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Spectroscopy of the hot pulsating star β Cephei. Velocities and EWs from C, N, O and Si lines ☆

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Abstract

Frequencies in oscillating β Cephei stars are usually inferred by means of radial velocities measured from the SiIII triplet λλ 4552–4574 Å. These lines, relatively insensitive to the variation of $T_{\rm eff}$ through a pulsation cycle, show small equivalent width variations.

In this study, we aimed to verify if the behavior of radial velocities and equivalent widths measured from other ions are compatible with the one observed from SiIII lines and than to verify the possible vertical stratification along the stellar atmosphere. For this reason we selected from our spectra a number of, unblended and well isolated, CII, NII and OII lines besides the famous SiIII triplet. All those lines cover the range in optical depth between −2.1 and −0.5.

Unfortunately, we did not find any differences in the radial velocities behavior line-by-line and then we derived the frequency of the principal radial mode combining all the velocities derived from each spectral line separately. The inferred frequency was $f_1 = 5.249677 \pm 0.000007$ c d^{-1}.

Another important task we would like to accomplish with this paper is to make available to the community our large sample of spectroscopic data, that is 932 velocities and equivalent widths measured from our sample of C, N, O and Si lines. All the spectra were acquired at the 1-m class telescope of the stellar station of the *INAF – Osservatorio Astrofisico di Catania*, in the period starting from July, the 27th 2005 to November, the 1st 2006.

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1. Introduction

The star β Cephei (HD 205021) is the prototype of a class of hot pulsating variables. For complete reviews on β Cephei stars, we refer the readers to Aerts and De Cat (2003), who describe in detail the line-profile variations and to Sterken and Jerzykiewicz (1992), who give an overview of the photometric behavior of all the β Cep stars known up to that time.

From the spectroscopic point of view, the data used to recover frequencies of oscillations are commonly the radial velocities. Checking through the most recent literature published on this topic, it is easy to realize that the common guideline is to derive the velocities from the lines of the SiIII triplet at 4552, 4567 and 4574 Å. There are three common reasons for this choice: they are strong lines not affected very much by blending and almost insensitive to the temperature variations (De Ridder et al., 2002).

Up to the study by Aerts et al. (1994), β Cephei has been believed to oscillate with only a single radial mode. In

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☆ Based on observations collected at the 91 cm telescope of the INAF – Osservatorio Astrofisico di Catania.

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their analysis, these authors revealed the multi-periodicity of this star detecting three frequencies in total: $f_1 = 5.2497104\ \mathrm{c\,d^{-1}}$, $f_2 = 5.385\ \mathrm{c\,d^{-1}}$ and $f_3 = 4.920\ \mathrm{c\,d^{-1}}$. Later on, Telting et al. (1997) by a CLEANing analysis of the same data added two more frequencies: $f_4 = 5.083\ \mathrm{c\,d^{-1}}$ and $f_5 = 5.417\ \mathrm{c\,d^{-1}}$.

Further, the star β Cep ($V = 3.2$) is actually a complicated multiple system. In fact the star, beside to have a visual companion ($V = 7.9$) at a distance of 13.4″, is also a member of a spectroscopic system whose second star was discovered by Gezari et al. (1972), using speckle interferometry, at a distance of ≈0.25″ ($V = 6.6$). The parameters of the close binary orbit have been determined later by Pigulsky and Boratyn (1992) from speckle interferometry and the variations in the pulsation period, due to the so-called light time effect. Recent speckle measurements by Hartkopf et al. (2001) place the position of the companion to about 0.1″ from the primary. More observation are still necessary to improve the orbital solution.

Another question, people are still debating, is the nature of the random variable H_α emission which was the cause of the Be status assigned to β Cep. The problem was that typically Be stars are rapid rotators while β Cep has an equatorial velocity of 26 km s^{-1} (Morel et al., 2006). Hadrava and Harmanec (1996) attempted to solve this problem argued that the observed emission is due to the secondary component of the spectroscopic binary which is probably a Be star. They, for the first time, separated the emission and absorption component of the H_α profile. Recently, Schnerr et al. (2006) confirmed this result using data obtained at Nordic Optical Telescope. Unfortunately, they obtained only one spectrum and, then, no conclusion about the variability of the emission could be drawn.

Starting from the pioneering work by Osaki (1971), a lot of studies have been undertaken with the aims to infer the oscillation modes from the analysis of line profile variation (LPV). It is generally accepted that the weakness of these studies is the lack in the knowledge of how some important thermodynamic quantities change during the pulsation. For instance, during each pulsation cycle effective temperature, surface gravity and microturbulent velocity are expected to change with time and than the knowledge of their effect on the line profiles could avoid errors in the modes determination.

It is a matter of fact that, because of its low rotational velocity, the spectrum of β Cephei is full of lines generated by various chemical elements at different depths in the photosphere. The analysis of the radial velocity inferred from a sample of lines opportunely selected could be useful to study the velocity stratification along the photosphere. A similar approach has been tempted by Baldry et al. (1998) in a spectroscopy study of the roAp star α Cir. In this study, latter authors selected a sample of spectral region containing various metallic lines and they found a dependence of the amplitudes with the depth along the atmosphere.

With the aim to infer if a similar stratification is present also in β Cep, we selected from our spectra as many as possible lines not affected by blends, sufficiently isolated to allow an easy measurements and well distributed along the atmosphere. A complete list of selected lines is reported in Table 2. In this paper, we present a large time-resolved dataset of line-by-line radial velocities collected from July 2005 to November 2006, for a total of 932 spectra and, moreover, for the first time we present also their equivalent widths.

Velocities and equivalent widths can be retrieved from the CDS via anonymous ftp.

2. Observations and data reduction

All the data analyzed in this study have been obtained at the 91 cm telescope of the *INAF – Osservatorio Astrofisico di Catania*. The telescope is fiber linked to a REOSC echelle spectrograph, which allows to obtain $R = 20{,}000$ spectra in the range 4300–6800 Å. The resolving power has been checked using emission lines of the Th–Ar calibration lamp. Spectra were recorded on a thinned, back-illuminated (SITE) CCD with 1024 × 1024 pixels of 24 μm size, typical readout noise of 6.5 e$^-$ and gain of 2.5 ph/ADU.

Our observations (932 spectra in total) were spread over a baseline greater than one year, precisely from July, the 27th 2005 (JD = 2,453,579) to November, the 1st 2006 (JD = 2,454,041), for a total of 462.14 days (see Table 1). The exposure time was set to 5 min, with the exception of a couple of nights in October 2006 during which we had to increase it to 10 min because of the bad weather condition. This leads to a temporal resolution of ≈2% and ≈4%, respectively, of the pulsational period, small enough in both cases to avoid phase smearing effects. The signal-to-noise ratio of our spectra resulted always above 150.

The stellar spectra, calibrated in wavelength and with the continuum normalized to a unity level, were obtained using standard data reduction procedures for spectroscopic observations within the NOAO/IRAF package, that is: bias frame subtraction, trimming, scattered light correction, flat-fielding, fitting traces and orders extraction and, finally, wavelength calibration. IRAF package *rvcorrect* has been used to include the velocity correction due to

Table 1
Journal of observations

JD	*n*	JD	*n*
3579	56	3933	49
3580	44	4013	35
3581	46	4016	30
3635	65	4017	26
3672	64	4018	41
3673	95	4019	43
3674	82	4021	19
3871	58	4022	18
3872	61	4023	5
3873	64	4041	31

JD are in the form JD – 2,450,000, *n* is the number of spectra collected in each night.

Table 2
Parameters and relative errors of the sinusoidal fits presented in Figs. 1 and 3

λ (Å)	$\log\tau_0$	HRV fit parameters				EW fit parameters			
		Frequency (c d^{-1})	γ_0 (km s^{-1})	K (km s^{-1})	ϕ	Rel. (%)	γ_0 (mÅ)	K (mÅ)	ϕ
C ii 6578.052	-2.11	5.24967(1)	-3.2 ± 0.6	15.5 ± 0.1	0.526 ± 0.001	9.5	88.2 ± 0.2	8.4 ± 0.2	0.28 ± 0.01
C ii 6582.882	-1.84	5.24967(1)	-3.3 ± 0.5	13.5 ± 0.1	0.544 ± 0.002	9.9	82.4 ± 0.2	8.1 ± 0.2	0.19 ± 0.01
N ii 4607.153	-0.53	5.24969(2)	-1.9 ± 0.4	15.3 ± 0.2	0.456 ± 0.002	9.1	56.0 ± 0.2	5.2 ± 0.3	0.19 ± 0.01
N ii 5010.621	-0.53	5.24967(2)	-1.8 ± 0.5	13.1 ± 0.2	0.530 ± 0.002	7.4	51.0 ± 0.3	3.8 ± 0.4	0.24 ± 0.02
N ii 5666.629	-0.97	5.24967(2)	-3.1 ± 0.5	14.1 ± 0.2	0.528 ± 0.002	8.4	83.3 ± 0.2	7.0 ± 0.2	0.18 ± 0.01
N ii 5676.017	-0.82	5.24967(2)	-4.3 ± 0.4	13.3 ± 0.2	0.536 ± 0.003	7.9	69.4 ± 0.2	5.5 ± 0.2	0.19 ± 0.01
N ii 5679.558	-1.27	5.24968(1)	-4.5 ± 0.6	14.3 ± 0.2	0.500 ± 0.002	7.1	120.2 ± 0.2	8.5 ± 0.2	0.21 ± 0.01
O ii 4591.010	-0.82	5.24967(1)	-5.3 ± 0.7	15.1 ± 0.1	0.544 ± 0.001	1.2	120.5 ± 0.3	1.5 ± 0.4	0.05 ± 0.04
O ii 4661.643	-0.97	5.24966(1)	-4.7 ± 0.7	15.9 ± 0.1	0.597 ± 0.001	1.9	121.5 ± 0.3	2.4 ± 0.4	0.39 ± 0.03
Si iii 4552.622	-1.70	5.24967(1)	-1.9 ± 0.8	14.4 ± 0.1	0.535 ± 0.002	2.5	209.0 ± 0.2	5.2 ± 0.3	0.33 ± 0.01
Si iii 4567.840	-1.41	5.24967(1)	-2.6 ± 0.7	15.0 ± 0.1	0.556 ± 0.001	2.7	174.3 ± 0.2	4.8 ± 0.3	0.36 ± 0.01
Si iii 4574.757	-0.97	5.24968(1)	-3.2 ± 0.6	15.4 ± 0.1	0.505 ± 0.001	2.9	117.9 ± 0.2	3.4 ± 0.3	0.27 ± 0.02
All		5.249677(7)	-3.5 ± 0.4	15.5 ± 0.1	0.516 ± 0.001				

For each line we report, respectively: wavelength, $\log\tau_0$, derived frequency of the principal radial mode (in parentheses the estimated error), γ_0, semi-amplitude and phase of the variation. Columns from seventh to tenth reported the parameters derived for the fits of EWs, that is: relative amplitude, average, semi-amplitude and phase of the variations.

the Earth's motions, all the spectra were then reduced into the heliocentric rest of frame.

Systematic errors on radial velocities have been estimated observing stars with constant and well known radial velocity taken from the list of standard stars published by Udry et al. (1999): HD 12929, HD 20902, HD 186791 and HD 206778. Whenever it was not possible to obtain a spectrum of a standard star, we evaluated the systematic shift from the wavelength positions of the strong telluric lines between 6275 Å and 6320 Å.

3. Radial velocities and equivalent widths measurements

As we stated before, radial velocities in this class of pulsating stars are usually measured from the Si iii triplet. Here we have considered the heliocentric $V_{\rm rad}$ measured from lines of other ions with the final aim to verify if their behavior is different line-by-line. Thus, we selected all the strong, unblended lines present in the spectral range covered by our spectra. These lines are reported in the first column of Table 2 and are, precisely, 2 lines belonging to C ii, 5 to N ii, 2 to O ii and 3 lines to Si iii.

For each of these lines we adopted as radial velocity the value obtained from the barycentric wavelength which has been converted in radial velocity via the classical Doppler shift formula. The integrations evaluated to compute $\lambda_{\rm bar}$ and the equivalent width (EW) of each line extend over a carefully chosen, constant region in wavelength and they have been evaluated after a local re-normalization of the continuum close to the edges of the line. This procedure let us to minimize the systematic effects due to the arbitrary choice of the lines boundaries or the position of the continuum. Errors on $V_{\rm rad}$ and EW have been computed from a formal application of the error propagation rules to the used equations, assuming that the main source of error is the noise in the observed spectrum.

Single values of radial velocities and equivalent widths are presented only in the online tables,[1] available at the *CDS*, which are organized as follow: the first column reports the heliocentric julian date, the others reported line-by-line the measured radial velocities and equivalent widths together with their errors. Blank space means a discarded line profile contaminated by cosmic rays.

4. Data analysis

One of the most used code to analyze a large set of periodic data in order to obtain frequency, velocity of center of mass (γ_0), amplitude of the variation (K) and phase (ϕ), is *Period04* developed by Lenz and Breger (2005). We used this code to perform a line-by-line sinusoidal fit of our velocities. For each selected line, we reported in Table 2 frequency, γ_0, amplitude K and phase ϕ and relative errors as determinated by using that code. Each box on the left side of Fig. 1 shows the velocities derived line by line folded with the corresponding frequency and with the sinusoidal fit over-imposed.

With the aim to search for vertical stratification, we plotted all the quantities reported in Table 2 regarding the velocity versus optical depths. To compute the optical depths, we used the code XLINOP (Kurucz and Avrett, 1981) applied to LTE atmospheric model with $T_{\rm eff} = 24{,}000$ K, $\log g = 3.9$, solar metalicity and $\xi = 8$ km^{-1}. These atmospheric values have been derived by us in the framework of a detailed abundances revision that it is currently under study. As we shown in Fig. 2, there is no evidence of some kind of stratification through the stellar atmosphere, at least in the range of optical depth probed by our lines.

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[1] Table 3 reports lines from C ii 6578 to N ii 5676 and Table 4 reports lines from N ii 5679 to Si iii 4574.

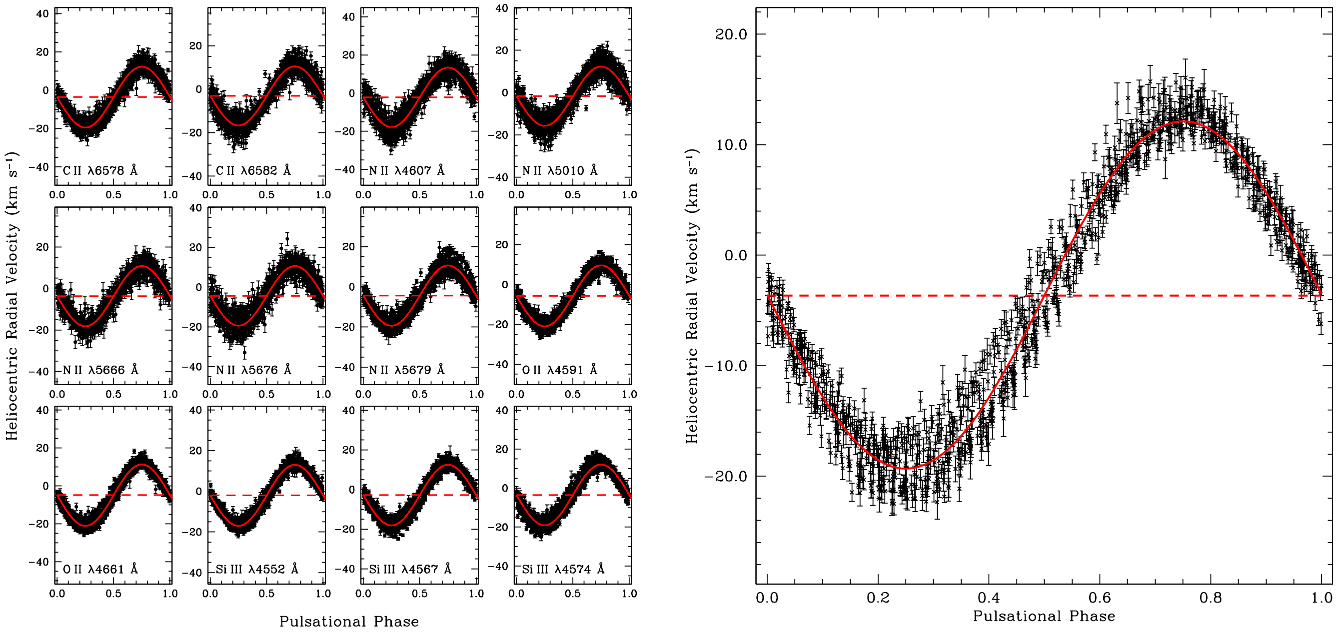

Fig. 1. Phase diagrams of the radial velocity variations derived by carbon, nitrogen, oxygen and silicon lines (left) and velocities computed from average over all the lines selected (right). Parameters of the over-imposed sinusoidal fits are reported in Table 2. Error bars extend for $\pm 1\sigma$.

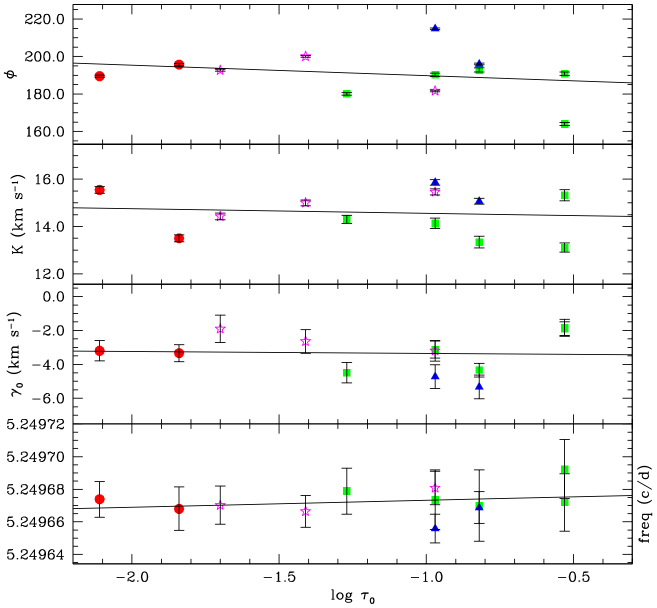

Fig. 2. In this figure we report as a function of optical depth the computed frequencies, center of mass (γ_0), amplitudes and phases derived from the fit of velocities for each of the selected lines. Meaning of the symbols is: circles (red) carbon lines, stars (magenta) silicon lines, triangles (blues) oxygen lines and boxes (green) nitrogen lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Since the results obtained line-by-line are consistent, with the aim to improve the quality of our measurements, we computed the radial velocity as an average over the values obtained from all lines, without paying any attention to the different chemical species. In this case, the fitting procedure described before gave us the results presented in the last row of Table 2 and then we adopted it as frequencies of the radial mode of β Cep: $f_1 = 5.249677 \pm 0.000007$ c d^{-1}. The corresponding phase diagram is shown in the right side of Fig. 1. The epoch used for the plot is that of the minimum radius, that is $\mathrm{HJD}_{(\mathrm{R}_{*\min})} = 2453579.2649$.

Since the study by Pigulsky and Boratyn (1992), it is well known that β Cephei shows apparent changes of its pulsation period because the light-time effect induced by the orbital motion of the binary system. In our conclusion we have neglected this effect since our time baseline covers scarcely 1.4% of the orbital period, estimated by those authors in 91.6 years.

As a by-product, we measured also the equivalent widths of each selected line. In Fig. 3 (left), we show the phase diagrams obtained for all the EW measured for the selected lines phased with the ephemeris derived from the velocities. As we stated in the previous section, all these lines are unblended and sufficiently isolated to avoid contamination from nearby lines. Sinusoidal fits over-imposed on the experimental data have been computed neglecting those points for which their relative errors exceed 20% and keeping all the points within $\pm 3\sigma$ from the mean value, where σ is the standard deviation. The parameters of the sinusoidal fits with their errors are presented in Table 2. We did find variations with small amplitude for some lines as for example O II 4661 Å and Si III lines (relative amplitudes $\leqslant 3\%$). A more marked variability, up to ≈10%, has instead been inferred for N II and C II lines.

Despite difficulties in measuring the EW of a spectral line, for instance the choice of line limits and continuum, the phase diagrams showed a scatter not justified if related to errors. For the sake of clarity, we showed in Fig. 3

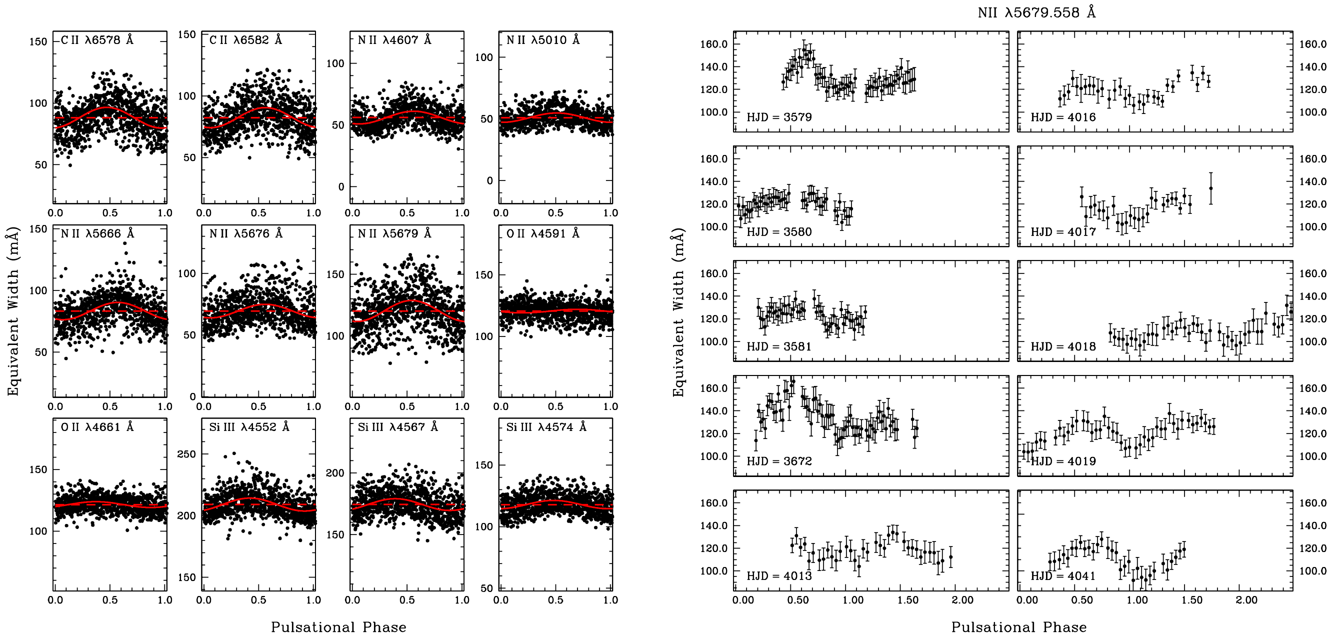

Fig. 3. (Left) Variability of the measured equivalent widths for all the selected lines. Parameters of the sinusoidal fits over-imposed are those reported in Table 2. (Right) Equivalent width variations for the NII λ 5679 Å observed in 10 different nights. In each box we indicated the julian day – 24 50000.

(right) the EW measured in 10 different nights for the NII λ 5679 Å line. Similar behavior have been observed also in the variations of the others spectral lines here considered. A so complex changing, observed night by night, could be ascribed to the multi-periodic nature of β Cep (Aerts et al., 1994; Telting et al., 1997).

5. Conclusions and discussion

Spectroscopic observations of β Cephei have been carried out at the stellar station of the *INAF – Osservatorio Astrofisico di Catania*, in total we collected 932 spectra with a time baseline covering more than 1 year.

As for the radial velocities we checked the behavior of velocities coming from different lines and for each group of velocities we computed the pulsation frequency of the radial mode, the γ_0, amplitude and phase of the relative sinusoidal fit. Plotting these values as a function of the optical depth of each line we do not see any evidence of stratification through the stellar atmosphere. For what that concerns equivalent widths, we showed their behavior in time and, in the case of the NII λ 5679.558 Å, the possible influence of the non-radial pulsation on the amplitude and shape observed night by night. Further, we did find clear variability for CII and NII lines, while SiIII and OII λ 4661 Å show very small amplitude. For OII λ 4591 Å we concluded that its EW is constant with time, at least at the resolving power of our spectra.

At the end, we think that such large data set of data, radial velocities and equivalent widths, could be useful for a number of studies, like for instance the study of the orbit utilizing the light-time effect or frequencies analysis, so we would like put them at astronomical community's disposal.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.newast.2007.07.005.

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