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Asteroseismology of exoplanets host stars: the special case of ι Horologii (HD 17051)

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ABSTRACT

Aims. This paper presents detailed analysis and modelisation of the star HD 17051 (alias ι Hor), which appears to be a specially interesting case among exoplanet host stars. Like most of these stars, ι Hor presents a metallicity excess that has been measured by various observers who give different results, ranging from [Fe/H] = 0.11 to 0.26 and associated with different atmospheric parameters. Meanwhile, the luminosity of the star may be determined thanks to the Hipparcos parallax. Although it is in the southern hemisphere, this star belongs to the Hyades stream, and its external parameters show that it could even be one of the Hyades stars ejected during cluster formation. The aim of this work was to gather and analyse our present knowledge of this star and to prepare seismic tests for future observations with the HARPS spectrometer (planned for November 2006).

Methods. We computed evolutionary tracks with various metallicities in the two frameworks of primordial overmetallicity and accretion. We concentrated on models inside the error boxes given by the various observers in the $\log g$–$\log T_{\rm eff}$ diagram. We then computed the adiabatic oscillation frequencies of these models to prepare future observations.

Results. The detailed analysis of ι Hor presented in this paper has already allowed its external parameters, mass, and age to be constrained . Some values given in the literature could be rejected as inconsistent with the overall analysis. We find that a model computed with the Hyades parameters (age, metallicity) is clearly acceptable, but other ones are possible too. We are confident that observations with HARPS will allow for a clear conclusion about this star and that it will shed new light on the physics of exoplanet host stars.

Key words. stars: abundances – stars: oscillations – stars: planetary systems – Galaxy: kinematics and dynamics

1. Introduction

Studying the internal structure of exoplanet host stars is particularly important for the understanding of planetary formation. In this framework, asteroseismic studies represent an excellent tool for determining the structural differences between stars with and without detected planets. Among these differences, the observed overmetallicity of exoplanet host stars compared to other stars (Santos et al. 2003, 2005; Gonzalez 2003; Fischer & Valenti 2005) needs to be understood. Two extreme scenarios are still possible to account for this observed overmetallicity: the primordial origin that assumes that the stars formed out of an overmetallic nebula and the accretion origin for which the observed metallicity is due to the accretion of hydrogen poor material onto the star during planetary formation (see Bazot & Vauclair 2004).

These authors pointed out that the evolution of stars with masses around 1.1 $M_\odot$ is very sensitive to their internal metallicity, due to the possible formation of a convective core. In this particular region of the HR diagram, main-sequence stars with solar internal metallicities have no convective cores, while overmetallic stars develop convection in their central regions. This means that evolutionary tracks computed with different internal metallicities may cross the same point in the HR diagram, even though they correspond to models of quite different masses and different past histories. This behavior was used to try to derive whether the exoplanet host star μ Arae is overmetallic from its surface down to its centre (overmetallic scenario) or only in its outer layer (accretion scenario). The star was observed with the HARPS spectrometer in June 2004. Up to 43 p-modes could be identified (Bouchy et al. 2005) and a detailed modelisation could be achieved (Bazot et al. 2005). A possible test to determine the internal metallicity of the star, using the frequency small separations, was discussed. Unfortunately, the modes with frequencies around and above 2.5 mHz could not be identified with enough precision to reach a definitive answer. More sophisticated signal processing techniques should be developed to try to go further in this direction for μ Arae.

As discussed in this paper, the situation for the star ι Hor (HD 17051, HR 810) is quite different from that of μ Arae. With a slightly higher effective temperature, hence suggesting a higher mass (between 1.14 and 1.22 $M_\odot$, as will be seen below), this star may be able to develop a convective core for solar internal metallicity, as well as for higher metallicities. The evolutionary tracks corresponding to the overmetallic and accretion scenarios both show the characteristic behaviour induced by the presence of a convective core during evolution.

However, among planetary host stars, ι Hor is a special case for several reasons. Three different groups have given different stellar parameters for this star, summarised in Table 1. Meanwhile, Santos et al. (2004) suggest a mass of 1.32 $M_\odot$ for this star, while Fischer & Valenti (2005) give 1.17 $M_\odot$.

This star belongs to the "Hyades stream", which means that it has the same kinematical characteristics as the Hyades cluster in the Galaxy, although it is located several tens of parsecs away from the cluster itself (Chereul et al. 1999; Grenon 2000; Chereul & Grenon 2000; Kalas & Delorn 2006). There are two possibilities to explain this behaviour: either the star has been

Table 1. Effective temperatures, gravities, and metal abundances observed for ι Hor (in dex), with the references for the given values are given in Col. 4.

$T_{\rm eff}$ (K)	$\log g$	[Fe/H]	Reference
6136 ± 34	4.47 ± 0.05	0.19 ± 0.03	Gonzalez et al. (2001)
6252 ± 53	4.61 ± 0.16	0.26 ± 0.06	Santos et al. (2004)
6097 ± 44	4.34 ± 0.06	0.11 ± 0.03	Fischer & Valenti (2005)

captured inside the stream by tidal effects in the Galaxy or it was formed together with the cluster and then evaporated during cluster formation. In this case, the star should have the same age and internal metallicity as the Hyades stars. As seen below, asteroseismology can solve this question, thereby giving important clues to the general understanding of exoplanet-host stars.

For the present paper we computed evolutionary tracks and models lying inside the error boxes, as given by the observers for this star, in the $\log g$–$\log T_{\rm eff}$ and $\log L/L_{\odot}$–$\log T_{\rm eff}$ planes, using the TGEC code (Toulouse-Geneva Evolutionary Code) as described in previous papers (e.g. Bazot & Vauclair 2004; Bazot et al. 2005). We tested the differences obtained in the internal structure of the models for the various possible observed metallicities and the overmetallic versus accretion scenarios. We computed the oscillation frequencies for several characteristic models with the aim of discussing asteroseismic tests and suggesting specific observations.

The present computations already lead to important results concerning the metallicity, mass and age of this star. We find that a metallicity higher than [Fe/H] = 0.20 dex is quite improbable and that the stellar mass cannot exceed 1.22 $M_{\odot}$, contrary to the Santos et al. (2004) estimate. Furthermore, models with the metallicity and age of the Hyades are quite realistic. We show how asteroseismic observations of this star could solve this question: if we can observe this star and identify the oscillation mode frequencies, we should be able to derive whether this star has been formed together with the Hyades or not. While a negative answer would be interesting in itself, a positive answer would be taken as proof that the overmetallicity has a primordial origin.

The computations of evolutionary tracks and various modelisations of this star are described in Sect. 2. Some conclusions are already given at this point. Section 3 is devoted to the model computations, the asteroseismic tests, and predictions. A summary and discussion of the results are given in Sect. 5.

2. Evolutionary tracks and models

Three different groups of observers have determined the metallicity and external parameters ($T_{\rm eff}$, $\log g$) of ι Hor: Gonzalez et al. (2001); Santos et al. (2004), and Fischer & Valenti (2005) (see Table 1). We compare their results below and discuss the computations of models which satisfy the observing constraints.

2.1. Observational boxes and computations

Gonzalez et al. (2001) observed ι Hor with the CTIO 1.5 m with the fiber-fed echelle spectrograph. To compute the stellar parameters ($T_{\rm eff}$, log g, and [Fe/H]), they use the line analysis code MOOG (Sneden 1973), the Kurucz (1993) LTE plane parallel atmospheres, and Fe I and Fe II equivalent width (EW) measurements. The gf-values of the iron lines were calculated from an inverted solar analysis using the Kurucz et al. (1984) Solar Flux Atlas and their spectrum of Vesta.

Santos et al. (2004) obtained spectra with the FEROS spectrograph (1.5-m and 2.2-m ESO/MPI telescope, La Silla, Chile). They derived stellar parameters using standard LTE analysis with the code MOOG (Sneden 1973), a grid of Kurucz (1993) ATLAS atmospheres, and 39 Fe I and 12 Fe II lines. The $\log gf$ values for the iron line were computed from an inverted solar analysis using the Kurucz et al. (1984) Solar Flux Atlas and Kurucz grid models for the Sun (Kurucz 1993).

The spectra used by Fischer & Valenti (2005) were obtained with the Anglo-Australian Telescope. The computations of stellar parameters were done assuming LTE. They created a synthetic spectrum with a radiative transfer code using the Kurucz stellar atmosphere models (Kurucz 1993) and with an atomic-line data basis (Vienna Atomic Line Data-base [VALD]; Kupka et al.1999; Ryabchikova et al.1999). This code uses a fitting algorithm to obtain $T_{\rm eff}$, $\log g$, $v \sin i$, and abundances. They made small adjustments to obtain astrophysical atomic line parameters ($\log gf$ values) by fitting it to the Kurucz et al. (1984) Solar Flux Atlas and by analysing several Vesta observations.

This star has also been observed with the Hipparcos satellite from which the parallax was derived: $\pi = 58.00 \pm 0.55$ mas. The visual magnitude of ι Hor is given as $V = 5.40$ (SIMBAD Astronomical data base). The overall interval of effective temperatures obtained from the three observing groups is: $T_{\rm eff} = 6179 \pm 126$. Using this as an uncertainty on temperatures and with the tables of Flower (1996), we obtained BC $= -0.023 \pm 0.01$ for the bolometric correction. With a solar absolute magnitude of $M_{\rm bol,\odot} = 4.746$ (Lejeune et al. 1998), we deduce a luminosity of $\log L/L_{\odot} = 0.219 \pm 0.024$

We computed series of "overmetallic" and "accretion" models that could account for the observed parameters of ι Hor. We used the Toulouse-Geneva stellar evolution code with the OPAL equation of state and opacities (Rogers & Nayfonov 2002; Iglesias & Rogers 1996) and the NACRE nuclear reaction rates (Angulo et al. 1999). In all our models, microscopic diffusion was included using the Paquette prescription (Paquette et al. 1986; Richard et al. 2004). The convection was treated in the framework of the mixing length theory and the mixing length parameter was adjusted as for the Sun ($\alpha = 1.8$). The effect of changing this value is discussed in Sect. 2.4. For the overmetallic models, we considered two different cases for the helium value. In the first case, we assumed that helium was enriched, as well as metals, according to the law given by Isotov & Thuan (2004): $\mathrm{d}Y/\mathrm{d}Z = 2.8 \pm 0.5$. In the second case, we assumed that the primordial cloud was only metal-enriched, with a solar helium value. The accretion models were computed with the same assumptions as in Bazot & Vauclair (2004) with an instantaneous fall of matter at the beginning of the main sequence and instantaneous mixing inside the convection zone. Neither extra-mixing nor overshoot were taken in account into the present paper.

2.2. Evolutionary tracks for overmetallic models

We first present the evolutionary tracks computed for overmetallic models, that is, models with initial overmetallicities, using the three different values given by the observers: [Fe/H] = 0.11, 0.19, and 0.26. In these models, the mixing length parameter is $\alpha = 1.8$, adjusted as in the Sun. Figure 1 displays the results obtained in the $\log L/L_{\odot}$–$\log T_{\rm eff}$ frame (on the left) and in the $\log g$–$\log T_{\rm eff}$ frame (on the right). In each graph, the three error boxes are drawn, but the one that corresponds to the chosen metallicity (as given by the same authors) is presented in thicker lines.

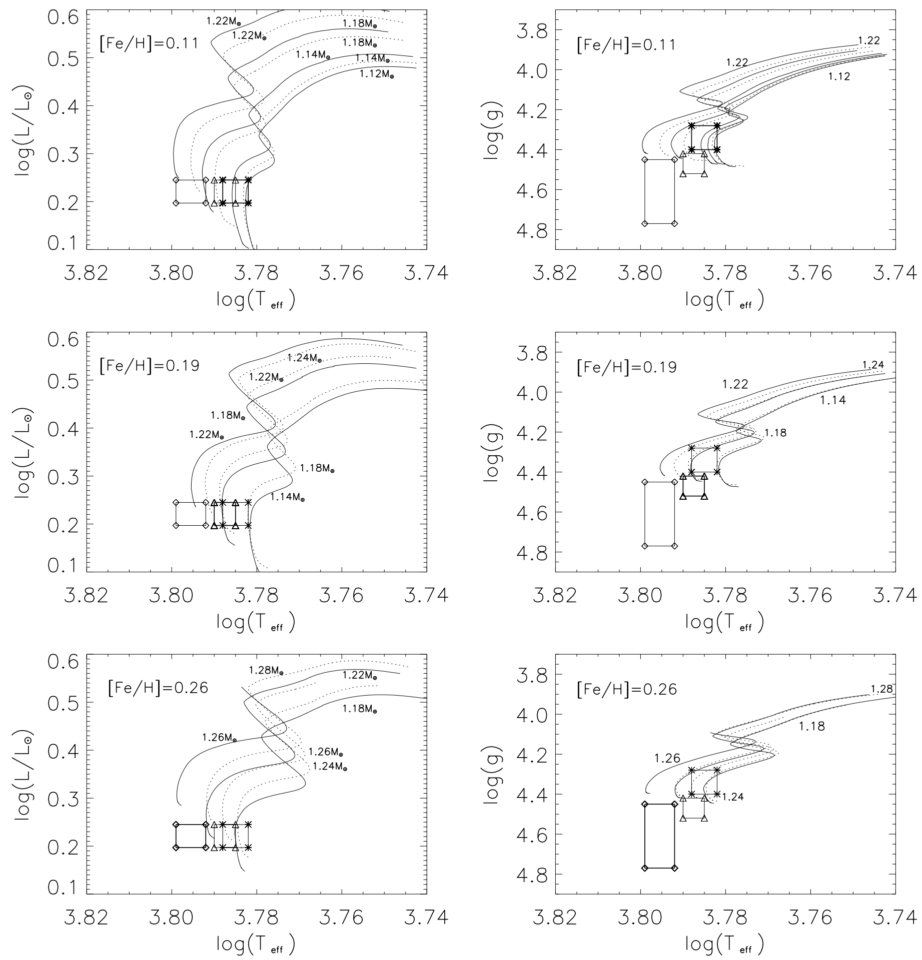

Fig. 1. These graphs display the error boxes for the position of the star ι Hor in the log $L/L_{\odot}$–log $T_{\rm eff}$ diagram (*left*) and in the log g–log $T_{\rm eff}$ diagram (*right*), as given by the three groups who have observed this star (Table 1). The luminosity is obtained from the Hipparcos parallax (see text). Evolutionary tracks are computed for completely overmetallic cases. Those computed with enhanced helium are drawn in solid lines, while those computed with solar helium appear in dashed lines. The three error boxes are: Santos et al. (2004: diamonds), Gonzalez et al. (2001: triangles), Fischer & Valentini (2005: asterix). The author's boxes, which correspond to the chosen metallicity in each graph, are enhanced in boldface lines.

Some differences can be observed between the two presentations (log $L/L_{\odot}$–log $T_{\rm eff}$ and log g–log $T_{\rm eff}$ planes). This occurs because the error boxes do not correspond to the same observable parameters. The luminosity is computed from the Hipparcos parallax and from the visual magnitude, and does not depend on the other observed parameters. On the other hand, the log g values are directly related to the other observed parameters as determined by each observing group. In the following, we choose to work in the log g–log $T_{\rm eff}$ plane, which is more consistent than the log $L/L_{\odot}$–log $T_{\rm eff}$ plane from the observing viewpoint.

We note from Fig. 1 that none of the evolutionary tracks cross the Santos et al. (2004) error box. We will come back to this result below (Sect. 2.4). The masses of the models that may be found in error boxes are in the range 1.12 $M_{\odot}$ to 1.18 $M_{\odot}$ for enhanced helium, and in the range 1.14 $M_{\odot}$ to 1.22 $M_{\odot}$ for solar helium.

2.3. Evolutionary tracks for accretion models

In Fig. 2 (left), the evolutionary tracks of models with accretion are displayed for the same three metallicities. The masses of those models consistent with the observed parameters lie between 1.11 $M_{\odot}$ and 1.16 $M_{\odot}$: they are lower than those of the overmetallic models, while the ages are similar.

For these stellar masses, a convective core appears during stellar evolution in the accretion models, as well as in the overmetallic models, which explains why both kinds of tracks have the same characteristic behaviour. We will see however in Sect. 3 that the accretion models that could account for ι Hor are too young for the convective core to be developed in the accretion models, while it already exists in the overmetallic ones

We note that for both the accretion and the overmetallic models, no solution can be found in the Santos et al. (2004) error box, which correponds to a high metallicity [Fe/H] = 0.26, while the metallicity of ι Hor is certainely lower.

2.4. The effect of changing the mixing length parameter

The evolutionary tracks displayed in Figs. 1 and 2 (left) were computed with a solar mixing length parameter (α = 1.8). We studied the effect of increasing the value of this parameter. Figure 2 (right) displays overmetallic models computed with α = 2.2. For the same position in the log g–log $T_{\rm eff}$ diagram, the models are more evolved and less massive than for a smaller mixing length parameter. In this case, we can find very young models in the Santos et al. (2004) error box.

Such a large mixing length parameter does not seem realistic for this star. Israelian et al. (2004) have derived its lithium abundance, giving log ϵ(Li) = 2.63, a somewhat high value that is of the order of the value determined for the Hyades in this spectral range. It is also consistent with the computations of lithium depletion obtained with a mixing length parameter adjusted on the Sun. A larger lithium depletion would be expected with an increased depth of the outer convection zone. However, as these results still depend on the details of hydrodynamics, with unknown parameters, we did not eliminate the models computed with high α and kept one of them for asteroseismic studies (model OM3, Table 2).

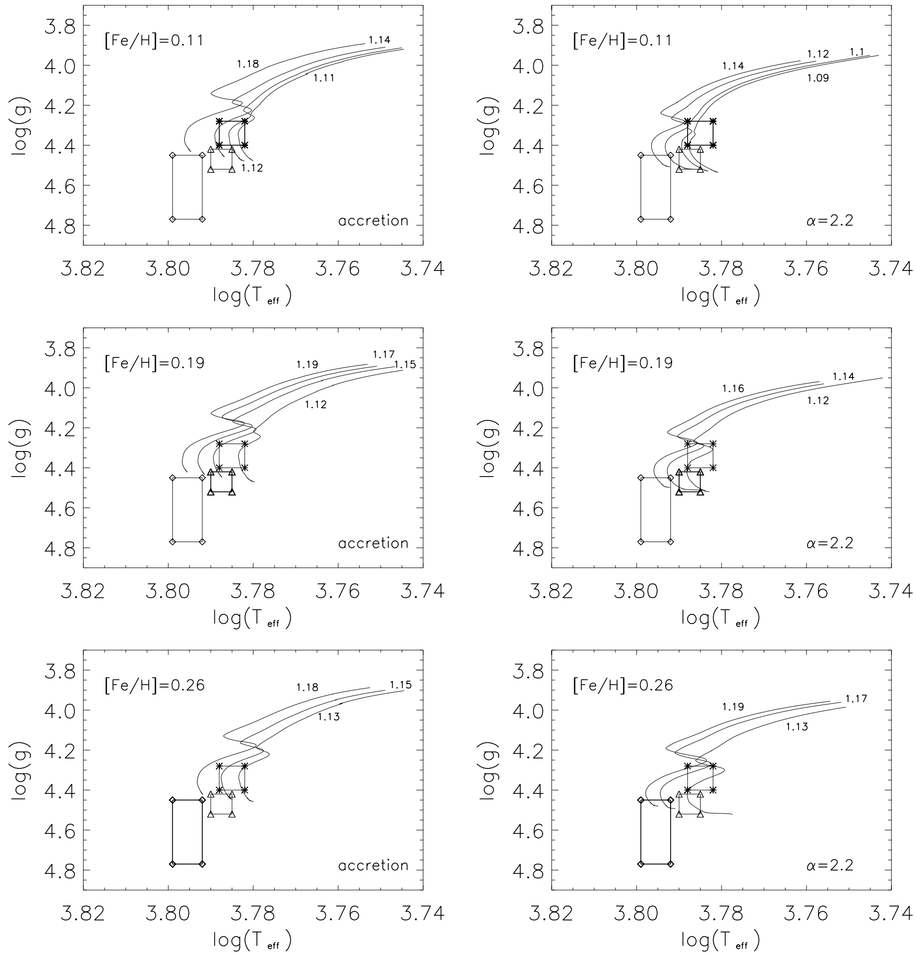

Fig. 2. Evolutionary tracks in the $\log g$–$\log T_{\rm eff}$ diagram for the three metallicities, as in Fig. 1. Here are presented the evolutionary tracks obtained with the accretion hypothesis (*left*) and evolutionary tracks obtained with an increased mixing length parameter: $\alpha = 2.2$ instead of $\alpha = 1.8$. The error boxes are the same ones as in Fig. 1.

Table 2. Mass, age, gravity, effective temperature, luminosity, surface metallicity, acoustic depths and large separations for stellar models satisfying the observational constraints for ι Hor.

Model	$M_\star$ ($M_\odot$)	Age (Gyr)	$\log g$	$\log T_{\rm eff}$ (K)	$\log L/L_\odot$	[Fe/H]	$t_{\rm ac}$ (s)	$\Delta\nu$ (μHz)
OM1	1.140	2.231	4.38	3.786	0.207	0.11	4167	120
OM2	1.180	0.522	4.43	3.787	0.185	0.19	3876	129
AC1	1.120	2.979	4.36	3.786	0.225	0.11	4310	116
AC2	1.150	0.522	4.43	3.788	0.170	0.19	3817	131
OM3 (α = 2.2)	1.190	0.508	4.46	3.797	0.191	0.26	3650	137
OM4 (Hyades)	1.180	0.627	4.42	3.790	0.202	0.14	3906	128

3. Models and seismic studies

We chose six different models that could all account for the observable parameters of ι Hor, to prepare their seismic analysis (Tables 2 and 3). Overmetallic models OM1 and OM2 and accretion models AC1 and AC2 lie in the Fischer & Valentini (2005) and Gonzalez et al. (2001) error boxes. Models OM2 and AC2 have a luminosity that is slightly too high compared to the one determined from the Hipparcos parallax ($\log L/L_\odot = 0.219 \pm 0.024$). It was not possible to find models satisfying both constraints of $\log g$ and $\log L/L_\odot$ for this metallicity. Model OM3 was computed with a larger mixing length parameter $\alpha = 2.2$, and it lies in the Santos et al (2004) error box. Finally, model OM4 is a special overmetallic model that was computed to fit the parameters of the Hyades as precisely as possible: we chose an age of 627 Myr (Perryman et al. 1998) and a metallicity [Fe/H] = 0.14 (Cayrel de Strobel et al. 1997).

Adiabatic oscillation frequencies were computed for the models chosen in Sect. 2, using the PULSE code (Brassard et al. 1992). The frequencies were computed for angular degrees $l = 0$ to $l = 3$ and radial orders ranging typically from 4 to 100.

We first computed the large separations, $\Delta\nu = \nu_{n+1,l} - \nu_{n-1,l}$ (Table 2) and drew the echelle diagrams for the six selected models (Fig. 3). We then computed the small separations, $\delta\nu = \nu_{n,l} - \nu_{n-1,l+2}$, which are presented in Fig. 4. All these computations are similar to those presented in Bazot & Vauclair (2004) and Bazot et al. (2005) for μ Arae.

The star μ Arae was observed during eight nights with the HARPS spectrometer at La Silla in June 2004. The precision of the observations was such that the large separation could be determined with an accuracy better than 1 μHz, and the observed echelle diagram could be precisely compared with those obtained from modelisation. We are confident that for ι Hor, similar observations will allow an unambiguous selecion among the models presented here.

Table 3. Radii, depth, and mass of the convective core, radius at the bottom of the outer convective zone, mass of the outer convective zone, initial and present surface chemical composition for stellar models satisfying the observational constraints for ι Hor.

Model	$R_\star$ (cm)	$r_{cc}/R_\star$	$M_{cc}/M_\star$	$r_{ec}/R_\star$	$M_{ec}/M_\star$	Y_0	Z_0	Y	Z
OM1	7.91e10	–	–	0.774	0.008	0.2787	0.0220	0.2503	0.0207
OM2	7.65e10	0.036	0.0033	0.782	0.008	0.2878	0.0260	0.2802	0.0257
AC1	8.08e10	–	–	0.767	0.008	0.2698	0.0226	0.2440	0.0210
AC2	7.50e10	–	–	0.780	0.007	0.2670	0.0263	0.2735	0.0255
OM3(α = 2.2)	7.38e10	0.0463	0.0060	0.755	0.013	0.2970	0.0300	0.2909	0.0296
OM4	7.71e10	0.031	0.0022	0.788	0.006	0.2820	0.0235	0.2724	0.0230

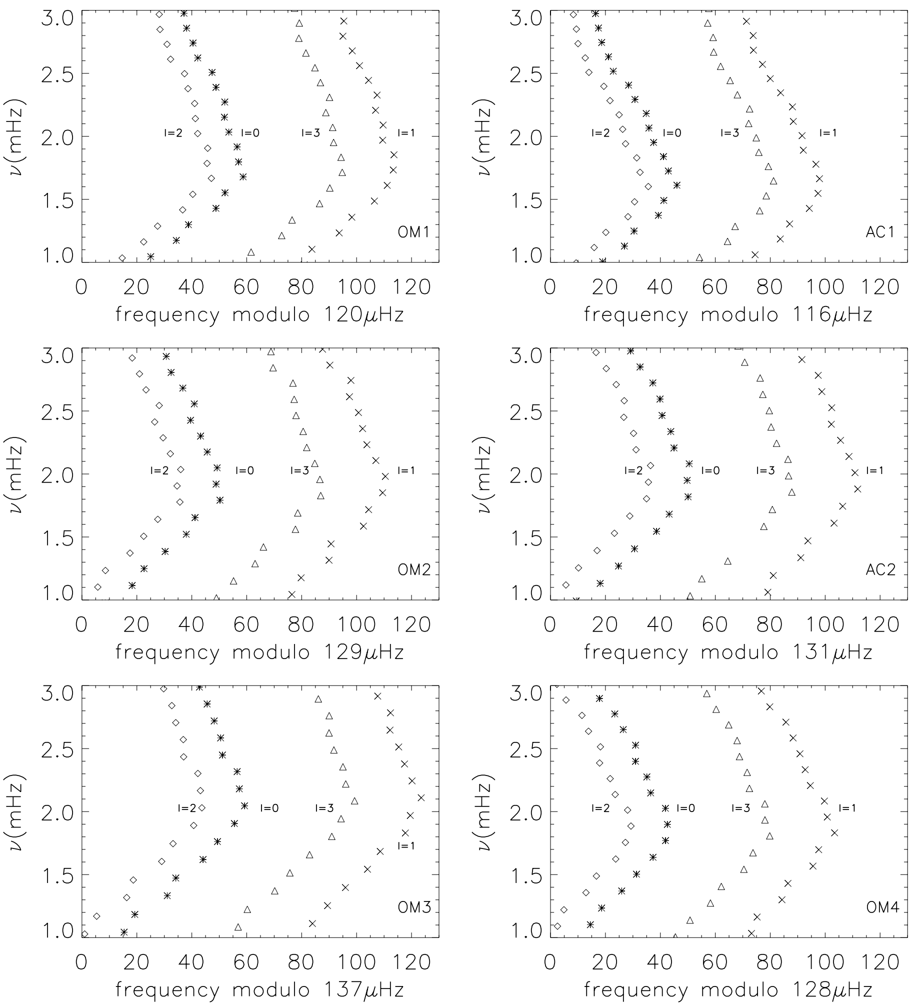

Fig. 3. Echelle diagrams for the six models presented in Tables 2 and 3. They display the frequencies of the oscillation modes (ordinates) versus the same frequencies represented modulo the large separations (abscissae).

4. Summary and discussion

We have presented a detailed modelisation of the exoplanet-host star ι Hor, in view of future seismic analysis. Like most of these stars, ι Hor has a higher metallicity than stars without planets. A special interest of this star is due that it belongs to the Hyades stream and could possibly have been formed together with the cluster stars and ejected during their formation process.

We computed models with the two extreme hypotheses of primordial overmetallicity, on the one hand (overmetallic models), and accretion induced overmetallicity on the second (accretion models). We gathered the various determinations of the observable parameters for this star, as given by several observing groups: Gonzalez et al. (2001), Santos et al. (2004), and Fischer & Valenti (2005). The luminosity of this star was obtained using Hipparcos parallax.

In this first step of modelisation, we were already able to constrain the values of the external parameters, compared to those given by the observers, simply because of the consistency of the whole set of parameters. A high metallicity of [Fe/H] = 0.26, as given by Santos et al. (2004), seems excluded. We expect a value between 0.11, as given by Fischer & Valenti (2005) and 0.19, as given by Gonzalez et al. (2001). We can also exclude masses higher than 1.22 $M_\odot$: we find that the mass of this star should lie between 1.14 and 1.22 $M_\odot$.

We have computed the oscillation frequencies, the large separations, and the small separations, and we have drawn the echelle diagrams for six possible models of ι Hor. Two of these models (OM1 and OM2) are overmetallic, with metallicities 0.11 and 0.19, and they have a mixing length parameter adjusted on solar models. Overmetallic models with a higher metallicity were inconsistent with the measured parameters ($\log g$, $\log L/L_\odot$), except if we increased the mixing length parameter, which we did although it is highly unprobable; this is model OM3. Two models (AC1 and AC2) were computed with

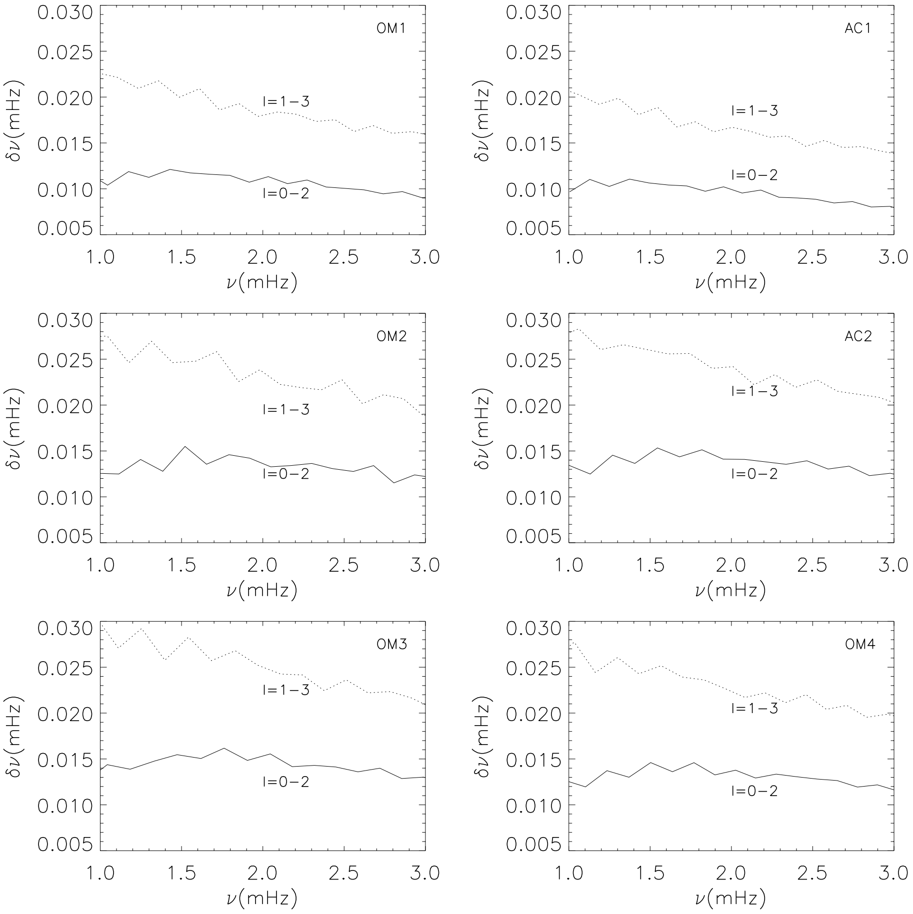

Fig. 4. Small separations for the six models presented in Tables 2 and 3.

the accretion hypothesis and external metallicities 0.11 and 0.19. Finally, a special model (0M4) was computed with the precise external parameters of the Hyades stars.

Observations of this star are planned with the HARPS spectrometer in La Silla. Considering the precision of the results that were obtained for the star μ Arae (Bazot et al. 2005), we are confident that it will be possible to distinguish between the different possible models from the asteroseismic observations. We will then obtain the mass, age, outer, and hopefully internal, metallicity of this star.

These results will show whether ι Hor was formed with the Hyades or not. If it does not belong to the Hyades, this conclusion will be interesting in itself. If the results show that the star belongs to the Hyades, it will be taken as evidence that the overmetallicity is primordial and reflects the metallicity of its formation site in the Galaxy. This will give a way to identify the right scenario for the exoplanet-host stars overmetallicity.

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