PROBING CONVECTIVE-CORE OVERSHOOTING THROUGH SEISMOLOGY OF INTERMEDIATE-MASS STARS

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ABSTRACT We study the effects of convective-core overshooting on acoustic and gravity modes of low degree $\ell$ of stars of 1.7 $M_\odot$ and 2 $M_\odot$. At given effective temperature, we show that overshooting substantially decreases the acoustic frequencies $\nu_{n,\ell}$, which could give rise to a problem for identifying the radial order $n$ of modes. Overshooting affects the behaviour of modes of low frequency during their evolution along the main sequence. We show that it must be taken into account for the estimation of the stellar age and mass from seismological observations. We find that the frequency combination $(\nu_{n,0} + \nu_{n-1,0} - 2 \nu_{n-1,1})/(\nu_{n,0} - \nu_{n-1,2})$ varies a lot according to the age and to overshooting and could therefore be a powerful tool for probing the deep stellar interior and for evaluating the extent of convective-core penetration.

1 - STELLAR MODELS WITH CONVECTIVE-CORE OVERSHOOTING

1 - Convective-Core Computation
With the CESAM code (Morel, 1993), we have computed two sequences of stars of 1.7 $M_\odot$ and 2 $M_\odot$ along the main sequence, first by using the standard description and second by including convective-core overshooting which extends the core from $r_c$ to $r_c + \alpha_o H_p$, where $\alpha_o$ is the parameter of overshoot and $H_p$ the pressure scale height. We chose $\alpha_o = 0.1$ and 0.2, which leads to a better agreement between observations and predictions of computed models based on the improved OPAL opacities (Iglesias et al 1992) (see Maeder and Meynet 1989, Stothers and Chin 1991).

2 - Effects of Overshooting on the Stellar Structure
Convective-core overshooting extends the region of hydrogen depletion, thus the time spent on the main sequence increases and the end of the main sequence occurs at lower effective temperature. This variation of the hydrogen abundance in the stellar core strongly affects the sound speed and the Brunt-Väisälä frequency which are predominant in determining the oscillation frequencies.

Hereafter we shall compare properties of models of the same effective temperature, in which case overshooting increases the luminosity.
II - EFFECTS OF OVERSHOOTING ON LOW-DEGREE MODES

We have limited the range of $p$ modes to the acoustic cut-off frequency.

At given effective temperature, overshooting decreases the frequencies, mainly due to the increase in stellar radius it induces. This decrease, small at low frequency, increases linearly with the frequency, and for high-order $p$ modes the frequency difference is up to twice the value of the large separation $\nu_{n,0} - \nu_{n-1,1}$ which characterizes the $p$-mode spectrum. This could give rise to a problem for identifying the radial order of the oscillation modes.

1 - Evolution of Frequencies of Low Radial Order

At certain evolutionary stages, modes of consecutive radial orders have frequencies which approach very closely and acquire a dual status, related to the so-called avoided crossing. We show that overshooting makes the exchange of physical nature of these mixed modes occur at lower effective temperature. The distribution of the kinetic-energy density of modes of classical and overshoot models of the same effective temperature can then be drastically modified.

These mixed modes have substantial amplitude both in the central regions and in the outer parts so that they can potentially be observed (see Dziembowski and Pamyatnykh 1991, Dziembowski 1994). They could therefore help to probe the stellar interior and to test convective-core overshooting.

2 - Sensitivity of Observables to Stellar Parameters

The $p$-mode spectrum of high frequency can be represented by two seismological observables: $\nu_0 \sim \nu_{n,0} - \nu_{n-1,1}$ and $\Delta \nu_{0,2} \sim \nu_{n,0} - \nu_{n-1,2}$ (see Audard and Provost 1994). Overshooting affects the determination of the age and mass that can be derived from observations by means of the oscillation HR diagram ($\nu_0, \Delta \nu_{0,2}/\nu_0$) (Fig. 1).

Until now, the uncertainties on the estimation of stellar parameters (mass, age, mixing-length parameter, initial composition in hydrogen and heavy elements) inferred from observable quantities (radius, luminosity, seismological observables) has been carried out without considering convective penetration (Gough and Novotny 1993, Brown et al 1994). However the observables are sensitive to this process (Audard et al 1994).

III - A CORE-DEPENDENT FREQUENCY COMBINATION

We have computed the ratio of the two small frequency separations $d_{n,0}^{(1)}$, introduced by Jones et al (1993), and $d_{n,0}^{(2)}$

$$\frac{d_{n,0}^{(1)}}{d_{n,0}^{(2)}} = \frac{\nu_{n,0} + \nu_{n-1,0} - 2 \nu_{n-1,1}}{\nu_{n,0} - \nu_{n-1,2}}.$$

It is sensitive to the deep stellar interior throughout the whole main sequence; this is due to the opposite variation of $d_{n,0}^{(1)}$ which increases while $d_{n,0}^{(2)}$ decreases during evolution.
CONVOLUTION-CORE OVERSHOOTING

Fig.1. Oscillation HR diagram: $\Delta \nu_{0.2}/\nu_0$ versus $\nu_0$ (in $\mu$Hz), for stars of 1 $M_\odot$, and of 1.7 $M_\odot$ and 2 $M_\odot$ without and with convective-core overshooting over 0.2 $H_\odot$ (full and dotted lines respectively). We have reported the error bars provided by the space experiment IPHIR (Toutain and Fröhlich, 1992) and the one we expect from COROT (Catala et al, 1993). Note that this diagram corresponds to given initial chemical composition and mixing-length parameter.

Fig.2. Evolution of the ratio $d_{n,0}^{(1)}/d_{n,0}^{(2)} = (\nu_{n,0} + \nu_{n-1,0} - 2 \nu_{n-1,1})/(\nu_{n,0} - \nu_{n-1,2})$ as a function of the frequency $\nu_{n,1}$ (in $\mu$Hz), for models of 2 $M_\odot$ without overshooting, from age zero to the end of the main sequence. Age (in million years) is indicated for some models.
The quantity $d_{n,0}^{(1)}/d_{n,0}^{(2)}$ varies with age, by up to a factor 2 along the main sequence (Fig. 2). At given effective temperature, it varies by up to 40 per cent between 2 $M_{\odot}$ classical and overshoot models with $\alpha_o = 0.2$, and by a factor 2 between models of 1.7 $M_{\odot}$ and 2 $M_{\odot}$.

IV - CONCLUSION

- At given effective temperature, convective-core overshooting strongly diminishes oscillation frequencies, which could lead to a problem for identifying the radial order of the observed oscillation modes.
- Mixed modes, which are quite sensitive to the conditions at the convective-core frontier, appear at lower effective temperature when overshooting is included; their observation would help to probe convective-core overshooting.
- Convective penetration must be taken into account for the determination of stellar parameters (mass, age, initial chemical composition, mixing-length parameter) inferred from observations (radius, luminosity, seismological observables).
- The frequency combination $(\nu_{n,0} + \nu_{n-1,0} - 2 \nu_{n-1,1})/(\nu_{n,0} - \nu_{n-1,2})$ is quite sensitive to the structure of the stellar core and constitutes a good indicator of stellar age and of the extent of convective-core penetration.

Future space experiments will provide measurements of high accuracy. The analysis of these data will give strong constraints on stellar models, and so enable one to investigate the deep structure of stars and to test the nature and the extent of convective-core overshooting.

A more detailed study can be found in Audard et al (1994).

REFERENCES

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