Ensemble Pulsational Characteristics of beta Cep pulsators in eclipsing binaries

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Abstract

Fast rotating massive pulsators in eclipsing binaries are ideal candidates for studying interior mixing and angular momentum transport in massive stars. Different mixing processes such as convective overshooting, which transports only matter, and convective penetration, which transports both matter and heat, occur at the boundary between the convective and the radiative layers in a massive star. These processes increase the core mass of the star and are also strongly affected by fast internal rotation. Fast internal rotation also diminishes the effect of tidal forces, often resulting in non-synchronous rotation, and causes rotational mode splitting, complicating mode identification. This study investigates the pulsational characteristics and their impact on the structure and evolution of fast-rotating β Cep pulsators in eclipsing binaries. Here, we analyse an ensemble of 73 such systems, identify rotationally split modes where possible, and statistically derive the dependence of pulsational properties on stellar and binary dynamical parameters. Interior properties of the systems were also derived using pre-computed grids of stellar structure models using MESA and associated pulsation frequencies using GYRE. The rotational parameters are also derived for 12 systems exhibiting clear rotational mode splitting. The inferred properties provide new insights into the structure and evolutionary pathways of β Cep stars in binary systems.

Introduction

Massive stars are predominantly found in eclipsing binary or multiple systems (e.g. Sana et al. 2012). However, until recently, the number of massive pulsators in eclipsing binary is significantly few (see Eze and Handler 2024), impeding ensemble asteroseismology. Fritzewski et al, (2025) conducted the ensemble asteroseismology of 116 β Cep pulsators (including three binaries), marking one of the first of such studies in the β Cephei class. This paper seeks to conduct an ensemble pulsational analysis of the β Cep pulsators in eclipsing binaries to identify possible relations between pulsation and binary parameters in β Cep stars.

References

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Statistical Characterisation

Using TESS 2 minutes cadence data obtained from the Barbara A. Mikulski Archive for Space Telescopes (MAST), we conducted the ensemble analysis of β Cep stars reported in Eze and Handler, (2024). β Cep pulsations of $3 - 14\,d^{-1}$ are considered. The distributions of the pulsation frequencies and amplitudes are shown in Figure 1.

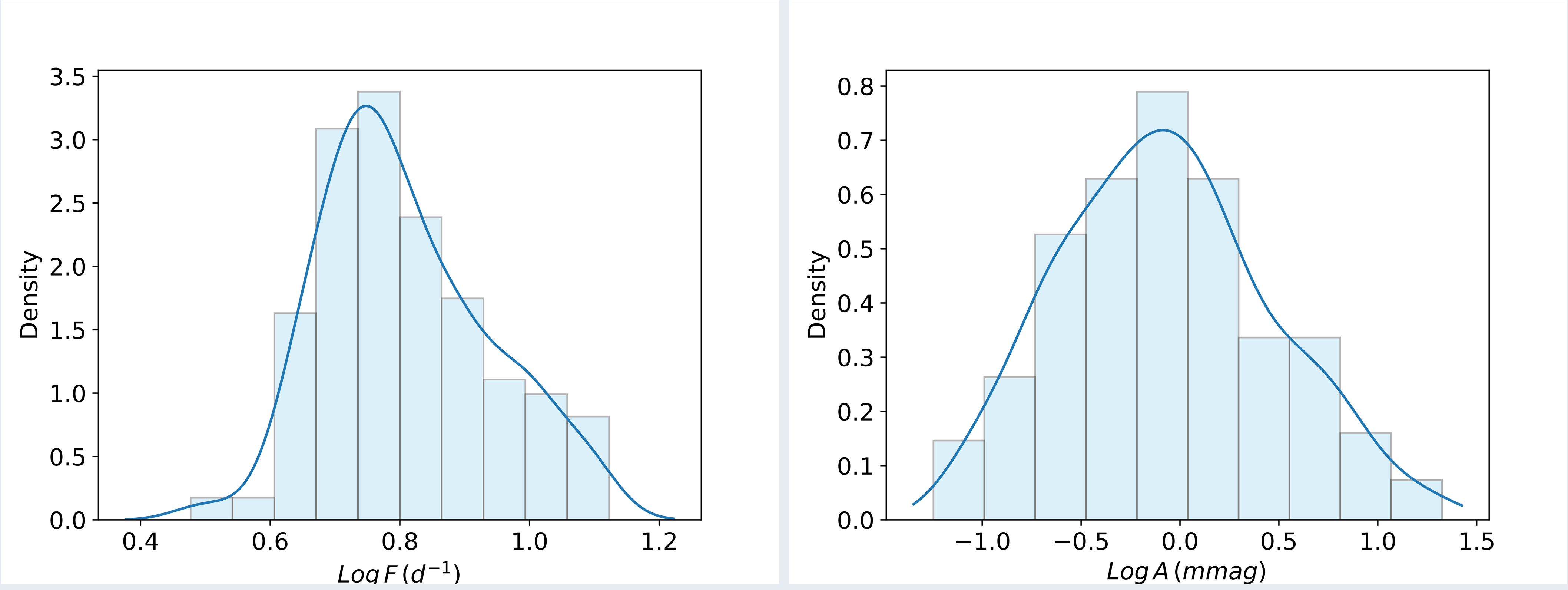

Figure 1:The distribution of the pulsation frequency (lp) and pulsation amplitude (rp)

Bayesian Multivariate Regression Analysis

$$\log A_i = \beta_0 + \beta_1 \log f_i + \beta_2 \log P_i + \beta_3(\log f_i)(\log P_i) + \epsilon_i \tag{1}$$

where A_i and f_i are the pulsation amplitude and frequency, respectively, P_i is the orbital period, β_0 is the intercept, $\beta_1, \ldots, \beta_n$ are the coefficients and ϵ is the Gaussian noise. The 2D posterior mean response surface in Figure 2 reveals smooth curves arising from possible interaction, gradient along the frequency axis, implying that higher frequency modes tend to have lower amplitudes, which is consistent with increased damping or geometric cancellation effects at higher frequencies, and non-linear trends with logP, with the uncertainty plot showing that the model is better constrained for short-period systems, where tidal interaction is very strong. In particular, the effect of binarity on the pulsation amplitude depends on the pulsation frequency, and the orbital period weakly interacts with the pulsation frequency, suggesting possible modulation of pulsations by tidal gravity.

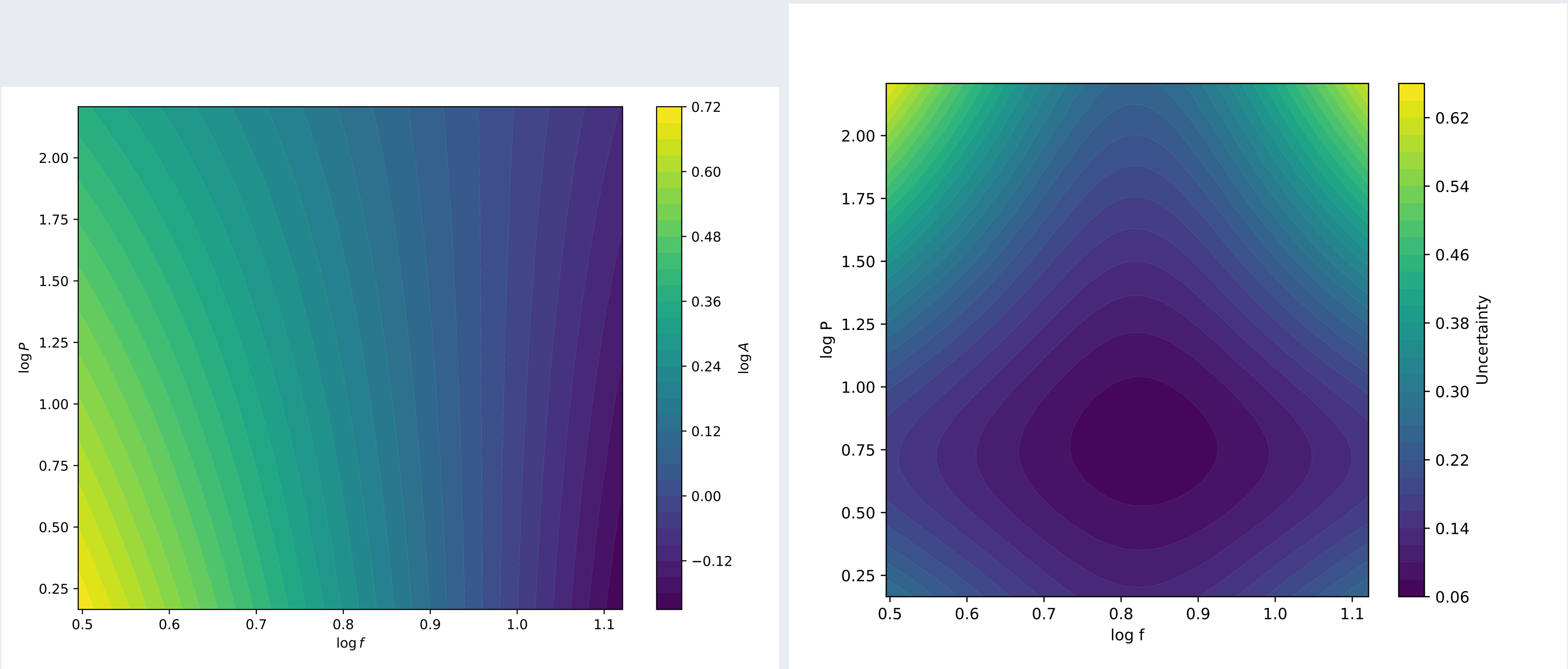

Figure 2:2D posterior mean response surface showing the relation between pulsation and orbital parameters (lp) and their uncertainties (rp)

Mode Identification via rotational splitting

For a slow rotating β Cep non-radial pulsation modes, the observed frequency of a mode with quantum numbers (n, ℓ, m) is defined, following the the first order perturbative treatment of rotational effects as:

$$f_{n,\ell,m} = f_{n,\ell,0} + m \cdot \Omega \cdot (1 - C_{n,\ell}) \tag{2}$$

where Ω is the rotational frequency and $C_{n,\ell}$ is the Ledoux constant. Using Equation 2, the rotationally split modes and their rotational frequency were inferred.

Asteroseismic modelling of selected cases: HD 112485

Forward Asteroseismic modelling of selected cases were performed using MESA/StORM grid (e.g. Paxton et al. 2011, Vanlaer et al. submitted) of varying M, fov, logDmix, Xc and f_{rot} using the χ^2 minimisation algorithm as implemented in AMPHAROS code (Vanrespaille et al. submitted) to derive the asteroseismic parameters of the target.

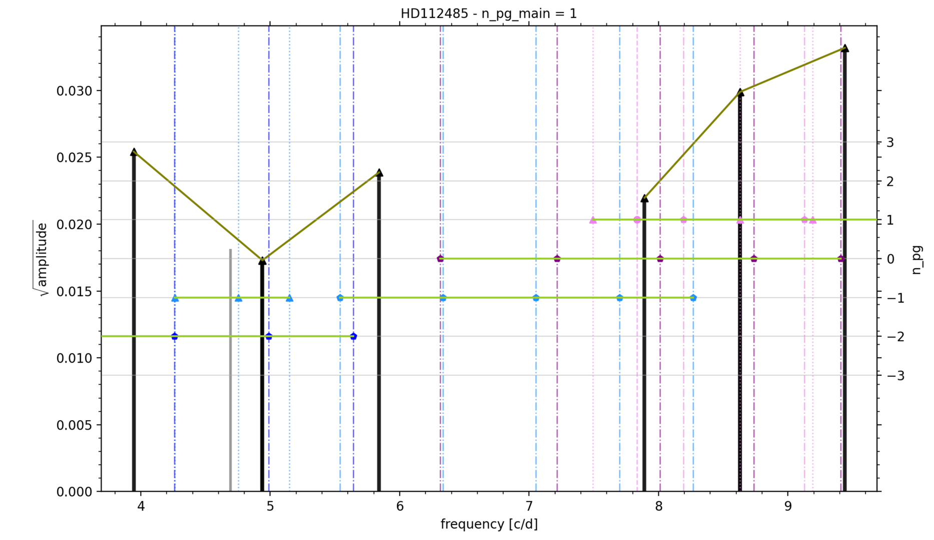

Figure 3:Frequency comparison of the best fit model with observation.

Conclusion

The paper shows unimodal distributions for both the frequency and amplitude. The amplitude is not governed by a simple relation with frequency or orbital period alone, but by a coupled, non-linear interaction between both quantities. The observed frequencies in HD 112485 were fairly reproduced by the best fit model.

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