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Phase Variation and NRP Modes in Southern Be Stars

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Abstract. ζ Ophiuchi and η Centauri are hot, rapidly rotating, southern Be stars showing multi-mode nonradial pulsations (*nrp*). We use high resolution, high signal-to-noise ratio spectroscopic observations of these objects to test the Telting and Schrijvers' method (TS) of mode degree l and azimuthal order $\mid m \mid$ estimation. In this method, these quantum numbers are calculated from the blue-to-red phase difference of the corresponding main frequency and its first harmonic, respectively. The phase differences were obtained withe the help of the CLEAN and CLEANEST algorithms. Quantum numbers calculated with TS are compatible with those obtained with the Fourier Doppler method within the estimated errors. In the absence of other tools, the TS method can thus be used to estimate l and $\mid m \mid$ with reasonably accuracy.

1. Introduction

The ζ Oph Be stars show multiperiodicity and their line-profile intensity variations (*lpv*) are characterized by the presence of features ("moving bumps") traveling from blue to red across the profile. They are generally attributed to the presence of *nrp* (e.g., Gies 1994). The problem of adiabatic *nrp* in rotating stars were examined in a series of papers presented recently (Schrijvers et al. 1997; Telting & Schrijvers 1997a, hereafter TS; Telting & Schrijvers 1997b). The effects of *lpv* caused by spheroidal *nrp* modes are studied in detail, with special emphasis to the dependence of observable spectroscopic diagnostics on relevant stellar parameters (rotation, inclination angle, intrinsic line width) and pulsational characteristics (velocity amplitude, nature of the mode, degree and azimuthal order). An especially interesting result of these calculations is that the *lpv* cannot be reproduced theoretically by a single sinusoid: at least one harmonic needs to be included. This effect appears even for a sinusoidal oscillations, and is due to the Doppler mapping of the three-dimensional velocity space, which has only a one-to-one correspondence in the limit of zero pulsation amplitude. The harmonic amplitudes will depend on the intensity of the line profile deformations, ie of the "moving bumps". This result is of fundamental importance in the interpretation of *lpv,* as the presence of multiperiodicity can no more be taken as a signature *nrp,* because of the unavoidable projection effect that introduces periodicities at multiples of the "true" (stellar) frequencies. In this context, extensive numerical simulations performed by TS showed that the blue-to-red phase differences of the main frequency and its first harmonic can be used to estimate the mode degree l and the azimuthal order $\mid m \mid$, respectively: TS derive empirical formulae to calculate these two parameters. We thought that it was important to make a detailed test of the extensive numerical simulations of *nrp* referred to above by using real spectroscopic data. In this communication, we apply the TS method to frequencies found in high resolution, high signal-to-noise ratio optical spectra of two ζ Oph Be stars: ζ Oph itself and η Cen. Observations were performed with a CCD (1152×770 pixels) EMI camera installed at the coudé spectrograph of the B & C 1.6 m telescope of the Brazilian Laboratório Nacional de Astrofísica, (Pico dos Dias, Brazil). Spectra were taken with a grating of 1,800 l/mm (first inverse order) centered on the He I λ667.8 nm line. This arrangement yields a spectral resolution of $\simeq$ 60,000 and a wavelength range of $\simeq$ 89 Å. The signal-to-noise ratio was between 100 and 300 for time exposures of 3 - 5 minutes. The hot, rapidly rotating, southern Be stars ζ Oph (HR 6175, HD 149757, $V = 2.6$, O 9.5 Ve, $V\sin i =$ 400km/s) and η Cen (HR 5440, HD 127972, $V = 2.3$, B1-B2 Ve, $V\sin i = 350$ km/s) show multiperiodicity which is attributed to *nrp* (Kambe et al. 1990; Jankov et al. 1999; Janot-Pacheco et al. 1999).

2. Time analysis and *nrp* parameter estimation

We applied the CLEAN (Roberts et al. 1987) and the CLEANEST (Foster 1995) algorithms to series of spectra of the stars (135 spectra for ζ Oph obtained during four nights from May 30th to June 2nd, 1996 and 209 spectra of η Cen obtained during six nights from March 11–18th, 1995). Detailed results are presented elsewhere (Janot-Pacheco et al. 1999; Souza Jr. et al. 1999). Frequency analysis was performed on each of the individual time series formed by data at each resolution step across the He I λ667.8 nm line profile. Phase variations inside the line were determined with the help of a least-squares sinusoidal fitting method. The *lpv* were also analyzed with the Fourier Doppler Imaging technique (FDI) (Kennelly et al. 1992). In this method the temporal variations of the line profile series are transformed in both time and Doppler space. A two-dimensional Fourier representation of the variations is thus obtained, where the frequencies along the velocity axis can be identified with the (apparent) azimuthal orders. TS give for the *nrp* mode degree and azimuthal order: $l \simeq 0.1 + 1.09 \mid \Delta\Psi_0 \mid/\pi$ ($\pm$ 1) and $\mid m \mid \simeq - 1.33 + 0.54 \mid \Delta\Psi_1 \mid/\pi$ ($\pm$ 2), were $\mid \Delta\Psi \mid$ are the phase difference of the fundamental frequency (0) and of its first harmonic (1), respectively. The estimated errors are ± 1 for l and ± 2 for $\mid m \mid$. Quantum numbers l and $\mid m \mid$ calculated with TS method for ζ Oph and η Cen are in good agreement with those deduced with FDI as can be seen in Tables 1, 2. For

η Cen, the sign of the azimuthal quantum number could be deduced assuming a stellar rotation frequency of 1.5 c/d (Janot-Pacheco et al. 1999).

Table 1. Degree and azimuthal order for ζ Oph

frequency (c/d)	TS	FDI[a]
7.19	l=4 $\mid m \mid$=3	l=4-5
8.85	l=5 $\mid m \mid$=5	l=7
11.89	l=7 $\mid m \mid$=4	l=6-8

[a] Souza Jr. et al. 1999

Table 2. Degree and azimuthal order for η Cen

frequency (c/d)	TS	FDI[a]	Ω_{rot}=1.5 c/d[a]
0.78	l=1 $\mid m \mid$=1	l=1-3	l=1 m=−1
1.29	l=3 $\mid m \mid$=0	l=1-3	l=2 m=−1
1.48	l=4 $\mid m \mid$=0	l=3-5	
1.78	l=2 $\mid m \mid$=0	l=1-3	
3.82	l=4	l=1-3	
4.34	l=3 $\mid m \mid$=2	l=2-4 m=−3	l=3
4.51	l=6 $\mid m \mid$=3	l=3-5	$l \geq 4$ m=−3
7.80	l=8 $\mid m \mid$=5	l=6	$l \sim 7$ $m \sim -6$

[a] Janot-Pacheco et al. 1999

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