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A line-profile analysis of the large-amplitude β Cephei star ξ^1 Canis Majoris

S. Saesen[1], M. Briquet[1], C. Aerts[1,2]

[1] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200B, B-3001 Leuven, Belgium
[2] Department of Astrophysics, Radboud University Nijmegen, PO Box 9010, 6500 GL Nijmegen, the Netherlands

Abstract

We present a detailed line-profile study of the β Cephei star ξ^1 Canis Majoris, for which we have assembled numerous high-resolution spectra over a period of 4.5 years. It is the first time that the line-profile variations of this star have been analysed. We focused on the Si III line profiles centered on 4560 Å. We searched for oscillation frequencies in different line diagnostics and find the star to be monoperiodic with frequency $f = 4.77153 \text{ c d}^{-1}$. By means of the moment method and from amplitude and phase variations across the line profiles we identified the oscillation mode of the star as radial. ξ^1 CMa is among the very few β Cephei stars with a radial-velocity amplitude larger than the local speed of sound and profile variations that clearly deviate from those predicted by linear oscillation theory.

1. Introduction

Stars of spectral type B are very interesting objects upon which to perform asteroseismology. Indeed, they have a convective core which strongly determines the evolution of the star and how they will end as supernovae of type II, thus chemically enriching the interstellar matter. This is why several observational campaigns were set up for β Cephei stars, which led to recent breakthroughs in the modelling of this class of B-type pulsators. E.g. from a long-term single-site campaign, HD 129929 (Aerts et al. 2003) was found to have a non-rigid rotation and a small core overshooting. From recent multisite campaigns, similar results were obtained for ν Eri (Pamyatnykh et al. 2004, Ausseloos et al. 2004) and 12 Lac (Handler et al. 2005a), but for these stars problems arise with the excitation of some modes. Our goal is to add new β Cephei stars to the sample of those with asteroseismic modelling. For this purpose, Handler et al. (2005b) and Briquet et al. (2005) investigated the star θ Ophiuchi and Desmet et al. (2006) got some first results for β CMa. This paper concerns a study of ξ^1 CMa.
ξ^1 CMa (HD 46328, spectral type B1III, V mag = 4.33) was discovered to be a star with variable radial velocities by Frost (1907). McNamara (1955) was the first one who disentangled the period of 0.209574 days by means of his own radial velocity data. After him, Van Hoof (1963), Shobbrook (1973) and Heynderickx (1992) confirmed this period by analysing photometric data and they reported that the first and possibly the second harmonic is present as well. Heynderickx et al. (1994) identified the mode as a radial one. We observed and investigated this star hoping that it bears similarities with β Cephei (Telting et al. 1997), a star with a dominant radial mode and additional low-amplitude non-radial modes.
This paper is organized as follows. We begin with a description of our data. We then

discuss the frequency analysis after which we perform the mode identification. We end with a recapitulation and future work.

2. Observations

In an effort to find frequencies other than the dominant one, ξ^1 CMa was monitored during 4.5 years with the CORALIE échelle spectrograph attached to the 1.2 m Euler telescope in La Silla (Chile). The observations took place between February 2000 and October 2004 and in total we gathered 401 high-resolution spectra. All raw data were reduced into interpretable line profiles and made heliocentric. We considered the Si III triplet of which we used the line with central wavelength $\lambda_0 = 4552.654$ Å. This line is very suitable for a seismic study of β Cephei stars since the line is strong, not too much affected by blending and dominated by temperature broadening, such that Stark broadening can be ignored. We also computed the equivalent width (EW) and the first three normalized velocity moments $\langle v \rangle$, $\langle v^2 \rangle$ and $\langle v^3 \rangle$ of the line profile as defined by Aerts et al. (1992). In the calculation of the moments the integration limits were dynamically chosen by visual inspection because the lines vary a lot and we want to retain as much information as possible and avoid the noisy continuum.

3. Frequency analysis

We performed Phase Dispersion Minimisation (PDM, Stellingwerf 1978) and Scargle (Scargle 1982) analyses on the three velocity moments, the EW and the line profiles themselves. The results obtained by both methods are similar. We tested frequencies from 0 until 40 cycles per day (c d^{-1}) which corresponds to the Nyquist frequency of the data, as estimated by the program PERIOD98 (Sperl 1998). For the accuracy of the frequency value we adopted the approximation of Bloomfield (1976): $\sigma_f = \sqrt{6}\ \sigma_R/(\pi\sqrt{N}AT)$, with σ_R the average noise level of the individual measurements, N the number of data points, A the amplitude of the variation and T the total time span of the observations. As we do not know σ_R for our dataset, we used the standard deviation of the residuals after prewhitening with the significant frequencies. This formula leads to a frequency uncertainty of 10^{-5} c d^{-1}.
We started by calculating the spectral window to check to what extent the analysis suffers from aliasing. This spectral window reveals a clear one-day-alias as shown in the left panel of Fig. 1. Then we examined the first moment. After subsequent stages of prewhitening, we found $f = 4.77153$ c d^{-1} with three harmonics, so $2f$ and $3f$ are also present in $\langle v \rangle$. Note that the frequency f corresponds to the one in the literature. A harmonic fit with these frequencies is illustrated in the right panel of Fig. 1: the model, indicated by the full line, matches the data, represented by dots, extremely well. The variance reduction is more than 99%. The amplitude of the oscillation is very large, about 16.4 km s^{-1}. The fact that we find several harmonics demonstrates that we are dealing with a non-linear oscillation. This follows from a peak-to-peak velocity amplitude higher than the local speed of sound. No frequencies different from f were found in the first moment. We continued our quest in the second and third moment. f, $2f$ and $3f$ were detected, but no additional frequencies. The equivalent width varies sinusoidally with f. Finally we attempted to find other frequencies with low amplitudes in the spectral lines but failed to detect any.

4. Mode identification

We used different methods for the mode identification. A first diagnostic for the mode was provided by the harmonic fit of the second moment $\langle v^2 \rangle$. In this fit the amplitude of $2f$ is much larger than the one of f, indicating an axisymmetric mode (Aerts et al. 1992).
Secondly we used the latest version of the moment method (Briquet & Aerts 2003) in which

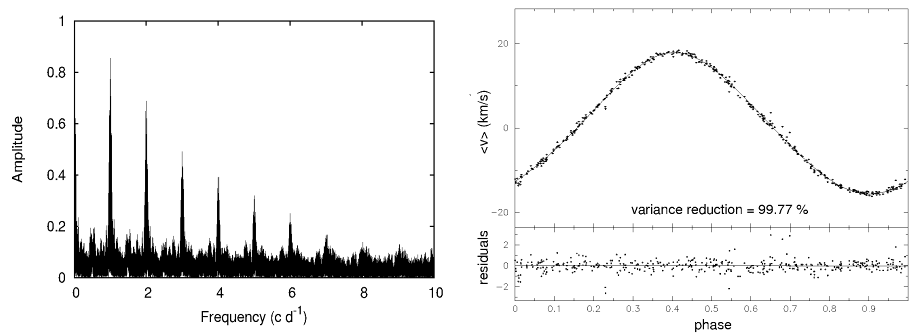

Figure 1: Left: The spectral window of the dataset. No significant peaks were found for frequencies higher than 10 c d^{-1}. Right: A harmonic fit of the first moment $\langle v \rangle$ with frequencies $f = 4.77153$ c d^{-1}, $2f$ and $3f$ (top) and the remaining residuals (bottom).

the theoretical expressions of the first three velocity moments are compared with their observed values by minimizing the discriminant Σ. As these theoretical formulas are dependent on ℓ, m and some continuous stellar parameters such as the inclination angle i of the star (defined as the angle between the rotation axis and the line of sight) and the equatorial velocity $v_{\rm eq}$, we can determine values for these. The moment method takes only realistic situations into account by testing that the equatorial rotation velocity is smaller than the break-up velocity. Since no significance level is available for Σ, we compared the moments of the best solutions with the observed ones. This indicates a preference for $(\ell, m) = (0, 0)$ or $(1, 0)$ with a small inclination. Note that we cannot distinguish between those two modes because they have the same visual geometric configuration.
To discriminate further, we performed a mode identification based on the amplitude and phase distributions across the line profile. With the simulation study of Schrijvers et al. (1997), we deduced again that f agrees with a radial or dipole mode. In order to refine this outcome, we proceeded by comparing the observed amplitude and phase variations with the theoretically predicted ones, generating time series of spectral lines for different modes. The theoretical line profiles were generated by the codes BRUCE and KYLIE implemented by Townsend (1997). An example of this comparison is shown in Fig. 2 for the observational amplitude plot and the one of a good solution of the moment method for $(\ell, m, i) = (2, 0, 2^\circ)$. Due to poor agreement, we eliminated this possibility. Analogously for the other modes, we again favored $(\ell, m) = (0, 0)$ or (1,0). We also applied this technique with a fixed mode to compute a range for the continuous parameters and we got the velocity amplitude $A_p = 69 \pm 10$ km s^{-1}, the thermal broadening $\sigma = 6.5 \pm 0.5$ km s^{-1} and $v_{\rm eq} \sin i = 17.5 \pm 1.5$ km s^{-1}.
By means of the spectroscopic mode identification methods, we cannot choose between the two couples $(\ell, m) = (0, 0)$ or $(1, 0)$ with a small inclination.

5. Conclusions

After a detailed study of the variability of ξ^1 CMa by means of spectroscopic data, we confirm that this star varies monoperiodically with frequency $f = 4.77153\,{\rm c\ d}^{-1}$. ξ^1 CMa oscillates in a non-linear way: 3 harmonics of f are present in the data. Several spectroscopic mode identification methods reveal that f corresponds to either a radial $(\ell, m) = (0, 0)$ or a dipole mode $(\ell, m) = (1, 0)$ with a small inclination. Luckily, the photometric mode identification of Heynderickx et al. (1994) indicates that only the radial mode agrees with f. Additionally, the spectroscopic methods enable us to determine ranges for some continuous parameters. Unfortunately, seismic tuning is impossible for ξ^1 CMa as we need at least two frequencies

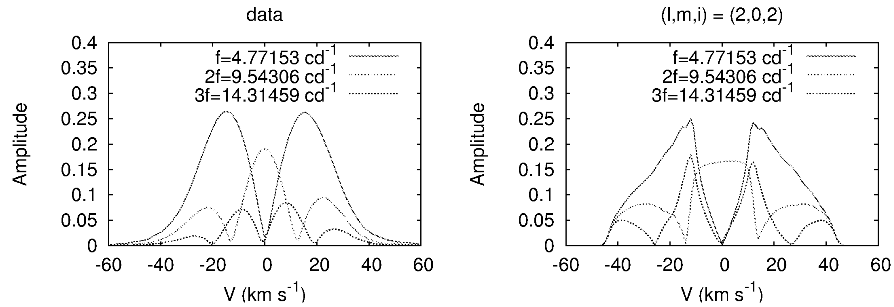

Figure 2: A comparison between the observed (left) and theoretical (right) amplitude across the Si III profile.

to do so.
We shall investigate in the future why this star does not pulsate multiperiodically in contrast to most other β Cephei stars.

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References

Aerts, C., De Pauw, M., Waelkens, C. 1992, A&A 266, 294
Aerts, C., Thoul, A., Daszyńska, J., et al. 2003, Science 300, 1926
Ausseloos, M., Scuflaire, R., Thoul, A., Aerts, C. 2004, MNRAS 355, 352
Bloomfield, P. 1976, "Fourier Analysis of Time Series: an Introduction", John Wiley & Sons, New York
Briquet, M., Aerts, C. 2003, A&A 398, 687
Briquet, M., Lefever, K., Uytterhoeven, K., Aerts, C. 2005, MNRAS 362, 619
Desmet, M., Briquet, M., Mazumdar, A., Aerts, C. 2006, This volume
Frost, E.B. 1907, ApJ 25, 59
Handler, G., et al. 2005a, MNRAS, in press
Handler, G., Shobbrook, R. R., Mokgwetsi, T. 2005b, MNRAS 362, 612
Heynderickx, D. 1992, A&AS 96, 207
Heynderickx, D., Waelkens, C., Smeyers, P. 1994, A&AS 105, 447
McNamara, D. H. 1955, ApJ 122, 95
Pamyatnykh, A.A., Handler, G., Dziembowski, W.A. 2004, MNRAS 350, 1022
Scargle, J.D. 1982, ApJ 263, 835
Schrijvers, C., Telting, J.H., Aerts, C., Ruymaekers, E., Henrichs, H.F. 1997, A&AS 121, 343
Shobbrook, R.R. 1973, MNRAS 162, 25
Sperl, M. 1998, CoAst 111, 1
Stellingwerf, R.F. 1978, ApJ 224, 953
Telting, J.H., Aerts, C., Mathias, P. 1997, A&A 322, 493
Townsend, R.H.D. 1997, MNRAS 284, 839
Van Hoof, A. 1963, Zeitschrift für Astrophysik 56, 141