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LINE PROFILE VARIABILITY OF NON-RADIALLY PULSATING Be STARS

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Abstract. The Be phenomenon is one of the most standing non-resolved problems in stellar astrohysics. Recently, it was proposed that non-radial stellar pulsations could be a key to understand the mass loss in Be stars. Also, the study of the oscillation spectrum of a star can be used to probe its interior and therefore represents an excellent tool to improve theories of structure and evolution of the Be stars. In this paper we review the previous contributions in this field and give the new results from high spectral and temporal resolution and high signal-to-noise ratio spectroscopy of the prototype non-radially pulsating Be star ζ Oph obtained at the Laboratório Nacional de Astrofísica, Brazil.

1. INTRODUCTION

Classical B stars with emission lines (Be) stars are a group of rapidly rotating post zero age main sequence stars that occasionaly exibit emission in one or more Balmer lines. The emission features in this stars, lasting on time scales of months to decades, are interpreted as the episodic formation of circumstellar disc mainly expanded in the equatorial plane. Quirrenbach et al. (1994) confirmed the existence of such disc structure directly - by the interferometric observations.

However, the mechanism of the episodic mass loss in Be stars is as yet unknown. Previously, Be stars were presumed to be at break-up velocity and to eject their mass from the equator. However, there is not observational evidence that any Be star is at brak-up velocity (eg. Hutchings & Stoeckley 1977). Other mechanisms, such as magnetic fields, stellar winds, binarity have also been proposed, but none succeeded in explaining all the key aspects of observations.

Now it is generally accepted (for rewiev see Gies 1994) that the line profile variations (*lpv*) are one of the key features to understand the mass loss mechanism in Be stars. Non-radial pulsations (NRP) have been proposed as an explanation for the line profile variability in hot stars (eg. Smith 1977; Vogt & Penrod 1983) and references therein, although there are still some debates about the nature of the line profile variations. Baade & Balona (1994) discuss the NRP model with respect to an alternative rotational modulation (RM) model.

After the traveling bumps were first discovered in ζ Oph (Walker et al. 1979) and tentatively associated to photospheric temperature inhomogeneities (RM), the phenomenon has been observed in other Be stars. High signal-to-noise ratio spectroscopy and theoretical developments in the field of asteroseismology have stimulated an extensive monitoring of the *lpv* in Be stars suspected to be non-radial pulsators. The ζ Oph type variables show the strong line profile variability characterized by bumps traveling from blue to red within the spectral lines and multiperiodicity (Kambe et al. 1990) while the other subclass of B stars with emission lines (λ Eri stars) appear to show strictly mono-periodic light variations (Balona 1990).

After Dziembowski et al. (1993) the idea that *lpv* in B-Be stars can be caused by NRP has been reinforced. They showed that the presence of NRP in this stars is a consequence of the usual κ excitation mechanism acting in a large region in the main-sequence band, bridging the gap between δ Sct and β Cep stars. An alternative excitation mechanism is a resonance coupling between the overstable convection in the core and an envelope g-mode (Osaki 1974).

The effects of NRP are considered to be possible additional forces for the episodic mass loss of Be stars to the centrifugal force of rotation. Vogt and Penrod (1983) pointed out the possible mass-loss by shock waves generated by NRP, while Kambe et al. (1993) found a weak relation between the amplitudes of NRP and the Be cycle in ζ Oph. Observationally Penrod (1987) suggested that a Be star has a low-degree oscillation modes in addition to high-degree modes, while a normal B star has only high-degree modes. This difference may indicate that low-degree nonradial modes and rapid rotation are essential ingredients that allow a B star to become a Be star. In this scenario the radial motion (compression/expansion) caused by the passage of the waves through the photosphere puffs up the stellar material from the surface into the circumstellar envelope. Hahula & Gies (1994) in a spectroscopic survey of ten Be stars (o And, λ Eri, ω Ori, 28 Cyg, η Cen, 48 Lib, ζ Tau, ψ Per, 2 Vul, KY And) found that the $l = -m = 2$ NRP mode is predominant in all stars, with the sole exception of o And.

Theoretically, NRP are related to episodic mass loss in Be stars (Ando 1986; Osaki 1986). If NRP are excited in the interior of the star by some mechanism, angular momentum transported by the oscillations is deposited near the surface due to dissipation. This results in an increase in rotational velocity at the surface leading to the mass loss at the equator. Once the mass loss starts NRP leak into the newly formed extended envelope and the mass loss may be accelerated. In the meantime NRP are damped owing to increased disipation in the envelope and the mass loss comes to an end. The star remains quiet until new NRP are built up to sufficient amplitude and a new episode begins. In this scenario the rotation profile should vacillate quasi-periodically around uniform rotation. Observational facts predicted by this models should be checked, that is: a) quasi periodic variations of the rotation b) predominance of prograde oscillations during acceleration and retrograde oscillations during deceleration of the stellar rotation. For this more precise line profile variations have to be accumulated over the whole cycle of a Be episode.

2. OBSERVATIONAL EVIDENCE FOR NRP IN A PROTOTYPE STAR ζ Oph

The main sequence O9.5 star ζ Oph (HR 6175) is particularly interesting as a prototype of the subclass of supposingly pulsating OB stars (associated to its name). We applied both methods of time series analysis and Fourier Doppler Imaging (FDI), (Kennelly et al. 1992) technique to examine multi-periodic line profile behavior of ζ Oph from our time resolved, high signal-to-noise ratio spectra. A total of 242 high resolution (R = 60 000), high signal-to-noise (S/N $\approx$ 200) ratio spectra were obtained during the observing run carried out over 3 nights in 1996 May 3 to May 5, with a 1.60m B&C telescope using the coudé spectrograph equipped with a CCD camera. This research was performed for the purpose of monitoring of *lpv* in southern Be stars at the brazilian Laboratório Nacional de Astrofísica (Janot-Pacheco & Leister 1994) in order to intercompare the line profile variability of the star in different time scales: rapid - less than one rotation period, short - several rotation periods, medium - up to hundred rotations and long - more than hundred rotations and to search for the origin of mass ejections in Be stars.

Our results do not favorize the rotational modulation model for the line profile variability so we discuss them in the frame of the alternative non-radial pulsator model for the star. In fact, the multiperiodic behavior of line profile variations in ζ Oph favorize the NRP model, since many modes of NRP can be simultaneously excited in the star and the presence of multiple frequencies is expected, while the rotational modulation (RM) model would need an exotic mechanism to account for that. Also, the frequencies deduced in our analysis are not consistent with the RM model. In the frame of the RM model the frequencies themselves as well as their difference should be multiples of the rotation frequency. While two dominant observed frequencies $\omega = 7.19$ cycles per day (c/d) and $\omega = 11.89$ c/d require stellar rotational frequencies 1.44 c/d and 1.48 c/d respectively, their difference indicates a rotational frequency of 1.57 c/d. In the context of NRP model this difference is just a consequence of the correction term due to the effect of Coriolis force on the NRP velocity field. In addition we found the double peaked distribution of the oscillation power over the line profile. This is hard to explain by any spot model, where the modulation should be highest in the line center or by the circumstellar spoke model (Harmanec 1989), where a single maximum is shifted redward or blueward depending on a tilt of the spokes, while it is just a natural consequence of the velocity field associated with NRP g-modes for which the tangential component of the velocity is important.

We detected several new modes and frequencies in addition to others found previously. The exceptional time resolution of our high signal-to-noise ratio spectra has allowed detection and identification of of high azimuthal order modes up to at least $m = -17$. The oscillations are characterized by negative values of the spherical azimuthal order m - waves prograde in the inertial frame.Two distinct groups of modes are detected: medium ($5 \leq |m| \leq 9$) and high-degree ones ($11 \leq |m| \leq 17$). The oscillations are strongly confined in an equatorial belt narrower than 20°. Together with the results from FDI diagrams this indicate that the sectoral modes dominantly determine the observed line profile variability. The predominance of sectoral modes may be a selection effect, since for a given l and m the surface is divided into $l-|m|+1$ sections in latitude and mutual cancellation is weaker for $l = |m|$, but can also reflect a mechanism within the star that allows these modes of oscillation to be dominant. Lee & Saio (1986) show that an overstable convective mode penetrating into the envelope of a massive main-sequence star has a dominant $l = |m|$ component. There could also be some other selection mechanisms. For example, if a high latitudinal differential rotation has a destabilizing effect, a tesseral mode distributed over wide latitude range would have a short lifetime, while an equatorially confined sectoral mode would not be affected and its oscillation power, integrated in time, would be dominant.

From FDI diagrams we deduced that the co-rotating frequencies of all observed pulsations are very small (more that one day), which is generally expected for high radial order gravity modes (Unno et al. 1979). We detected also a quasi-sinusoidal variation of the projected rotational velocity $V_e \sin i$ of approximately 15 kilometers per second in amplitude. For a star inclined by $i = 45°$ (Jankov et al. 1997) this translates in 20 km/s amplitude of the rotational velocity. These variations can be interpreted as a consequence of velocity fields introduced by other sources (as non-radial pulsations) present in the stellar atmosphere and superposed to the global rotation velocity field, deforming the individual rotation profiles and producing corresponding variations in the measured velocities. Since the radial component of the equatorial velocity field is zero at the limb, only the horizontal component can produce such a variation. In the frame of the NRP model this is an indication of gravity waves that have a significant horizontal component of the oscillatory velocity field, in contrast to acoustic waves.

The star showed rapid redistribution among modes in time scale less than one stellar rotation suggesting that the phenomena of resonance or (and) beating coul be effective. The phenomenon of resonance have already been reported in B stars (Baade 1984; Smith 1985; Janot-Pacheco et al. 1977).

3. CONCLUSIONS

The fact that low frequency gravity modes are dominant is crucial for the asteroseismological potential of non-radial pulsations in Be stars. In addition to the study of such oscillations themselves in the particular stellar conditions, the related research is very promising in the exciting task of probing the stellar interior. In order to achieve this task the accurate period determination from long-time baseline observations as well as theoretical developments concerning pulsations of very fast rotators are needed.

Furthermore, the study of multi-periodicity will provide important implications concerning the driving mechanisms for NRP. The selective mode excitation deserves particular attention since it could be an important clue to the excitation mechanism of non-radial pulsations in these stars. Particularly, a search for the low degree modes may be important in order to accept one of the two proposed excitation mechanisms: metal opacity bump (Dziembowski & Pamyatnykh 1993) or a resonance coupling between the overstable convection in the core and an envelope g-mode (Osaki 1974).

The rapid rotation of the star combined with NRP has certainly deep effects on the star's circumstellar environment. Although the amplitude of an individual mode is smaller than the difference between break-up and equatorial velocity, its sum can be important and phenomena as beating and resonance mode coupling deserve particular attention in order to study the possible link between the oscillations and Be episodes. For this purpose pulsation parameters (direction of propagation in the co-rotating frame, azimuthal and radial order of oscillations) and fundamental stellar parameters (as the measured rotational velocity) should be monitored at least over one Be activity cycle through the line profile variability.

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