Spectroscopic and photometric variability of the O9.5 Vp star HD 93521

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ABSTRACT

Aims. The line profile variability and photometric variability of the O9.5 Vp star HD 93521 are examined in order to establish the properties of the non-radial pulsations in this star.

Methods. Fourier techniques are used to characterize the modulations of the He I λ5876, 6678 and Hα lines in several spectroscopic time series and to search for variations in a photometric time series.

Results. Our spectroscopic data confirm the existence of two periods of 1.75 and 2.89 hr. The line profiles, especially those affected by emission wings, exhibit also modulations on longer time scales, but these are epoch-dependent and change from line to line. Unlike previous claims, we find no unambiguous signature of the rotational period in our data, nor of a third pulsation period (corresponding to a frequency of 2.66 d⁻¹).

Conclusions. HD 93521 very likely exhibits non-radial pulsations with periods of 1.75 and 2.89 hr with l = 8 ± 1 and l = 4 ± 1 respectively. No significant signal is found in the first harmonics of these two periods. The 2.89 hr mode is seen at all epochs and in all lines investigated, while the visibility of the 1.75 hr mode is clearly epoch dependent. Whilst light variations are detected, their connection to these periodicities is not straightforward.

Key words. Stars: early-type – Stars: individual: HD 93521 – Stars: oscillations – Stars: variables: other – Stars: fundamental parameters

1. Introduction

Time resolved spectroscopy of O-type stars has shown that absorption line profile variability at the level of a few per cent is a common feature (e.g. Fullerton et al. 1996). Various mechanisms, including magnetic fields, stochastic structures at the base of the wind and non-radial pulsations have been proposed to explain this variability. Despite their rather subtle signature, the diagnostic potential of these phenomena is considerable. Especially in the case of non-radial pulsations, the emerging discipline of asteroseismology offers the possibility to gain insight into the interiors of early-type stars. However, to characterize the nature of the phenomenon requires a rather long and well sampled time series of spectra with a high resolution and a high S/N (see e.g. Aerts et al. 2004 for the case of the β Cephei variable ν Eri). Up to now, such detailed studies have therefore been restricted to a few, rather bright and well-known O-stars such as ζ Pup (Baade et al. 1991) and ζ Oph (Kambe et al. 1997).

In this context, the high Galactic latitude O-star HD 93521 (l⊙ = 183.14°, b⊙ = 62.15°) is an extremely interesting target.

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* Based on observations collected at the Observatoire de Haute Provence (France), the Flemish 1.2 m Mercator telescope at the Roque de los Muchachos observatory (La Palma, Spain) and the Observatorio Astronómico Nacional de San Pedro Mártir (Mexico).
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Based on optical spectroscopy, Fullerton et al. (1991) and Howarth & Reid (1993) found HD 93521 to exhibit bumps at the 1% level moving from blue to red across the profiles of the He i lines, whilst no variability was detected in the He ii lines. Fullerton et al. (1991) as well as Howarth & Reid (1993) accordingly interpreted these features as the signature of non-radial pulsations with a period of 1.8 hours. The He i – He ii dichotomy was interpreted as arising from the substantial gravity darkening that favours He i line formation near the cooler equatorial regions where the pulsational amplitude attains a maximum (Townsend 1997). The existence of non-radial pulsations was subsequently confirmed by Howarth et al. (1998) using IUE spectra and three different periods were identified. Recently, Rzavek & Panchuk (2005) reported on the existence of slightly different variability patterns between the strong and weak He i lines. However, since the Rzavek & Panchuk (2005) data set covered only 2.7 hours, it yields hardly any constraint on the properties of the pulsations.

HD 93521 has one of the largest rotational velocities known among O-stars (341 km s⁻¹, Penny 1996; 432 km s⁻¹, Howarth et al. 1997; 390 km s⁻¹, see below in this paper). The stellar wind has an apparently low terminal velocity and is likely heavily distorted by rotation (e.g. Bjorkman et al. 1994). In the optical, the wind produces emission features in the wings of the Hα line, although this line has so far never been reported as a pure emission feature.

While the optical spectrum of HD 93521 leads to an O9.5 V classification, the nature of this star has been subject to debate over many years. In fact, assuming a typical absolute magnitude...
Table 1. Summary of our observing runs (see text for the meaning of the different columns). The green and red wavelength ranges stand respectively for 5500 – 5920 and 6530 – 6710 Å, whilst SPM stands for the echelle spectra taken at San Pedro Mártir. The last column yields the mean signal-to-noise ratio of the spectra gathered during the corresponding campaign. The last line refers to the photometric monitoring campaign that took place in coordination with the April 2005 spectroscopic campaign.

| Epoch       | Domain | ΔT (days) | N  | Δνmax (d⁻¹) | νmax (d⁻¹) | S/N |
|-------------|--------|-----------|----|-------------|------------|-----|
| February 1997 | red    | 4.155     | 35 | 2.49 × 10⁻² | 0.241      | 20.1 | 165 |
| April 2005   | red    | 3.809     | 55 | 1.72 × 10⁻² | 0.263      | 29.1 | 280 |
| April 2005   | SPM    | 5.096     | 90 | 0.84 × 10⁻² | 0.196      | 59.6 | 250 |
| February 2006 | green  | 6.173     | 75 | 1.60 × 10⁻² | 0.162      | 31.3 | 650 |
| April 2006   | green  | 0.180     | 13 | 1.49 × 10⁻² | 5.55       | 33.5 | 580 |
| April 2007   | green  | 6.191     | 56 | 1.46 × 10⁻² | 0.162      | 34.2 | 550 |
| April 2005   | U B B₁ V V₁ G | 28.221 | 378 | 0.31 × 10⁻² | 0.035     | 161.3 |}

Fig. 1. Average spectrum (top) and temporal variance spectrum (TVS, bottom) computed from the green, red and SPM spectra taken in February + April 2006 (left panel), April 2005 (middle) and April 2005 (right) respectively. The dotted lines yield the 99% significance level for the variability evaluated following the approach of Fullerton et al. (1996).

In this paper, we present the results of a spectroscopic and photometric monitoring campaign of HD 93521. The aim of this project was to check the long-term stability of the periodicities identified in previous investigations.

2. Observations

2.1. Spectroscopy

We observed HD 93521 during five observing campaigns (in February 1997, April 2005, February and April 2006 as well as April 2007) with the Auriéle spectrograph at the 1.52 m telescope of the Observatoire de Haute Provence (OHP). The 1997 and 2005 data were taken with a 1200 lines/mm grating blazed at 5000 Å and covered the wavelength domain from 6530 to 6710 Å with a resolving power of R ≃ 21000. The 2006 and 2007 data were obtained with a 600 lines/mm grating also blazed at 5000 Å and covering this time the region between 5500 and 5920 Å with R ≃ 10000. In 1997, the detector was a Thomson TH7832 linear array with 2048 pixels of 13 μm each, whilst later observations used an EEV 42-20 CCD with 2048 × 1024 pixels. All the OHP data were reduced in the standard way (see Rauw et al. 2003) using the MIDAS software provided by ESO. To correct the observed spectra to first order for telluric (mainly water vapor) absorption lines, a template of the telluric spectrum was built from observations of a bright star at very different airmasses (usually around 1.2 and 3.0). The stars used for this purpose were γ Ori (B3 V) and HD 100889 (B9.5 Vn) in February 1997, HD 177724 for a Population I O9.5 V star, HD 93521 is located about 1.4 kpc above the Galactic plane (Irvine 1989), far away from any site of recent massive star formation. While there is still some uncertainty concerning the motion of the star (towards or away from the Galactic plane, see Gies 1987), it seems unlikely that HD 93521 could have formed in the plane and subsequently moved to its current position. Furthermore, based on the rather low stellar wind terminal velocity of HD 93521 and assuming that \( v_{\infty} = 3 \times v_{esc} \), Ebbets & Savage (1982) concluded that this star was likely a low-mass evolved Population II object. However, Irvine (1989) showed that the relation between \( v_{\infty} \) and \( v_{esc} \) does not hold for late O-type stars such as HD 93521 and he proposed that the star is in fact a normal main sequence star that has formed in the Galactic halo (another example of a massive star born in the halo can be found in Heber et al. [1995]). Lennon et al. (1991) measured the equivalent widths (EWs) of several metal lines in the spectrum of HD 93521. Though these lines are washed out by rotational broadening and the EWs are affected by large uncertainties, their strengths are inconsistent with Population II metal abundances. Finally, Massa (1995) showed that the other peculiar features of this star (its unusually low UV continuum, its abnormally strong wind lines in the UV, its low excitation photospheric lines) can all be accounted for by the effect of gravity darkening in a ‘normal’ Population I star rotating at 90% of its breakup velocity and seen nearly equator on.
(A0 Vn) in April 2005 and Regulus (α Leo. B7 V) in February 2006. Finally, the spectra were normalized using properly chosen continuum windows. Special care was taken to ensure that all the data were normalized in a homogeneous way to allow a self-consistent search for variability.

In April 2005, we gathered a series of 90 spectra with the echelle spectrograph mounted on the 2.1 m telescope at the Observatorio Astronómico Nacional of San Pedro Mártir (SPM) in Mexico. The instrument covers the spectral domain between about 3800 and 6800 Å with a resolving power of 18000 at 5000 Å. The detector was a SITe CCD with 1024 × 1024 pixels of 24 μm². The data were reduced using the echelle context of the MIDAS software and specific orders covering several important lines (He i λ λ 4471, 5876, Hβ and He λ) were normalized using a set of selected continuum windows. Unfortunately, the He i λ 6678 line could not be studied because it fell too close to the edge of an order.

A summary of the main characteristics of our various data sets is provided in Table 1. For each run, ΔT gives the time elapsed between our first and our last observation, while N is the total number of observations. ΔT is the average time interval between two consecutive exposures during the same night. In light of the Fourier analysis in Section 3.2, we further list the typical FWHM of a peak in the power spectrum Δν max = 1/ΔT, as well as ν max = 1/(2 ΔT) which provides a rough indication of the highest frequencies that could be sampled with our time series.

During the April 2006 campaign, HD 93521 was also observed in the near-infrared with the Aurélie spectrograph. The data were obtained with a 300 lines/mm grating blazed at 6000 Å and covering the region between 8055 and 8965 Å with R ≈ 6500. Whilst the individual spectra in this wavelength domain do not have a sufficient quality to perform a meaningful variability analysis, we present the mean spectrum over the useful band from 8420 to 8900 Å in Fig. 2. The spectrum is largely dominated by broad and shallow hydrogen absorption lines of the Paschen series (from Pa i11 to at least Pa i16) with some modest contributions from He i and possibly He ii, C iii and N iii lines. The RVs instrument onboard ESA’s forthcoming astrometry mission GAIA will cover a sub-domain (from 8470 – 8740 Å) of the band shown in Fig. 2 with a resolving power twice as large as that of our data to measure among other things the radial and rotational velocities. Our spectrum indicates that the only prominent features in the RVs spectra of rapidly rotating late O-type dwarfs are the Paschen lines.

2.2. Photometry

Time resolved photometry of HD 93521 through the (U B V) Geneva filter system (see e.g. Rufener [1981] Bessell [2005]) was obtained with the Mercator telescope in April 2005. Mercator is a 1.2 m semi-robotic telescope, situated at Roque de los Muchachos (La Palma Island, Spain). The telescope is equipped with the P7 photometer, which is a two channel photometer for quasi simultaneous 7 band measurements. The first channel (A) is centered on the star while the second channel (B) is centered on the sky. The position angle of the sky can be changed by turning the derotator while changing the distance between both channels needs manual interaction. The filter wheel turns at 4 Hz and a chopper directs both channels alternatively to the photomultiplier. As such, the photomultiplier measures both beams A and B through the seven filters four times each second.

The strategy for performing the observations is oriented towards obtaining high-precision photometry. In order to achieve this, we measure stars within a range of 0.1 in air-mass F z for nights of good atmospheric conditions. It is advantageous to measure a variable star with a period of the order of hours frequently each night, so we have opted for the interval F z ∈ [1.05; 1.15] to measure HD 93521. For the reduction process of such a type of observing night, typically 2–3 standard stars of different colour are observed each hour. The determination of the extinction coefficients was done according to the method outlined in Burki et al. (1995) and results in measurements with a typical accuracy of a few mmag for the colours of stars with visual magnitude between 5 and 10. A total of 378 data points were gathered between 29 March and 27 April (UT dates). In our analysis we have restricted ourselves to those 315 data points that have weights of 3 or 4 (for good or exceptional quality measurements) respectively, see Rufener (1981). Nights with these quality weights are characterized by standard deviations on the measurements of standard stars of less than 0.005 mag.

3. Results

3.1. Spectroscopy

The average spectra of the star over the wavelength domains investigated here are shown in Fig. 1. Besides a few diffuse interstellar bands (DIBs), identified following the catalogue of interstellar features from Herbig (1995), we note the broad absorption lines as well as the emission components of Hα and He i λ 5876. Note that the He i lines appear relatively strong compared to the Hα line. This can be understood in view of the helium overabundance (γ = 0.18 ± 0.03) reported by Lennon et al. (1991) and Howarth & Smith (2001).

In addition to the O iii λ 5592, C iv λ 5801, 5812 and He i λ 5876 absorptions that are typical for an O-type star, the spectrum in the region between 5500 and 5900 Å also reveals several unusual features, such as the N iii λ 5667, 5767, 5680 blend and the Si iii λ 5740 line. These lines are strong in the spectra of early B supergiants, but are usually absent from O-star spectra (see Walborn 1980). The same remark applies to the feature near the red emission wing of Hα that we identify as C iii λ 6578, 6583 which are clearly seen in the spectra of early B-type stars. These particularities are reminiscent of the description of the IUE spectrum of the star given by Massa (1995) and thus likely reflect the strong temperature gradient that exists at the stellar surface as a result of gravity darkening. According to Massa (1995), the polar region has a temperature close to that of an O7 star, whilst the

![Fig. 2. Mean spectrum of HD 93521 over the 8420 – 8900 Å wavelength domain. The ions responsible for the lines (either stellar, or telluric in the case of the OH emissions) are indicated above the spectrum, whilst the diffuse interstellar bands (DIBs) are indicated below.](image-url)
We have determined the star’s projected rotational velocity $v \sin i$ applying the Fourier method (see Gray 2005) to the mean profiles of the He I λ 6678, 6678 and O iii λ 5592 lines. To first order, the structure of the Fourier transforms of these lines can be explained by projected equatorial rotational velocities of 345, 395 and 380 km s$^{-1}$ respectively. While the results for the He I λ 6678 and O iii λ 5592 line are in very reasonable agreement, He I λ 5876 yields a significantly lower value. There are several reasons why the three lines do not yield exactly the same result. First of all, the profile of He I λ 5876 is affected by emission that could fill-in the absorption in the wings of the line, hence leading to an apparently lower $v \sin i$. In addition, although we have used the mean profiles evaluated from a large number of observations, the line profile variability (see below) leaves some residual structure in the profiles. These features lead in turn to a Fourier transform that deviates from the one expected for a pure rotational broadening. The cleanest result is obtained for the He I λ 6678 line (see Fig. 3). In summary, we conclude that the projected equatorial rotational velocity of the star is most likely 390 ± 10 km s$^{-1}$. There is a caveat here: our determination of $v \sin i$ likely represents a lower limit to the actual value. Indeed, Townsend et al. (2004) argued that the rotational velocities of very rapidly rotating Be-type stars might be systematically underestimated as a result of the effect of gravity darkening that would reduce the weight of the equatorial region (and hence of the highest rotational velocities) in the formation of the absorption line profiles. For B0 stars, Townsend et al. find that the He I λ 4471 and Mg II λ 4481 lines underestimate $v \sin i$ by about 10%. A similar underestimate could hold in our case.

![Fig. 3. Determination of the rotational velocity of HD 93521 using the Fourier technique. The top panel illustrates the mean profile of the He I λ 6678 line as observed in April 2005. The lower panel illustrates the resulting Fourier transform along with the Fourier transform $G(\sigma)$ of a rotational broadening function (see Gray 2005) evaluated for $v \sin i = 395$ km s$^{-1}$.](image-url)

To quantify the variability of the spectral lines, we have computed the temporal variance spectrum (TVS, Fullerton et al. [1996]) for the data of each observing campaign. The TVS diagrams of the spectral regions investigated here reveal no significant variability in the metallic lines, except perhaps for some marginal variations in the region between 5660 and 5810 Å. The significant variability is restricted to the He I λ 4471, Hβ, He I λ 5876, Hα and He I λ 6678 lines. The majority of these lines (except perhaps the Hβ line, see Fig. 3) exhibit evidence for emission wings.

### 3.2. Fourier analysis

For each of the variable lines, we have performed a 2-D Fourier analysis (see e.g. Rauw et al. [2001], 2003) where the Fourier power spectrum is calculated at each wavelength step across the line profile using the technique of Heck et al. (1985) revised by Gosset et al. (2001). This algorithm is specifically designed to handle time series with an uneven sampling. The periodograms were calculated for each line and for each campaign up to a maximum frequency of 30 d$^{-1}$.

For the frequencies that are identified from the periodograms, we have further applied the different techniques outlined in Rauw et al. (2001). For each line and for each observing campaign, we have fitted an expression of the type

$$I(\lambda, t) = I_0(\lambda) + \sum_{i=1}^q A_i(\lambda) \sin [2 \pi v_i t + \phi_i(\lambda)]$$

(1)

to the time series. Here $I(\lambda, t)$ is the line intensity at wavelength $\lambda$ and at time $t$, $v_i$ are the frequencies corresponding to the highest peaks in the periodogram, whilst $A_i(\lambda)$ and $\phi_i(\lambda)$ are respectively the semiamplitudes and the phases for these frequencies as a function of wavelength (see Rauw et al. 2001). The number $q$ of frequencies that were simultaneously fitted was progressively increased from 1 up to 3. This method not only allows us to characterize the properties of a given frequency, but further enables us to ‘prewhiten’ the data by removing the modulation at this frequency from the time series and re-compute the periodogram for the ‘prewhitened’ data set. We start by removing the highest peak frequency found in the periodogram of the original data set. Next, we identify the highest frequency in the periodogram of the new (prewhitened) time series and prewhiten then the data simultaneously for the two frequencies. The procedure is repeated for up to three different frequencies. Indeed, three frequencies are usually sufficient to reduce the residual amplitude in the prewhitened Fourier power spectra to a level compatible with the noise level of the data.

To evaluate the error bars on the semiamplitudes and phases of the various Fourier components, we have used Monte Carlo

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1. Macro turbulence also affects the shape of the Fourier transform, but this is mainly an issue for very slow rotators which is not the case of HD 93521.

2. These techniques are especially useful if the line profile variations are interpreted in terms of non-radial pulsations. Indeed, in this case, Telting & Schrijvers (1999) and Schrijvers & Telting (1999) have shown that the observable phase differences between the blue and red line wings can be related directly to the degree $l$ and to the absolute value of the azimuthal order $|m|$ of the pulsation mode.

3. We caution that some of the low frequencies identified throughout this work likely correspond to long-term trends rather than to actual periods.
The power spectrum calculated from the February 1997 time series of this line reveals its highest peak at 0.54 d\(^{-1}\) (see Fig. 4). Beside this low frequency peak, the periodogram exhibits a family of aliases associated with 7.30 d\(^{-1}\). In the raw periodogram, the one-day alias at 6.30 d\(^{-1}\) is stronger than the one at 8.29 d\(^{-1}\). However, this situation changes when the data are prewhitened for the 0.54 d\(^{-1}\) modulation with the 8.29 d\(^{-1}\) peak becoming stronger than the one at 6.30 d\(^{-1}\).
7.30 d\(^{-1}\) frequency is an alias of the \(v_2 = 8.28\) d\(^{-1}\) frequency reported by Howarth et al. (1998). We have prewhitened the data using either the 7.30 d\(^{-1}\) or the 8.29 d\(^{-1}\) frequencies. Due to the strong level of the noise ‘continuum’ in the February 1997 periodogram, the prewhitening procedure does not result in a clean periodogram. Still, the results obtained when prewhitening either of the alias frequencies are the same within the level of the noise in the periodogram. Both candidate frequencies display a progression of the phase constant \(\phi\) from the blue wing to the red wing. This progression is not fully monotonic (at least partially because of the noise level of the data). Nevertheless, assuming \(v_c \sin \iota = 395\) km s\(^{-1}\), we find that the blue – red phase difference \(\Delta \phi\) amounts to about 3 \(\pi\) radians, irrespective of the choice of the alias. However, we stress that the amplitude associated with \(v_2\) is largest over the radial velocity interval \(-350\) to \(+100\) km s\(^{-1}\): there is almost no significant signal outside this velocity domain (i.e. between \(+100\) km s\(^{-1}\) and \(+v_c \sin \iota\)).

![Fig. 6. The top panel yields the mean normalized He\( \lambda \) 6678 line profile as observed in April 2005 shown as a continuous line, as well as the mean profile after prewhitening (i.e. the \(I_0(\lambda)\) term in Eq. 1) shown by a dashed line. The next panels (from top to bottom) yield the semiamplitudes (in units of the continuum level) of the \(v_1\) (dots, second panel) and \(v_2\) (crosses, third panel) modulations, the phase constant \(\phi_1\) of the \(v_1\) signal and the phase constant \(\phi_2\) of the \(v_2\) component. The error bars were obtained from Monte Carlo simulations (see text). Phase 0.0 was arbitrarily set to the time of the first observation of this data set.](image)

The power spectrum of the April 2005 data looks completely different (Fig. 4). The periodogram is now dominated by a strong peak at \(v_1 = 13.68\) d\(^{-1}\) along with its one-day aliases. When the data are prewhitened for the \(v_1\) frequency, another family of aliases associated with \(v_2 = 8.31\) d\(^{-1}\) becomes dominant. Again, the mean power spectrum, averaged between 6660 and 6700 Å, reveals some power also at lower frequencies (near 0.25 d\(^{-1}\)), though the 2-D power spectrum indicates that this latter feature is mainly restricted to a narrow range of wavelengths in the line wings and mostly in the blue wing near 6671 Å (see Fig. 5).

Although the power spectrum reveals some structure near 26 d\(^{-1}\), the frequency of the strongest peak in this region (25.8 d\(^{-1}\)) is quite different from \(2 \times v_1 = 27.36\) d\(^{-1}\) and it seems therefore unlikely that this feature is related to the first harmonic of \(v_1\). The periods corresponding to \(v_1\) and \(v_2\) are respectively 1.75 and 2.89 hr, in excellent agreement with the periods \(P_1 = 1.76 \pm 0.04\) hr, \(P_2 = 2.90 \pm 0.12\) hr) reported by Howarth et al. (1998).

Figure 6 illustrates the mean line profile as observed in April 2005, as well as the semiamplitudes and phases of the two dominant frequencies (\(v_1\) and \(v_2\)) during this campaign. Again, we note the diagonal progression of the phase constant as a function of wavelength which is typical of non-radial pulsations. From Fig. 5 we infer a blue to red phase difference of \(\Delta \phi_1 = 7\pi\) and \(\Delta \phi_2 \approx 3.5\pi\) for the \(v_1\) and \(v_2\) frequencies respectively, although for \(v_2\), the progression of the phase constant is not strictly monotonic across the line profile.

3.2.2. He\( \alpha\) and H\( \beta\)

The power spectrum of the February 1997 H\( \alpha\) data shows the highest peak at 0.30 d\(^{-1}\) and its one-day alias at 0.70 d\(^{-1}\). A group of secondary peaks is found at 6.94 d\(^{-1}\) and its aliases. We further detect some weaker peaks at 6.26 d\(^{-1}\) (alias of \(v_2\)) as well as its aliases. The power spectrum is rather well cleaned by prewhitening these three frequencies (see Fig. 7). The low frequency variation corresponds to a global modulation of the line intensity in the core (radial velocity interval from \(-100\) to \(+100\) km s\(^{-1}\)) with a rather constant phase. Since the 6.26 d\(^{-1}\) frequency is an alias of \(v_2\), we have also prewhitened the data using 0.30, 6.94 and 8.28 d\(^{-1}\). For the latter frequency, we observe again a blue to red phase difference of about 3 \(\pi\) (within the uncertainties). However, as for He\( \lambda \) 6678, the amplitude of this modulation is really significant only in the blue wing of the line.

In the April 2005 OHP H\( \alpha\) data, the highest peak of the power spectrum occurs at 0.15 d\(^{-1}\) and its aliases (1.18 and 0.78 d\(^{-1}\)). Prewithening either of these frequencies yields a set of secondary peaks near 1.67 and 3.09 d\(^{-1}\). If these frequencies are removed in turn, the power spectrum of the residual data set displays some low amplitude peaks at 8.32 and 13.14 d\(^{-1}\) (note that while the former frequency is likely equal to \(v_2\), the latter one is formally not consistent with \(v_1\)).

The April 2005 SPM echelle spectra yield a similar picture: the bulk of the power of the H\( \alpha\) variations is again concentrated in variations that occur on low-frequency timescales (1.09 and 1.32 d\(^{-1}\), which are also found for the He\( \lambda \) 5876 line in the same data set) and affect mainly the wings of the line. Prewithening the data for these two frequencies yields a highest peak at 2.51 d\(^{-1}\) as well as a series of aliases of \(v_1 + 1\) and \(v_2 + 1\). For H\( \beta\), the SPM data reveal the strongest peaks at 0.01 and 0.44 d\(^{-1}\). Both, \(v_2\) and \(v_1\) are clearly detected though and the blue to red phase differences are about 3 \(\pi\) and 7 \(\pi\), though it should be stressed here that the evolution of the phase constants is not monotonic in the case of this line.
Fig. 7. Same as Fig. 4 but for the Hα line: February 1997 (left) and OHP April 2005 (right). The power spectra are averaged over the wavelength domain from 6540 to 6580 Å. The frequencies used for prewhitening are 0.30, 6.94 and 6.26 d\(^{-1}\) for the February 1997 data and 1.18, 3.09 and 1.67 d\(^{-1}\) for the April 2005 campaign.

3.2.3. He\(\lambda\lambda 5876, 4471\)

The power spectrum of the OHP 2006 data is dominated by low frequencies. When all the OHP data taken in February and April 2006 are analysed together, the highest peak is found at 0.02 d\(^{-1}\) (along with its aliases, Fig. 8). Prewhitening the time series for this frequency and its first harmonics, yields however some artefacts in the mean line profile (\(I_0(\lambda)\) in Eq. 1). Hence, we rather used the 1-day alias 1.10 d\(^{-1}\). When we prewhiten the data for the latter frequency, the highest peaks in the new periodogram are found at 12.63 and 8.26 d\(^{-1}\) (\(\nu_2\)). The former frequency is likely an alias of \(\nu_1\). Prewhitening the frequencies 1.10, 8.26 and 13.60 d\(^{-1}\), we find that the blue to red phase difference amounts to 6 \(\pi\) for \(\nu_1\) (for 12.63 d\(^{-1}\), this becomes \(\approx 7 \pi\)). For \(\nu_2\) we find a phase difference of about 3.5 \(\pi\) with the caveat that the phase progression is apparently not monotonic for this frequency (see Fig. 8). These results are largely confirmed by the analysis of the He\(\lambda 5876\) line in the April 2005 SPM time series. Whilst the variations in the wings of the line are dominated by two low frequencies at 1.08 and 1.30 d\(^{-1}\), \(\nu_1\) (or its alias at 12.59 d\(^{-1}\)) as well as \(\nu_2\) are detected with a roughly constant amplitude over the entire width of the line profile and the blue to red phase differences amount to \(\approx 7 \pi\) and \(\approx 4.5 \pi\) for \(\nu_1\) and \(\nu_2\) respectively.

The SPM echelle spectra also cover the He\(\lambda 4471\) line. The frequency content of the power spectrum of the latter essentially confirms the results obtained for the He\(\lambda 5876\) line: a dominant peak at 0.08 d\(^{-1}\) (alias of the 1.08 d\(^{-1}\) peak reported above), as well as two pulsation signals found at \(\nu_1\) as well as \(\nu_2 - 1\). The main difference with the above results concerns the blue to red phase differences which, in the case of the He\(\lambda 4471\) line, amount to \(\approx 5.8 \pi\) and \(\approx 3 \pi\) for \(\nu_1\) and \(\nu_2 - 1\) respectively.

A similar description applies also to the April 2007 periodogram of the He\(\lambda 5876\) time series. Indeed, the highest peak is again found at low frequencies, 1.06 d\(^{-1}\) (along with its aliases, Fig. 9). Prewhitening the time series for this frequency yields secondary peaks at 8.25 (\(\nu_2\)) and 14.61 d\(^{-1}\) (likely the \(\nu_1 + 1\) alias). Prewhitening the frequencies 1.06, 8.25 and 14.61 d\(^{-1}\), we find that the blue to red phase difference amounts to 6.5 \(\pi\) for the 14.61 d\(^{-1}\) frequency (the same result holds if we adopt \(\nu_1\) instead). For \(\nu_2\) we find a phase difference of about 4 \(\pi\) (see Fig. 9).

3.3. Photometry

We have analysed the time series of HD 93521 in each of the seven filters of the Geneva system using the Fourier method of Heck et al. (1985). For each filter, we find that the periodogram indicates significant power at frequencies below about 10 d\(^{-1}\). In all cases, we find that the power spectrum can efficiently be prewhitened with three frequencies (see e.g. Fig. 10). Some frequencies are found consistently in several filters though with different amplitudes. This is the case for 7.90 d\(^{-1}\) (found in six filters out of seven), 0.88 d\(^{-1}\) (detected in four filters) and 2.00 d\(^{-1}\) (detected in three filters). None of the frequencies reported here is observed in the April 2005 spectroscopic time series that was obtained in coordination with the photometric campaign.

The \(U\) photometry yields somewhat different results from most other filters: the variations are clearly dominated by the 2.00 d\(^{-1}\) frequency, while in most other filters the various frequencies appear with similar amplitudes. At first sight, this might seem surprising because, for OB stars, the signatures of non-radial pulsations are usually expected to be quite strong in the \(U\) filter (De Cat et al. 2007). We caution that frequencies close to an integer number of d\(^{-1}\) (such as the 2.00 d\(^{-1}\) frequency) could actually be artefacts due to the interplay between the sampling of our time series and a few deviating data points.

In this respect, we emphasize that the \(U\) filter is most heavily affected by atmospheric absorption and therefore, the 2.00 d\(^{-1}\) signal could be related to imperfect extinction corrections, at least in the \(U\) filter.
Fig. 8. Left: same as Fig. 4 but for the He\textsc{i} \(\lambda 5876\) line as observed in February and April 2006. The power spectra are averaged over the wavelength domain from 5860 to 5900 Å. The frequencies used for prewhitening are 1.10, 12.63 and 8.26 d\(^{-1}\). Right: same as Fig. 6 but for the He\textsc{i} \(\lambda 5876\) line as observed in February and April 2006. The semi-amplitudes and phases of the 1.10, 13.60 and 8.26 d\(^{-1}\) frequencies are shown from top to bottom in the right panel.

Fig. 9. Same as Fig. 8 but for the He\textsc{i} \(\lambda 5876\) line as observed in April 2007. The frequencies used for prewhitening are 1.06, 14.62 and 8.25 d\(^{-1}\).
The icantly brighter than the reference stars. The only exception is reference stars including in the filters where HD 93521 is signific-

measurements of HD 93521 is always larger than those of the two reference stars (HD 90250, K1 III and HD 96951, A1 V) that

dle panel corresponds to the power spectrum of the time se-

Fig. 10. Fourier power spectrum of the $B_1$ data of HD 93521. The top panel yields the raw power spectrum, whilst the middle panel corresponds to the power spectrum of the time series prewhitened for three frequencies (2.04, 6.74 and $8.54 \, d^{-1}$). The lower panel displays the spectral window of the photometric time series.

Table 2 also lists the mean magnitudes and the 1-$\sigma$ standard deviations of the measurements of HD 93521 as well as of two reference stars (HD 90250, K1 III and HD 96951, A1 V) that were observed during the same campaign. The dispersion of the measurements of HD 93521 is always larger than those of the reference stars including in the filters where HD 93521 is signifi-

cantly brighter than the reference stars. The only exception is the $U$ filter where the largest value of $\sigma$ is found for HD 90250, however this star is by far the faintest in the $U$ band. We furt-

her note that the Fourier power spectra of both reference stars are quite different from those of HD 93521 and are essentially consistent with white noise.

In summary, HD 93521 appears to be slightly variable in photometry, though the frequency content of the variations is rather complex and the frequencies found in the photometric time series have very small amplitudes. It is likely that an even longer time series of very accurate photometric measurements (maybe from a space-borne observatory) is needed to disentan-
gle the frequency spectrum.

4. Discussion

4.1. General properties

A summary of the amplitudes of all the frequencies detected in the spectroscopic part of this study is provided in Table 4.

A first conclusion from this table is that the $v_1$ frequency is not always detected: while it clearly dominates in the April 2005 data of the He I $\lambda 6678$ line, it is absent from our February 1997 time series of the same line. Also, this frequency is never de-

tected in the $H_\alpha$ line profile variations. In the He I $\lambda 5876$ and 6678 lines, this frequency is associated with a maximum semi-

amplitude of modulation of 0.004 – 0.006 in units of the con-

tinuum. On the other hand, $v_2$ or its aliases are detected in each line and each observing campaign. The maximum semiam-

plitudes of this mode are 0.003 (He I $\lambda 5876$, 6678 in 2006 and April 2005), 0.006 ($H_\alpha$, February 1997) and 0.008 (He I $\lambda 6678$, February 1997) in units of the continuum.

Another conclusion is the lack of any significant signal at the $v_3 = 2.66 \, d^{-1}$ frequency ($P_3 = 9.0 \pm 1.2 \, hr$) that was reported by Howarth et al. (1998) from their analysis of 103 IUE spectra with a median sampling of 0.60 hr. This frequency is thus appar-

ently absent from our data, except perhaps for the detection of the 2.51 $d^{-1}$ signal in the April 2005 SPM $H_\alpha$ data.

Generally speaking, the (low-level) periodic variations with frequencies $v_1$ and $v_2$ are not the dominant source of line profile variations in any of the lines investigated here (except for the He I $\lambda 6678$ line in April 2005). In the majority of the cases, the most important variations are actually characterized by low frequencies. These low-frequency variations affect both the core of the lines as well as the wings and emission lobes (in the case of the $H_\alpha$ and He I $\lambda 5876$ lines). Apparently, these modulations do not occur with a single stable clock: none of the low frequencies is detected in more than one line and for more than one observing campaign (except perhaps for the frequency around 1.10 $d^{-1}$). It seems thus more appropriate to talk about time scales than periods for these longer term variations. This result casts doubt on a rotational modulation as the origin of the long-term vari-

ations: Howarth & Reid (1993) reported the analysis of 21 optical echelle spectra of HD 93521 acquired over two nights in February 1992. From the variations of the emission wings of the $H_\alpha$ and He I $\lambda 5876$ lines, these authors estimated a rotational period of 35 hr ($v = 0.69 \, d^{-1}$). None of the lines investigated here displays a significant signal at this frequency. The closest detections are found for the 1997 OHP $H_\alpha$ data (the alias of the highest peak at 0.70 $d^{-1}$) and for the same line observed in 2005.
Table 3. Maximum semi-amplitudes (in units of the continuum) of the frequencies detected in the 2-D Fourier analyses of the line profile variability of HD 93521. For each line and each epoch, the amplitudes are given for those frequencies that were detected with a good significance above the noise level.

| ν (d⁻¹) | He I λ4471 | Hβ | He I λ5876 | Hα | He I λ6678 |
|---------|-------------|----|------------|----|------------|
| 14.61   | ~ l + ν₁    |    |            |    | 0.004      |
| 13.68   | ν₁          | 0.007| 0.004      | 0.006| 0.004      |
| 12.63   | ~ ν₁ − 1    |    |            |    | 0.004      |
| 8.31    | ν₂          | 0.005| 0.004      | 0.003| 0.005      |
| 7.30    | ~ ν₂ − 1    | 0.007|            |    | ~ 0.008    |
| 6.94    |              |    |            |    | ~ 0.006    |
| 6.26    | ~ ν₂ − 2    |    |            |    | 0.008      |
| 3.09    |              |    |            | 0.008| 0.008      |
| 1.67    |              | 0.008|            |    | 0.008      |
| 1.30    |              |    |            | 0.008|            |
| 1.08    |              | 0.014| 0.011      |    |            |
| 0.54    |              | 0.006|            |    | ~ 0.020    |
| 0.44    |              |    |            | 0.015|            |
| 0.30    |              |    |            |    |            |
| 0.25    |              |    |            | 0.011| 0.004      |
| 0.15    |              |    |            |    |            |
| 0.08    |              | 0.012|            |    |            |
| 0.02    |              |    |            |    | 0.023      |

4.2. ν₁ and ν₂ as non-radial pulsations

In this section, we assume that the line profile variability at the frequencies ν₁ and ν₂ is due to two different non-radial pulsation modes. For multi-mode pulsations, one expects to observe variability with the genuine pulsation frequencies and their harmonics, as well as with their sums and beat frequencies (see e.g. the case of the O9.5 V star ζ Oph, Kambe et al. [1997], Walker et al. [2005]). In HD 93521, we find no significant signal at the first harmonics of ν₁ and ν₂ nor at the sum or beat frequencies. Schrijvers & Telting [1999] argue that for non-radial pulsations with an amplitude of order 10% of the mean line depth, the absence of a first harmonic is an indication that the line profile variability is mainly due to temperature effects (rather than to the Doppler-redistribution of flux). In HD 93521, the amplitudes of the ν₁ and ν₂ modes in the He I λ6678 line are of order 5 – 10% of the maximum line strength. While these amplitudes might be somewhat low for the harmonics to be detected, we nevertheless note that temperature effects could play a significant role in the line profile variability observed in HD 93521.

Telting & Schrijvers [1997] and Schrijvers & Telting [1999] derived linear formulae relating the observable phase differences between the blue and red line wings to the degree l and the absolute value of the azimuthal order |m| of the pulsation mode. These relations are applicable to non-azonal (m ≠ 0) spheroidal and toroidal modes and are valid also for multi-mode pulsations including those cases where temperature effects dominate over radial velocity effects. The blue-to-red phase difference of the mode yields l, whilst the phase difference for the first harmonic leads to the value of |m| (Telting & Schrijvers [1997]).

For the ν₁ pulsation mode of HD 93521, the phase φ₁(l) is a monotonic function of wavelength (see Figs.6 8 and 9), i.e. there are no huge changes in the slope over the interval where the significant line profile variations are detected. Therefore, this mode is unlikely to be an ‘outlier’ in the sense defined by Telting & Schrijvers [1997] and the relation between l and the blue-to-red phase difference Δφ inferred by the latter authors should thus be applicable to these modes. Applying these relations to the phase differences given in Table 4 yields l values of 8 ± 1 for ν₁ and 4 ± 1 for ν₂.

Howarth & Reid [1993] interpreted the ν₁ modulation as the signature of sectoral mode non-radial pulsations with l = −m ≈ 9. They further inferred a horizontal to radial velocity variation amplitude of k < 0.3. Later on, Howarth et al. [1998] derived l ≈ 10 ± 1 and 6 ± 1 for ν₁ and ν₂ respectively, with m + l ≤ 2. Whilst our values of l are in rough agreement with those of Howarth & Reid [1993] and Howarth et al. [1998], the lack of a significant power in the first harmonics prevents us from deriving the value of |m| from the simple scaling relations for this frequency. We note that the low amplitudes (or actually the upper limits on the amplitude) of the first harmonics compared to those of the genuine frequencies, suggest indeed that |m| is likely close to l (Schrijvers et al. [1997]). However, we stress that in a rapidly rotating early-type star, such as HD 93521, the combined effects of a concentration of the pulsation towards the equator and of a non-uniform temperature distribution due to gravity darkening leads to more complicated amplitudes as a function of wavelength (e.g. Townsend [1997]). A detailed line profile modelling is therefore required to derive the values of m and we defer this to a forthcoming paper.

A priori, the shape of the modes as a function of wavelength (see Figs.6 8 and 9) suggests that the modes have a rather modest ratio between the amplitudes of the horizontal and radial velocity variations (k ≤ 0.5). However, Schrijvers & Telting [1999] showed that the typical double-peaked shape of the amplitude found for velocity-dominated line profile variability with high k values vanishes when temperature

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Note: The text mentions a caution about the relation between l and |m|, noting that it is likely close to l according to Telting & Schrijvers [1997]. However, the authors caution that this ratio could be less significant due to the effects mentioned, such as gravity darkening and rotation.
We have further found several other possible periodicities that could be present in the photometric data. If real, these modulations might correspond to either radial or lower degree non-radial pulsations. Such modes are difficult to detect in rotationally broadened line profiles, but might well produce an observable signature in the photometric data. Walker et al. (2005) reported on MOST photometry of ζ Oph: they found that the light curve is dominated by a 4.633 hr period with a semiamplitude of 7.3 mmag, whilst the other modes have semiamplitudes below 2.25 mmag. These authors suggested that the light variations of ζ Oph mainly result from radial pulsations. In the case of HD 93521, the vast majority of the frequencies detected in the periodogram of the time series have semiamplitudes that are significantly lower than what was found in the case of ζ Oph. Nevertheless, HD 93521 would be a very interesting target for an intensive photometric monitoring from space.

4.3. The need for an alternative interpretation?

Whilst multi-frequency non-radial pulsations offer an attractive interpretation of the line profile variability observed in the spectrum of HD 93521, we must nevertheless ask the question whether there could be alternative explanations. We stress that the stability of the frequencies over many years (when they are detected) likely implies that the profile variations are produced by one or several stable clocks such as pulsations (considered above), rotation, orbital motion... Generally speaking, the distinction between these different mechanisms is a non-trivial issue (see e.g. the discussion in Uytterhoeven et al. 2005). For instance, in the case of ζ Oph, Harmanec (1989) proposed a different scenario where the moving bumps in the absorption lines actually stem from rotating inhomogeneities of the circumstellar material rather than from non-radial pulsations.

In our case, there are also a number of reasons to consider alternative scenarios. Indeed, it is clear that currently a theoretical model to predict the line profile variations produced by non-radial pulsations in a rapidly rotating massive star such as HD 93521 is still lacking. Therefore, the interpretation of these features within the framework of the available models requires an extrapolation that might be difficult to justify a priori.
Another feature that is certainly puzzling is the fact that the line profile variability is significantly detected only in lines that are potentially affected by residual emission possibly associated with a circumstellar disk (or flattened wind). Whilst the lack of a TVS signal in the purely photospheric O\textsc{iii} \lambda 5592 line (see Fig.[1]) might be interpreted as this line forming near the hotter poles of the star where the pulsational amplitude is lower (as for He\textsc{ii} lines), the same explanation cannot hold for the photospheric features that occur at temperatures and gravities that are typical of those of the equatorial region (see the C\textsc{ii}, N\textsc{iii}, and Si\textsc{iii} lines discussed in Sect.[5]). The latter features produce at best a marginal signal in the TVS (see Fig.[1]). However, regarding the possibility that the variability stems from rotating features in the circumstellar material, we first note that the frequencies $\nu_1$ and $\nu_2$ are not detected in the emission wings of the lines analysed in this work. If the line profile variations were coming from the flattened wind, one would also expect them to affect the emission wings. We further note that all the lines where we have detected line profile variability are quite strong. Actually, the rather low amplitude of the profile variations might render them undetectable in the weaker equatorial lines.

In relation to this, we note that a recent study of HD 60848 revealed evidence for the existence of rather short (3.51 and 3.74 hr) periods in the radial velocities derived from the emission lines of this O9.5 Ve star (Boyajian et al. 2007). These authors argued that these features might result from changes in the disk density or illumination caused by non-radial pulsations in the underlying star. Therefore, it seems that a disk origin for short period variations cannot be ruled out a priori, although it would also reflect the existence of pulsations in this specific example.

Since HD 93521 was considered as a possible runaway object (Gies 1987) but see also the discussion in Sect.[1], it could host a compact companion which could then trigger a periodic structure in the inner part of the disk that is seen projected against the photosphere. However, the presence of a compact companion should make HD 93521 a bright X-ray source, at least episodically when the compact object crosses the equatorial wind (similar to Be-type high-mass X-ray binaries). We thus checked the ROSAT All Sky Survey images as well as several other X-ray catalogues. To the best of our current knowledge, there is no indication that HD 93521 is, or has ever been, a bright or even moderate X-ray emitter. Another point is that the detected frequencies $\nu_1$ and $\nu_2$ are much too high to correspond to the orbital period (\gtrsim 13.5 hr and likely of order several days) of such a putative companion. A compact companion scenario appears therefore rather unlikely.

Another point concerns the fact that both frequencies are too high to correspond to the rotational period of the star. In fact, whilst many of the physical parameters of HD 93521 remain unknown or poorly determined, we can obtain a rough estimate of the rotational frequency by considering typical parameters of a late O-type star. Let us assume that HD 93521 is an O8.5 star with a polar radius of 8 R\textsubscript{\odot} and a mass of 20 M\textsubscript{\odot}. If the star is actually seen equator-on, the resulting rotational frequency would be 0.81 d^{-1}. In general, we can say that for any reasonable assumption on the stellar parameters, we find that $\nu_{\text{rot}} \lesssim 1$ d^{-1}. Now, if the line profile variations actually stem from a regular pattern of moving spokes in the circumstellar disk, $\nu_1$ and $\nu_2$ would not necessarily have to correspond to $\nu_{\text{rot}}$, but could rather be some harmonics of the latter (see Uytterhoeven et al. 2005).

We would thus have to look for a “super” frequency such that $\nu_1 = n_1 \nu_{\text{sup}}$ and $\nu_2 = n_2 \nu_{\text{sup}}$, where $n_1$ and $n_2$ would be integer numbers. Within the uncertainties of our period determinations, a candidate for such a frequency would be $\nu_{\text{sup}} = 2.75$ d^{-1} (with $n_1 = 5$ and $n_2 = 3$). Again, the latter frequency is much too high to correspond to the rotational frequency. The super-frequency could be in agreement with the likely value of the rotational frequency if $n_1$ and $n_2$ were multiplied by 3. However, this would imply a large number (15 and 9) of co-rotating structures around the star which seems rather difficult to explain.

In summary, we conclude that, all the alternative scenarios envisaged here fail in explaining the modulations at the $\nu_1$ and $\nu_2$ frequencies. Hence, despite some difficulties, the multi-period non-radial pulsations model remains currently the most plausible explanation for the line profile variations seen in HD 93521.

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5 The observational classification as an O9.5 star is likely biased towards later spectral types as a result of gravity darkening due to the high rotational velocity and the nearly equator-on orientation of the star.
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