ABOUT SEISMOLOGICAL PROPERTIES
OF INTERMEDIATE MASS STARS

N.AUDARD, J.PROVOST
Département Cassini, Observatoire de la Côte d'Azur, BP 229, 06304 Nice cedex 4, France

ABSTRACT   Stars more massive than about $1.2 M_\odot$ are characterized by a convective core, which induces at its frontier a rapid variation of the sound speed and of the Brunt-Väissälä frequency, close to a discontinuity. We present preliminary results about the search of the signature this core could have on the p-mode spectra. For a set of frequencies of three stars of 1, 1.5 and 2 $M_\odot$, we study in particular the small frequency separation $\Delta\nu_{0,2} \sim \nu_{n,l} - \nu_{n-1,l+2}$, for high order and low degree oscillation modes, which is particularly sensitive to the interior of stars. We underline characteristic behaviours of the 1.5 and 2 $M_\odot$ stars, through the comparison between computed frequencies and their approximation obtained by asymptotic and polynomial fittings, and also through second order quantities relatively to the frequencies.
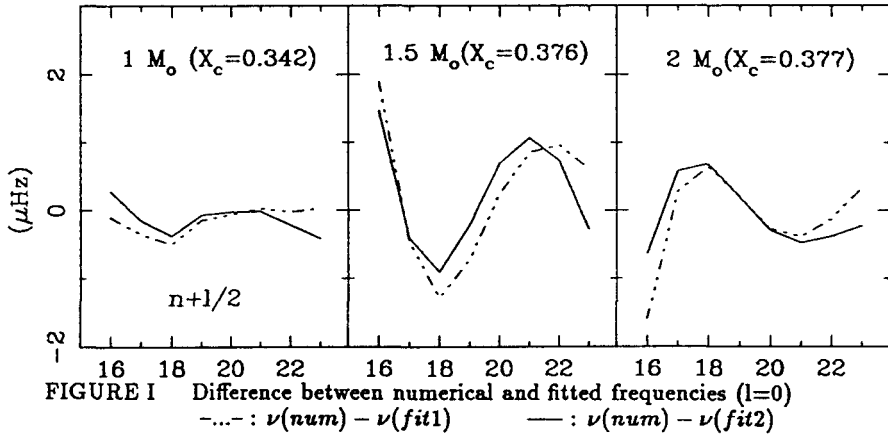
I - STELLAR MODELS

The evolution of three stars of 1, 1.5 and $2 M_\odot$ has been computed with the code CESAM (Morel, 1992), from age zero to an advanced stage on the main sequence, as well as the corresponding numerical frequencies of oscillations. We use the EFF equation of state, with the LAOL opacities, abundances $X_0 = 0.70$, $Z = 0.02$, and a mixing-length parameter $\lambda = 2.55$. The first five columns of table I give the characteristics of the three models closest to the solar central composition X_c; $\Omega_g = \sqrt{GM/R^3}$ is the characteristic frequency, ν_0 the equidistance between two modes of same degree and successive order.

TABLE I   Characteristics of our 1, 1.5 and 2 $M_\odot$ models near $X_{c\odot}$.

mass	age ($10^9 yrs$)	X_c	$\Omega_g(10^4)$ (rad/s)	ν_0 (μHz)	$\Delta\nu_{0,2}asym$ (μHz)	$\Delta\nu_{0,2}(fit1)$ (μHz)	$\Delta\nu_{0,2}(fit2)$ (μHz)
$1 M_\odot$	4.750	0.342	6.47	142.3	11.10	9.3	10.04
$1.5 M_\odot$	1.184	0.376	3.71	78.1	16.97	4.56	5.3
$2 M_\odot$	0.540	0.377	3.11	63.1	20.06	5.05	5.3

II - VALIDITY OF THE ASYMPTOTIC EXPRESSION

We analyse the frequencies of high-order low degree p-modes, by using two different approximations: the asymptotic expression derived by Tassoul (1980), and discussed by Gabriel (1989), hereafter noted $\nu_{n,l}(fit1)$, and a polynomial one (see Scherrer *et al.*(1983), and Christensen-Dalsgaard *et al.*(1988)), noted $\nu_{n,l}(fit2)$. From a set of numerically computed frequencies $\nu(num)$, and for degrees $l = 0, 1, 2, 3$, we calculate by a mean square root method the different coefficients entering in these formulations, from which we deduce the corresponding values of the small frequency separation $\Delta\nu_{0,2}(fit1)$

FIGURE I   Difference between numerical and fitted frequencies (l=0)
    -...- : $\nu(num) - \nu(fit1)$ —— : $\nu(num) - \nu(fit2)$

and $\Delta\nu_{0,2}(fit2)$ so that $\Delta\nu_{0,2}(fit1) = \nu_{n,0}(fit1) - \nu_{n-1,2}(fit1)$ and $\Delta\nu_{0,2}(fit2) = \nu_{n,0}(fit2) - \nu_{n-1,2}(fit2)$.
The general asymptotic expression provides a third formulation of $\Delta\nu_{0,2}$, that we calculate from the stellar models:

$$\Delta\nu_{0,2}(asym) = \frac{6}{4\pi^2}\left(\frac{c(R)}{R} - \int_0^R \frac{dc}{dr}\frac{dr}{r}\right)\frac{\nu_0}{\nu_{n,l}} \sim \nu_{n,l}(num) - \nu_{n-1,l+2}(num) \quad (1)$$

Table I gives this asymptotic value of $\Delta\nu_{0,2}$ (column 6) for $n = 22$ and $l = 0$, as well as both fitted ones (columns 7 and 8). We see the three values are relatively close for the solar-aged $1M_\odot$ star, as noted by Christensen-Dalsgaard (1988), but not for other cases; this discrepancy between both fitted values and the asymptotic one questions the validity of the asymptotic expression of the frequency.
Thereafter, we make a more refined analysis by comparing directly the frequencies obtained from asymptotic and polynomial expressions to the numerical ones: $\nu_{n,l}(num) - \nu_{n,l}(fit1)$ and $\nu_{n,l}(num) - \nu_{n,l}(fit2)$. An oscillatory component appears for the 1.5 and 2 $M_\odot$ stars, not for the 1 $M_\odot$ one; Figure I represents this aspect for the three models presented in table I, with a range for the order n from 16 to 23 and the polynomial parameter $n_0 = 20$.
    This peculiar behaviour of our 1.5 and $2M_\odot$ stars could be a mark of one of the effects of the convective core.

III - EFFECTS OF THE "DISCONTINUITIES"

In this final step, we underline a manifestation of the "discontinuity" of the sound speed of the 1.5 and 2 $M_\odot$ stars, which is not taken into account in the asymptotic expression used above, by examining the variation of $\nu_{n,l} - 2\nu_{n-1,l} + \nu_{n-2,l}$ for the computed frequencies. Figure II shows a great difference according to the mass: a sinusoidal behaviour appears for the three stars, but although there is two distinct oscillations for the sun-like star, only one seems to remain for the two other ones.
For the $1M_\odot$ star, as noted by Gough (1990), the smallest oscillation is related to the base of the convection zone and the largest one to the rapid variation of the adiabatic exponent γ, in the HeII ionization zone; we find that this last relation is also verified for the two other stars.
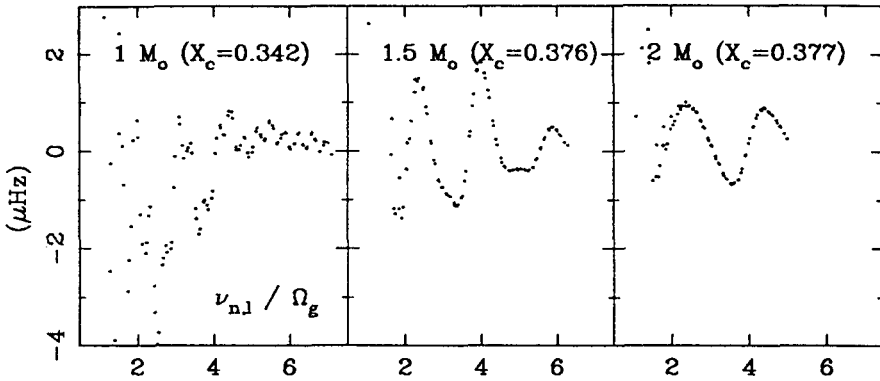
FIGURE II $\nu_{n,l} - 2\nu_{n-1,l} + \nu_{n-2,l}$ ($l = 0, 1, 2, 3$)

     Further results will be published later, among others the study of the asymptotic formula of the frequency taking the rapid variation of the sound speed into account, proposed by Provost *et al.* (1992).

IV - CONCLUSION

In this study, we have shown that the classical asymptotic theory of Tassoul (1980), valid in the solar case, is inadequate to represent with accuracy the p-mode spectra of a 1.5 and a 2 $M_{\odot}$ stars. Nevertheless, for these two stars, the characteristic oscillation obtained from the analysis of the fittings could be a manifestation of the rapid variation of the sound speed at the frontier of their convective core; we are also analysing the oscillation exhibited by the second order quantity $\nu_{n,l} - 2\nu_{n-1,l} + \nu_{n-2,l}$.
     Theoretical work is in progress to extract more accurate information of the internal structure of these intermediate mass stars from future observations.

REFERENCES

Christensen-Dalsgaard, J., 1988, in *Advances in Helio-and-asteroseismology*, Eds
        Christensen-Dalsgaard J. and Frandsen S., pp 295-298.

Gabriel.M., 1989, *Astron. Astrophys.* **226**, 278-283.

Gough.D.O., 1990, in *progress of seismology of the sun and stars, lecture notes in physics*, Eds Osaki.Y., Shibahashi.H., Spinger Verlag.

Morel P., 1992, these proceedings.

Provost J., Mosser B., Berthomieu G., 1992, to be submitted to *Astron. Astrophys.*

Scherrer Ph., Wilcox J.M., Christensen-Dalsgaard J., Gough D.O., 1983, *Solar phys.* **82**, 75.

Tassoul M., 1980, *Astrophys. J. Suppl.* **43**, 457-490.