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Solar-like oscillations in red giant ε Ophiuchi

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Abstract. Asteroseismology is a powerful tool to help determining the internal structure of the stars. Solar-like oscillations have been discovered in the G9.5 red giant ε Ophiuchi, and it opened up a new part of the Hertzsprung-Russell diagram to be explored with asteroseismic techniques. We present the detailed study of the properties of ε Oph including convective overshooting and extra-mixing.

Keywords. stars: oscillations, stars: evolution

1. Introduction

Asteroseismic observations, based on the ground and the MOST space experiment, have shown that solar-like oscillations can be excited stochastically by convection in several G and K-class red giant stars (Frandsen *et al.* 2002; Kjeldsen *et al.* 2005). These stars are very different from main-sequence stars, with highly condensed core and low density envelope. Therefore, red giant stars are extremely difficult to model since they can be very different states of evolution and still be at the same place in the HR diagram.

Very recently, the observations of oscillations in the red giant star ε Ophiuchi have reliably identified the presence of radial modes, and a possible large separations (De Ridder *et al.* 2006; Hekker *et al.* 2006; Barban *et al.* 2007; Kallinger *et al.* 2008). Meanwhile, Hekker *et al.* have found evidence for non-radial oscillations. If such confirmed, this would significantly make progress in understanding the structure and evolution of red giants by seismic analysis.

2. Stellar models

ε Ophiuchi (HD 146791) is a G9.5 giant star of low metallicity, with the visual magnitude of $m_v = 3.24 \pm 0.79$ (Blackwell *et al.* 1990) and the Hipparcos parallax of 30.34 ± 0.79 mas (ESA 1997). Fundamental stellar parameters for ε Oph we adopt are the mean value, e.g. the effective temperature $T_{eff} = 4877 \pm 100K$, luminosity $L/L_\odot = 59 \pm 5$ (De Ridder *et al.* 2006), radius $R/R_\odot = 10.4 \pm 0.45$ (Richichi *et al.* 2005). We have used these observations to constrain a grid of stellar models of ε Oph based on recent physics, with the Yale stellar evolution code (YREC; Guenther *et al.* 1992).

The influence of overshooting and a diffusion of helium and heavy elements on the evolutionary tracks is shown in Figure 1A, with initial heavy metal abundance $Z_i = 0.012$, initial helium abundance $Y_i = 0.28$ and mixing-length parameter $\alpha = 1.75$ calibrated on a solar model. It is found that the effects of overshooting and extra-mixing, ignored in these early studies, are significant during the main-sequence phase, leading to the important consequences in successive evolutionary stage of helium burning. In fact, the presence of overshoot and extra-mixing modify the chemical composition inside the star, and change the boundary between the radiative and convective zones, as well as the structure of the core (Bi, *et al.* 2008).

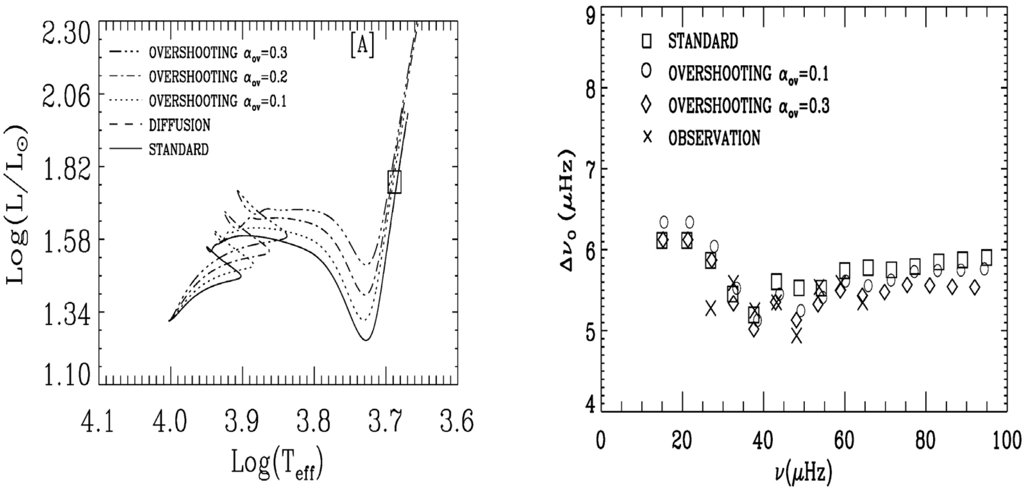

Figure 1. [A]: The effect of the diffusion and core overshooting on the evolution of ε Oph in the HR diagram. The evolutionary tracks are calculated by varying α_{ov} from 0.1 to 0.3, with $M = 2.0M_\odot$, $Z = 0.012$, to match the observed error box. [B]: Large spacings versus frequency for several models with and without convective overshooting. The symbols correspond to modes of degree $\ell = 0$.

3. Results and discussion

We used the stellar pulsation code of Guenther (1994) to calculate the p-mode eigenfrequencies with harmonic degree $\ell = 0, 1, 2, 3$, corresponding 3 evolutionary stellar models that fall within the observational error box, without and with overshooting respectively. It is interesting that the large spacing of modes with $\ell = 0$ appear to become small with including overshooting as the star evolves towards larger effective temperature, shown in Figure 1B. This indicates that the effects of overshooting on evolution and oscillation properties of the models may be important at red giant stage. In addition, we found, from calculation of the theoretical oscillation spectrum of ε Oph, that the average large spacing for $\ell = 0$ is about $5.5\,\mu Hz$, and near observational value.

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