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Asteroseismology of the β Cep star ν Eri: initial results

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Abstract. We have acquired about 1200 hr of both spectroscopic and photometric measurements of the β Cep star ν Eri with 22 telescopes around the world, detecting and identifying seven independent pulsation modes. They are the radial fundamental mode, an $\ell = 1$, g_1 triplet, an $\ell = 1$, p_1 doublet and an $\ell = 1$, p_2 singlet. Seismic model calculations by two independent teams suggest that it is not possible to explain the pulsational behaviour of ν Eri with standard stellar models. Some modifications of the input physics are required.

1. Introduction

The β Cep stars are a group of early B-type pulsators of luminosity classes III–V (Sterken & Jerzykiewicz 1993; Aerts & De Cat 2003). They pulsate in radial and nonradial pressure (p) and gravity (g) modes of low radial order. Multiperiodic pulsators amongst these stars are therefore promising targets for asteroseismology. As β Cep stars do not possess surface convection zones, observational mode identification methods, such as photometric colour amplitude ratios (see Handler et al. (2003a) for an application) or the spectroscopic moment method (Briquet & Aerts 2003, and references therein), can be applied reliably.

The astrophysical interest of the seismic study of these stars is quite high. The determination of the interior structures of several β Cep stars (such as examinations for convective core overshooting, differential interior rotation, interior magnetic field structure, etc.) has the potential to calibrate stellar evolution theory for these stars from the main sequence quite accurately. As β Cep stars are tomorrow's supernovae, which in turn dominate the chemical evolution of galaxies, we may even obtain constraints on this branch of astrophysics.

Pioneering work on asteroseismology of β Cep stars has been performed by Dziembowski & Jerzykiewicz (1996, 1999). Although some interesting results were derived, no detailed modelling of the stellar interiors could be made due to a lack of detected and identified pulsation modes. The first quantitative seismic study of a β Cep star was recently published by Aerts et al. (2003a). They detected and identified six modes of the star V836 Cen (HD 129929), which led to constraints on the stellar metallicity, convective core overshooting and to a detection of interior differential rotation.

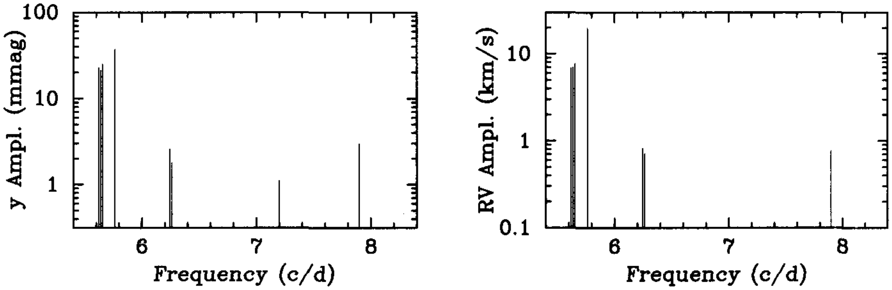

Figure 1. Schematic frequency spectra of ν Eri. Left: photometric data. Right: radial velocity measurements.

It can therefore be expected that large observing campaigns will lead to the detection and identification of even more modes of some stars. The most promising β Cep star for such an effort was deemed to be ν Eri. It is a bright ($V = 3.9$) equatorial object that can be observed both spectroscopically and photometrically from both hemispheres. Four pulsation frequencies were previously known, a singlet (already identified as a radial mode) and an equally spaced triplet (Kubiak 1980; Cuypers & Goossens 1981). It was clear that mode identification of the triplet components alone would already allow an asteroseismic study; any new pulsation modes detected would give independent additional information on the interior of the star. Consequently, we organised a multisite campaign on the star involving both spectroscopic and photometric methods.

2. Observations and their results

We acquired 605 hr of differential photoelectric $uvyV$ photometry with 11 telescopes during 148 clear nights (Handler et al. 2003b) as well as 2294 high-resolution spectra with 11 more telescopes (Aerts et al. 2003b). Frequency analyses of these data sets revealed the presence of 8 pulsation modes in the photometry and 7 modes in the radial velocity time series. Schematic amplitude spectra (independent modes only) from these data sets are shown in Fig. 1.

The photometric colour amplitude ratios allow a determination of the spherical degree ℓ of these modes. The singlet near 5.76 d^{-1} is a radial mode whereas all the other modes common to both data sets are dipole modes ($\ell = 1$). The weakest photometric mode that is not detected in the radial velocity curves is probably $\ell = 2$. This may be an explanation for its non-detection in the radial velocities: the radial velocity to light amplitude ratio for such modes is smaller than for modes of $\ell = 0$ or 1 (Cugier et al. 1994).

3. Theoretical modelling

To model these frequency spectra we restricted ourselves to the modes common to both photometric and radial velocity data. We used both the Liège and Warsaw-New Jersey stellar evolution and pulsation codes (described, e.g., by Thoul et al. 2003 and Pamyatnykh et al. 1998, respectively) for this purpose.

By comparing the observed mode spectra with model frequencies we were able to identify the radial overtone of the $\ell = 0$ and 1 modes. We found that the radial mode is the fundamental, whereas the dipole modes are the first overtone g-mode and the first and second overtone p-modes originating at the ZAMS, respectively.

Seismic modelling was performed by two different teams (Leuven/Liège and Warsaw/Vienna) independently, but only after the following consistency check. Both groups fitted first only the radial and $\ell = 1$, $m = 0$, g_1 mode frequencies for different metallicities and models without rotation or convective overshooting. The same range of models was recovered within a range of 1% in mass.

3.1. Results from the Liège codes

The Leuven/Liège group adopted the requirement that the frequencies of all the four well-identified modes, i.e. the radial and the three $\ell = 1$ modes, must be fitted by the models, realising that observational constraints on the position of a star in the HR diagram are not necessarily very accurate (see, e.g., Aerts et al. 2003a for an example). The requirement of fitting the four frequencies is perfectly fulfilled by models with X = 0.7 (kept fixed at first instance), Z = 0.015 ± 0.001 and overshooting with parameter $\alpha_{\rm ov} = 0.31 \pm 0.02$. This model has a mass of 7.8 $M_\odot$, which is well below previous estimates for ν Eri. Moreover, the overshooting is three times as high as the one found for V836 Cen (Aerts et al. 2003a). The accepted model leads to an internal rotation rate near the core which is less than twice that in the envelope. Driving of the modes, however, is not achieved for this low metallicity (see also below).

Currently, new model calculations are being done for lower X-values. This seems to solve (part of) the problem of the mode excitations and leads to slightly lower values of $\alpha_{\rm ov}$, while keeping a perfect fit to the four measured frequencies.

3.2. Results from the Warsaw/New Jersey codes

The Warsaw/Vienna team used a different approach, as it was not possible to fit all the mode frequencies with their codes for models located in the parameter space ν Eri can occupy in the HR diagram (as determined from colour photometry and its HIPPARCOS parallax). An examination of the kinetic energy density of the dipole modes showed that the p_2 mode is mostly located in the outer parts of the star and that only the g_1 and p_1 modes are sensitive to the conditions in the stellar interior. Consequently, only these modes and the radial fundamental were used for the initial modelling.

Under these assumptions it was found that a global metallicity parameter Z = 0.015 ± 0.001 reflects the interior conditions of ν Eri best. In addition, only models with overshooting parameters $\alpha_{\rm ov} \leq 0.12$ were consistent with the star's position in the HR diagram. An accurate determination of the effective temperature of ν Eri would allow a tighter constraint on $\alpha_{\rm ov}$.

For the family of models constrained in this way, it is possible to estimate the interior rotation of ν Eri because the properties of the g_1 and p_1 modes, for both of which the rotational splitting has been measured, do not vary considerably. It is found that the average rotation rate near the convective core of ν Eri must be about 3 times higher than the average rotation rate in the radiative envelope.

Pulsational driving in β Cep models is very sensitive to metallicity. With $Z = 0.015$ models it is neither possible to excite the observed $\ell = 1$, p_2 mode nor to match its frequency. Experiments showed that an ad hoc factor 4 enhancement of the iron-group elements in the driving zone would solve these problems.

4. Discussion and conclusions

We have organised a large observing campaign for the β Cep star ν Eri, involving both spectroscopic and photometric techniques. We were able to detect and identify seven pulsation modes common to both data sets.

Two independent teams have performed seismic model calculations for ν Eri. Their results may appear inconsistent, but this is a consequence of their different approaches. It now remains to be shown which strategy is physically more appropriate. One major result is, however, on safe grounds: it is not possible to explain the pulsational behaviour of ν Eri with standard stellar models; some modifications of the input physics are required. Hence, future detailed seismic investigations of additional β Cep stars are fully justified.

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