al.* 2004 and Fischer & Valenti 2005. The derived values for T_{eff}, g and [Fe/H] can be quite different, according to the scale the authors use for the effective temperature determinations. The associated error bars are quite large (Figure 2). Meanwhile, Santos *et al.* 2004 suggested a mass of 1.32 $M_\odot$ while Fischer and Valenti 2005 gave 1.17 $M_\odot$. The ages given in the literature for ι Hor vary between 0.43 and 6.7 Gyr (Saffe *et al.* 2005).

Some authors (Chereul *et al.* 1999, Chereul and Grenon 2001, Montes *et al.* 2001) pointed out that this star belongs to the Hyades stream. There could be two different

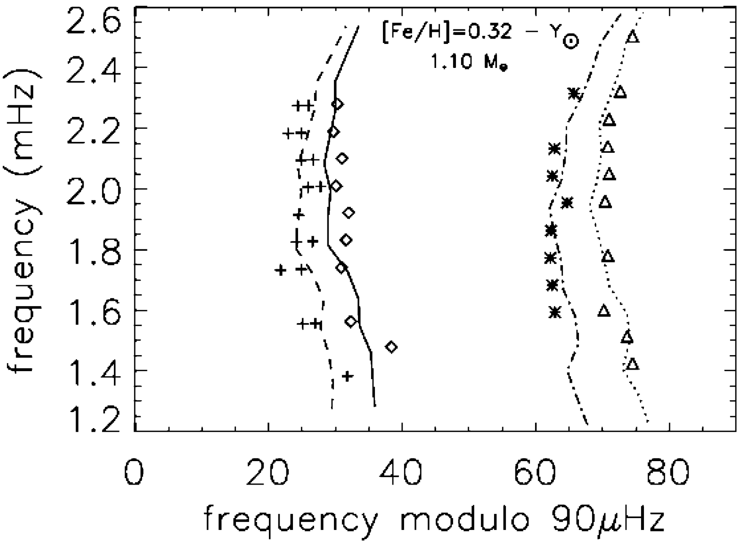

Figure 1. Echelle diagram for one of the best models obtained for the star μ Arae. The ordinates represent the frequencies of the modes and the absissae the same frequencies modulo the large separation, here 90 μHz. The lines represent the computational results for one of our models, respectively, from left to right : $l = 2$, 0, 3 and 1 and the symbols represent the observations (Soriano & Vauclair 2009).

reasons for this behaviour: either the star formed together with the Hyades, in a region between the Sun and the centre of the Galaxy, which would explain its overmetallicity compared to that of the Sun, or it was dynamically canalized by chance (see Famaey *et al.* 2007).

Solar-type oscillations of ι Hor were detected with HARPS in November 2006. Up to 25 oscillation modes could be identified and compared with stellar models. Our results first show that the error box given by Santos *et al.* lies below the zero age main sequence. No model can be computed in this box, while changing the effective temperature scale would move the box in the up right direction and become consistent with the other results (Figure 2).

We obtain the following general conclusions for this star: (Fe/H) is between 0.14 and 0.18; the helium abundance Y is small, 0.255 ± 0.015; The age of the star is 625 ± 5 Myr; the gravity is 4.40 ± 0.01 and its mass 1.25 ± 0.01 M$_\odot$. The values obtained for the metallicity, helium abundance and age of this star are those characteristic of the Hyades cluster (Lebreton *et al.* 2001). We proved from asteroseismology that ι Hor has been formed together with the Hyades cluster and that its metallicity is primordial, not due to planetary accretion.

4. Conclusion

From the few examples already available, asteroseismology has proved to be a powerful tool for determining stellar parameters and constraints on their internal structure. However, tests have to be done for individual stars, observed during long periods. Usual approximate theories are not precise enough to obtain such results. The scientific community is preparing for future observations with on-going or planned projects. Space missions like COROT, and later on KEPLER, are expected to give a large amount of new data for seismology, besides planet searches. Meanwhile ground based instruments

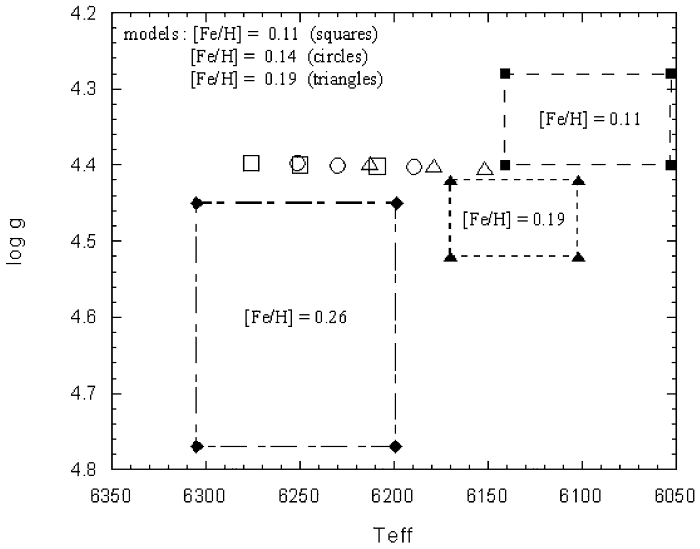

Figure 2. Observational boxes and models in the log g – log T_{eff} diagram for the star ι Hor. The three spectroscopic boxes correspond, from lower left to upper right, to Santos *et al.* 2004, Gonzalez *et al.* 2001 and Fischer & Valenti 2005. The open symbols correspond to the best models, which fit the observed echelle diagram. The squares are for [Fe/H] = 0.11, the circles for 0.14 and the triangles for 0.19. In each case three models are computed for three different helium abundances, decreasing from left to right (after Vauclair *et al.* 2008)

devoted to exoplanets like HARPS or SOPHIE can sometimes be deviated from their original purpose and be used for seismology. This represents a new dimension in the study of stellar structure and evolution.

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Discussion

G. MEYNET: This is more a comment than a question. First, I think that these observations on the size of the convective core are exactly what is needed to make progress on convection. Second, I am not surprised that there is no overshooting in the 1.1. $M_\odot$ star you studied. Works done, for instance, by the Padova group, the Yale group, and that we did also in Geneva, showed that indeed in a small mass range, let's say for masses between $\sim 1.1 - 1.3 M_\odot$, overshooting progressively increase from 0 to $\sim 0.1 - 0.2$.

S. VAUCLAIR: Yes, this is right. It would be interesting to check this behavior in the future.

R. WYSE: Could you comment on the large discrepancies in age determinations, particularly with the chromospheric activity ages?

S. VAUCLAIR: I am afraid this should be a question to the observers who derived these ages. I only think that this shows how poor these determinations are!

J. CHRISTENSEN-DALSGAARD: Have you measured the rotational splitting, and does this agree with other information about the rotation of the stars?

S. VAUCLAIR: Yes we did for μ Arae. For ι Hor we were not yet able to have convincing evidence of split modes. We intend to go on working on the data in the near future.

S. BARNES: In response to Joergen's question about gyrochoronology for any of these stars, ι Hor has a measured rotation period. Although I do not remember it right now, I remember calculating the gyro age when Sylvie's paper first came out on astro- ph and think that the gyro age worked out to be about 500 Myr, in rough agreement with Sylvie's age of $\sim$ 600 Myr.

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