Study of the line-profile variations in the spectrum of ζ Oph during the May/June '04 MOST satellite campaign

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1 Abstract

In support to the 3-week photometric observations of the O9 Ve star ζ Oph by the Canadian MOST satellite, high S/N spectra of ζ Oph were obtained over a similar time interval at DAO Victoria, Canada, GAO Gunma, Japan and Ondřejov, Czech Republic. They cover the H beta and He 4922 lines. Results of the time-series analysis based on local radial velocities are presented, with a special emphasis on identification of variability also on a time scale longer than some 0.5 days.

2 Introduction

ζ Oph (HD 149757, HIP 81377, HR 6175; $V = 2.58$, $B - V = 0.01$) is one of the most rapidly rotating Be stars ($v \sin i$ ~400 km.s^{-1}). It undergoes episodic mass loss (seen as emission at Hα) lasting for a few months roughly every decade (Kambe et al. (1993);Harmanec (1989)). While it is formally classified O9.5 V, Herrero et al. (1992) find the ζ Oph line profiles are more compatible with O9 III. For an assumed metalicity of $Z = 0.03$, ζ Oph lies close to the blue edge of the β Cephei instability strip of the HR diagram.
The profiles of stellar lines in ζ Oph are distorted by ripples at ~1% level travelling from blue to red over a few hours (Walker et al. (1979) or Kambe et al. (1997)). The ripples can be interpreted either as a Doppler redistribution of light within the profile caused by motions of the stellar surface or due to regular shadowing of the surface by circumstellar material. In the latter case, any shadowing leads to an apparent emission feature within the absorption profile with an accompanying, predictable photometric deficit. Vogt and Penrod (1983) demonstrated that the line profile variations (lpv) of ζ Oph could be explained by nonradial pulsations (NRP) and the star's rotation. They examined the possibility of shadowing by spokes and concluded that although they could indeed generate the ripples seen in the profiles but there was no matching photometric modulation. They also pointed out that the pulsation energy of the NRP in ζ Oph is sufficiently large to drive mass-loss by generating shock waves (see also Kambe et al. (1993) and Reid et al. (1993)).
Several campaigns have been organised to monitor the lpv of ζ Oph (e.g. Kambe et al. (1993), Reid et al. (1993), Kambe et al. (1997)). To determine periodicities, residuals are generated for each observed profile by subtracting a mean profile from the whole observing run. A temporal sinusoid is fitted at each wavelength which then defined a frequency and phase for each point in the profile. This analysis demonstrated in each campaign that the lpv were multiperiodic and could be reconciled with travelling sectorial modes of high degree. One frequency, 7.862 c d^{-1} (3.339 hr), was detected in all of the campaigns.
Being bright, ζ Oph is awkward photometrically and, although obviously variable, no consistent period has ever been found from the ground. Balona & Kambe (1999) sumarised the extensive photometric observations up to 1993. The only convincing periodicities were several close to 5.18 c d^{-1} seen in 1985 but not in subsequent years.
Although NRP is now the generally accepted explanation for the lpv, Harmanec (1999) pointed out that shadowing is still a viable option because dilution of the photometric signal by several simultaneously visible spokes could reduce the net variation to less than the available photometric precision ~ $0.^{m}007$. He has also drawn attention to the presence of a super, or comensurable, period of ~0.64 d associated with the various lpv periods which could be either the revolution rate of the spokes or the rotation rate of the star and for which Harmanec (1999) found evidence in Hipparcos satellite observations.
The absence of any robust photometric variability has made it difficult to test possible NRP or shadowing models. The periodicities found from lpv are typical of high degree modes but the technique is less sensitive to those of low degree and not at all to radial modes. Photometric observations of sufficient precision would complement the spectroscopic results by revealing low order and radial modes.

3 Observations

Thus, ζ Oph was proposed as an early target of the *Microvariability and Oscillations of Stars* (MOST) photometric satellite. The MOST satellite was launched into a 101.4 minute polar Sun-synchronous orbit (altitude 820 km) on June 2003 which allows it to stare continuously for weeks at stars within a zodiacal band some $54°$ wide. The instrument is fully described by Walker et al. (2003) and the first scientific results have been published by Matthews et al. (2004) and Rucinski et al. (2004). A 15/17.3 cm Rumak-Maksutov telescope feeds a Fabry image of the bright target star onto a CCD through a single broadband filter (350 – 700 nm). The experiment was designed to detect photometric variations with periods of minutes at micro-magnitude precision and does not rely on the use of comparison stars or flat-fielding for stabilty. Subsequent to commissioning and observation of the first science targets, tracking jitter was reduced to ~1 arcsec. MOST observed ζ Oph from 2004 May 19 to June 11, inclusive. Individual exposures were 1 sec with an exposure taken every 10 sec.
A ground-based spectroscopic campaign was undertaken to coincide with the MOST observations. McKellar 1.2-m telescope of Dominion Astrophysical Observatory at Victoria, 1.5-m telescope at Gunma Astronomical Observatory and 2.0-m telescope at Ondřejov Observatory were used during the campaign. Altogether 17 nights of observations were acquired while MOST was on target. The instrumentation provided different dispersion and wavelength coverage (classical coudé spectrographs at DAO and Ondřejov restricted to Hβ and He I λ4922 lines and échelle spectra at GAO covering the 4100 – 5300 Å range). An example of spectra taken almost continuously from all three stations over the period of 25 hours is presented in Fig. 1.

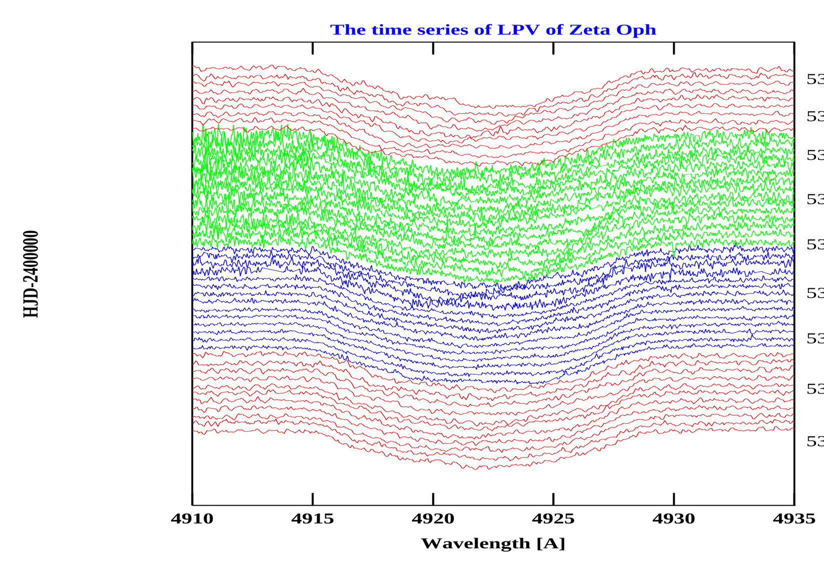

Fig. 1. An example of continuous HeI line observation. Data from Ondřejov is coloured red, data from DAO blue and GAO data green.

First results of the MOST campaign ζ Oph together with ground-based photometry and spectroscopy can be found in Walker et al. (2005). Fourteen independent frequencies were detected in MOST photometry and and eight of them in spectroscopic data.

4 Analysis of Data

Here we present results of the analysis of He I λ4922 line obtained at Ondřejov, Victoria and Gunma. We used a FORTRAN code HEC26 which measures local RV's at specified line depths. The procedure was described in Harmanec (1999) and successfully applied for analysis of 60 Cyg (Koubský et al., 2000).
18 levels were defined corresponding to depths from .995 to .950 of the continuum on each profile. The local RV's on both wings of the profile were interpolated for the pre-determined line intensities. In order to supress the noise, a certain number of points on the profile was used to derive the velocity(lambda) position. The number of points was determined according to the original dispersion of the spectra (16 GAO, 10 DAO and 7 OND).
The input spectra were in form of the table wavelength versus relative intensity. These tables were generated from the normalised spectra by code SPEFO used in an usual way as discribed e.g. by Koubský et al. (2000).

5 Normalization of Echelle Spectra

A serious problem presented the normalization of high resolution echelle spectra from GAO. The usual methods to remove the shape of echelle blaze are the fitting the smooth polynomial function through the segments of apparent continuum in every echelle order or the division by flat-field exposure. The errors introduced by these methods are, however, much larger than a size of expected variations (Škoda & Šlechta, 2004).
That is why we have developed a new unblazing method using only information from neigbouring echelle orders of the same stellar frame. We predict the shape of blaze function in echelle order contaminated by wide stellar line from the shape of the nearest line-free orders. We suppose the ratio of blaze functions in two succesive orders is the same in the sufficiently large range of orders arround the one with the stellar line under study.

6 Results

The results of the period analysis of all 18 time series for about 350 spectra obtained during the MOST campaign are presented in Fig. 2. When comparing it with the results of MOST photometry — Fig. 3, we see some differencies. First, the dominant frequency in photometry — 5.1806 c.d^{-1} — is not dominating the spectral data. Second, the best frequency for spectra – 7.1921 c.d^{-1} is not very outstanding in the photometry spectrum.

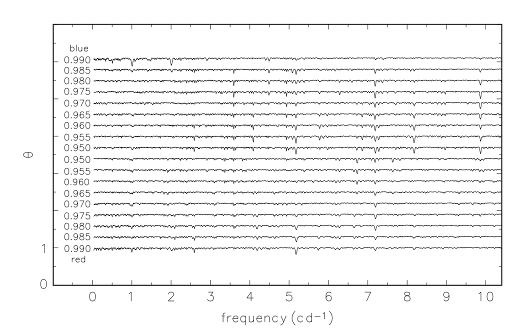

Fig. 2. Frequency analysis of local RV derived for the profiles of He I λ4922 line. Values for the 2 x 9 line depths are given on the left side.

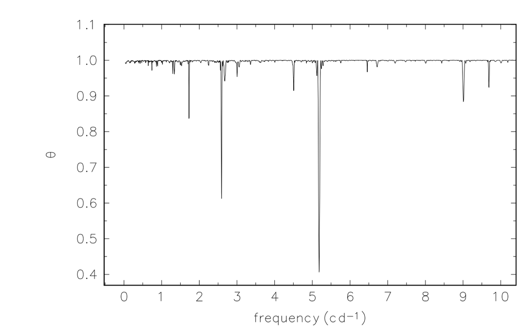

Fig. 3. Frequency analysis of the photometric data for ζ Oph obtained by the MOST satellite.

Third, in some cases frequency peaks are detected only at some levels determining the the local RV's. This pertains frequencies 5.1806 c.d^{-1}, 9.8614 c.d^{-1} and 8.18 c.d^{-1} (not detected in photometry) – seen mostly on the blue wing. Thus, bisector radial velocities of points on both blue and red wing could be derived for the frequency 7.1921 c.d^{-1} only. The phase diagram is presented in Fig. 4. The frequency analysis of the O-C to fit of Fig.4 resulted in best frequency corresponding to period of 0.98508 day, which is close to the value of rotational period derived by Balona & Kambe (1999) (Fig. 5).

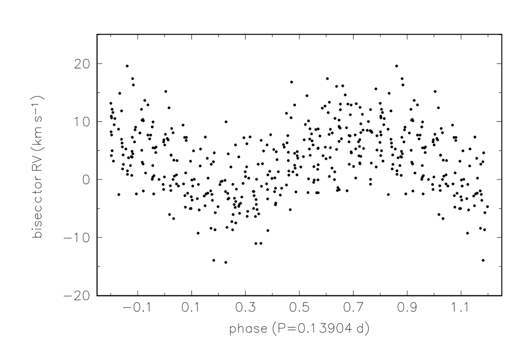

Fig. 4. Bisector radial velocities derived for the He I λ4922 line folded with a period P=0.13904 d, corresponding to frequency 7.1921 c.d^{-1}

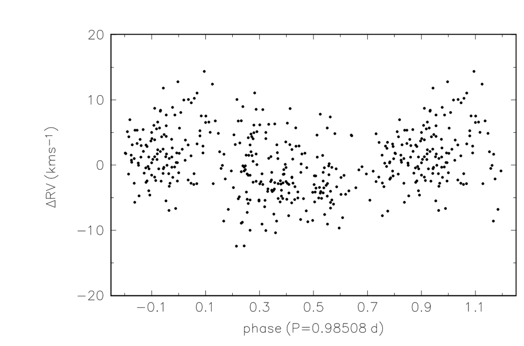

Fig. 5. O-C data after removing the period given in Fig.4 folded with the best frequency found. It corresponds to the period of 0.98508 d, close to the estimated rotational period of ζ Oph.

7 Acknowledgements

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