

PULSATION PROPERTIES OF THE β CEPHEI STAR SY EQU FROM COMBINED PHOTOMETRIC AND SPECTROSCOPIC DATA*

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ABSTRACT

We present the analysis of simultaneous multicolour $uvyI_C$ photometry and low-resolution spectroscopy for the rapidly rotating β Cephei star SY Equ. From the photometric time series, we confirm the dominant pulsation frequency, $f_1 = 6.029 \text{ d}^{-1}$, and we find an evidence for two additional modes. In spectroscopy, the highest peak occurs at $f_a = 0.197 \text{ d}^{-1}$ or its alias 0.803 d^{-1} . It can be interpreted either in terms of a binary motion or as the g -mode pulsation. In addition, we reveal the pulsation mode with frequency of about 6.029 d^{-1} , i.e. the same which dominates photometric variations, and a few new candidates. For the dominant frequency we obtain mode identification from the combined photometric and spectroscopic observations. From non-adiabatic pulsation calculations, we show that the frequency of the dominant mode in SY Equ is consistent with the stellar models of much lower effective temperature than used in many papers.

Key words: B-type stars; photometry; spectroscopy; β Cephei-type variables; pulsation; rotation.

1. INTRODUCTION

SY Equ (HD 203664) is the early-B spectral type star, B0.5 III_{ne}, classified as the β Cephei variable by [1] from the Hipparcos photometry. The star is one of the fastest rotators among β Cephei pulsators, having projected rotational velocity of about 200 km s^{-1} [7]. Moreover, it is a high Galactic latitude star with $b = -27.5^\circ$ which locates it more than 1 kpc out of the Galactic plane.

There are several determinations of stellar parameters for SY Equ. [7] derived $\log T_{\text{eff}} = 4.447$ dex, $\log g = 3.7$ dex from the high-resolution optical spectra and estimated a mass of $14 M_\odot$ from the evolutionary tracks of [8]. On the other hand, using Geneva photometry, [2] determined $\log T_{\text{eff}} = 4.47 \pm 0.01$ dex and $\log g = 3.9 \pm 0.3$ dex.

*Based on photometry obtained at the Białków Observatory (University of Wrocław) and on spectroscopy obtained at the David Dunlap Observatory (University of Toronto)

Much lower value of effective temperature, $\log T_{\text{eff}} = 4.401$ dex, was obtained by [6] from Strömgren photometry and equivalent width of the H ϵ line. We adopt here stellar parameters derived from the International Ultraviolet Explorer (IUE) spectra and visual photometry by [9]: $\log T_{\text{eff}} = 4.388 \pm 0.035$ and $\log g = 3.905 \pm 0.1$. These values result in a mass estimate of $11.5 \pm 1.5 M_\odot$ if the metallicity $Z = 0.02$ is assumed. The metallicity in terms of [m/H], obtained from the IUE/INES data, amounts to 0.00 ± 0.21 dex, which corresponds to $Z = 0.02^{+0.012}_{-0.007}$. We prefer to rely on this determination because it uses ultraviolet spectral region, where B-type stars emit most of their energy.

In this note we give only a brief outline of our results. The full analysis will be published elsewhere.

2. OBSERVATIONS

2.1. Photometry

The new CCD photometry of SY Equ was carried out in Białków Observatory (Wrocław University) during five nights between August 14 and September 3, 2004. We used Strömgren uvy and Cousins I_C passbands. The obtained frames were calibrated in a standard way and then reduced using the profile-fitting and aperture photometry of the Daophot package [12].

2.2. Spectroscopy

Spectroscopic observations of SY Equ were obtained with the Cassegrain spectrograph attached to the 1.88-m telescope of the David Dunlap Observatory (University of Toronto). The data consist of 171 spectra taken on 12 nights between August 8 and September 1, 2004, i.e., simultaneously with the Białków photometry. The spectra were sampled over the range 4000–4600 Å with the 600 lines per mm grating giving a dispersion of 0.62 Å per pixel. The exposure times were 15 minutes long. The re-

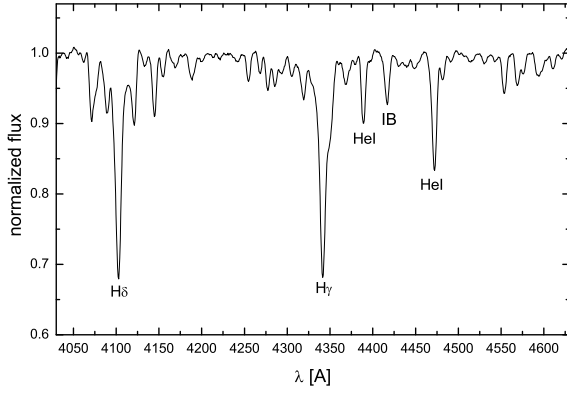


Figure 1. The mean spectrum of SY Equ in the observed range obtained by averaging of 171 normalized individual spectra. IB stands for interstellar band.

ductions were made with standard IRAF¹ routines, which include cosmic ray removal, bias correction, flat-fielding, and wavelength calibration. The spectra were moved to the heliocentric frame. In Fig. 1 we show the mean spectrum of SY Equ.

3. FREQUENCY ANALYSIS

The photometric light curve of SY Equ is dominated by the mode with frequency $f = 6.029 \text{ d}^{-1}$. The 2004 Białków $vbyI_C$ photometry folded with the period of $0.165871 \text{ d} = 1/f$ is shown in Fig. 2. In order to search for possible low-amplitude modes, we combined three photometric datasets: Geneva V -band data of [2], ASAS-3 V -band photometry [11, 10] and Białków 2004 data in the Strömgren y band. These data cover the time interval of almost 9 years, between 1997 and 2005. In Fig. 3 we plotted Fourier periodograms of the combined V/y data showing consecutive steps of prewhitening. We see that except for the well-known dominating mode, at least two low-amplitude modes are present. Their frequencies are equal to 8.360 and 7.821 d^{-1} , but due to the severe aliasing, their values are not certain.

For the spectroscopic data, we searched for intrinsic variations in the first four moments of four spectral lines: $H\gamma$, $H\delta$, He 4471, and He 4387, labeled in Fig. 1. Moreover, we did the same for radial velocities obtained by means of the cross-correlation function (CCF) technique using the whole observed spectrum excluding the region of the interstellar band (IB, Fig. 1). The frequencies of the terms we found are summarized in Tab. 1. In all lines and the CCF radial velocity, we have found low-frequency variation at 0.197 d^{-1} , which did not appear in photometry, and the peak known already from photometry, $\sim 6.029 \text{ d}^{-1}$. The radial velocity amplitudes of

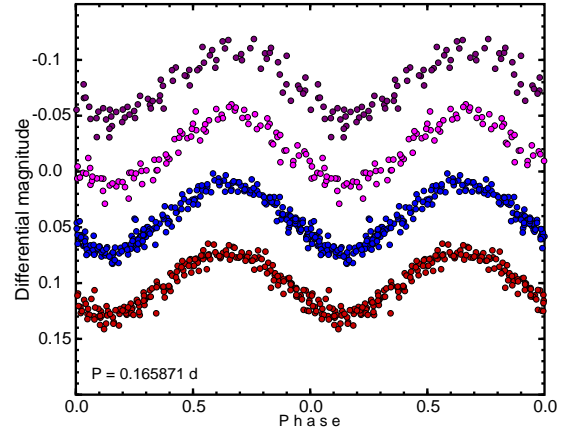


Figure 2. Phase diagrams of the Białków 2004 SY Equ light-curves folded with the period of 0.165871 d . Going from top to bottom, data in u , v , y , and I_C photometric passbands are shown.

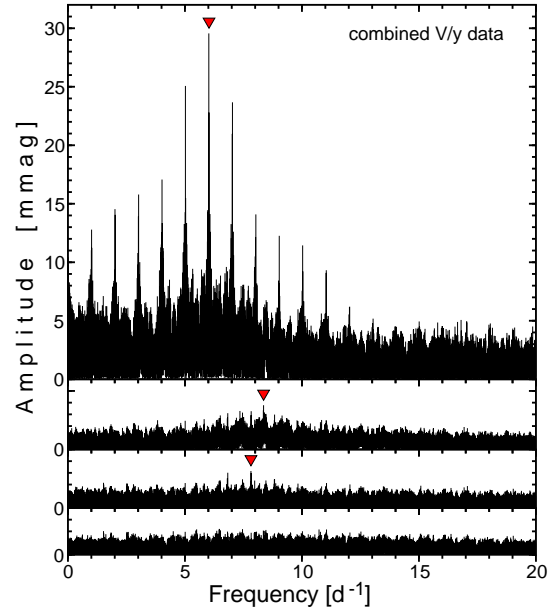


Figure 3. Fourier periodogram of the combined V/y photometric data of SY Equ (top) and after consecutive steps of prewhitening (lower panels).

these two frequencies are 15 and 12 km s^{-1} , respectively. Additionally, we found low-amplitude changes with 4.42 d^{-1} and 0.61 d^{-1} . The latter could be the rotation frequency of SY Equ. In Table 1 we give frequencies which were identified after subsequent stages of prewhitening for three moments of two lines ($H\gamma$ and $H\delta$) and V_{rad} (CCF). The important results is that we did not find the variation with frequency $2f_1$, where f_1 is the frequency of the dominant mode, in the second moments of the analyzed four lines. This leads immediately to the

¹IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Table 1. Frequencies [in d^{-1}] detected with signal-to-noise (S/N) ratio greater than 4 in the first three moments of $H\gamma$ and $H\delta$ lines, and CCF radial velocities. The frequencies are given in the order of detection. Numbers in parentheses denote the r.m.s. errors of the last digits.

$H\gamma$			$H\delta$			$V_{\text{rad}}(\text{CCF})$
M_0	M_1	M_2	M_0	M_1	M_2	
6.0318(39)	0.1970(15)	0.1921(27)	0.4683(42)	0.1970(16)	6.0354(14)	6.0241(12)
	6.0267(16)	6.0283(30)	6.0284(37)	6.0253(18)	0.3532(21)	0.1978(19)
	0.6094(21)			4.4205(33)		4.4281(28)
	9.0304(28)					0.6026(36)

conclusion that the dominant frequency has to be a non-axisymmetric mode ($m \neq 0$).

Recently [2] suggested two additional modes with frequencies of 6.82902 and 4.81543 d^{-1} , from the analysis of the Geneva photometry. The former is probably an alias of our mode with 7.821 d^{-1} , the presence of the latter was not confirmed in our analysis.

4. MODE IDENTIFICATION

We determined the amplitudes and phases of the light curves in $uvyI_C$ bands and of the radial velocity variations. Using these data for the dominant frequency, we identified its spherical harmonic degree, ℓ , by means of the method invented by Daszyńska, Dziembowski and Pamyatnykh [4, 5]. The method combines photometry and spectroscopy and consists of simultaneous determination of the ℓ value and the pulsation nonadiabatic parameter f . The f parameter describes the ratio of the relative luminosity variation to the radial displacement of the surface, and it gives information on subphotospheric layer. In the case of δ Scuti stars, this new diagnostic tool probes the efficiency of convection [4], while in the case of β Cep stars, it provides a stringent probe of stellar opacities [5]. From this method, we get the unambiguous $\ell = 2$ identification. In Fig. 4, we show the χ^2 value as a function of ℓ . The horizontal line at $\chi^2 = 2.1$ corresponds to 95% confidence level. In the next step, we identified the azimuthal order, m , from spectroscopy, using monochromatic amplitude and phase diagrams across the line profiles. In Fig. 5 we plot these diagrams across $H\gamma$. As one can see, the amplitude reaches a very sharp maximum in the line center, which indicates $|m| = 2$ as the most probable identification. The sign of m is obtained from the phase changes. Because the phase decreases across the line profile with increasing wavelengths, the mode must be prograde, $m = +2$. Thus, the dominant frequency of SY Equ is a sectoral prograde mode with $\ell = 2$. Such mode identification excludes low inclination angles because sectoral modes are poorly seen when the star is observed near pole-on.

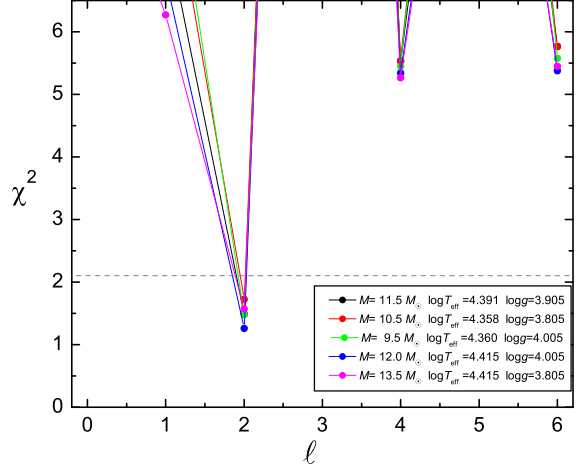


Figure 4. The value of χ^2 as a function of ℓ obtained for five models of SY Equ. The models are located in the error box defined in Sect. 1.

5. PULSATION MODELING

Having identified the geometry of the main pulsation mode in terms of ℓ and m parameters, we may compare the observed frequency of this mode with the theoretical predictions. For this purpose, stellar evolutionary models were calculated using Warsaw-New Jersey evolutionary code, assuming the OPAL opacities and the standard solar mixture of elements. Linear nonadiabatic pulsation calculations were performed with the use of Dziembowski's code, which includes the rotation effects on oscillation frequencies up to the second order in the rotational velocity. Although SY Equ rotates very fast (at least 35% of the break-up velocity), we can neglect deviations from the spherical symmetry due to effects of centrifugal force, because the ratio of the rotation frequency to pulsation frequency is still much less than 0.5.

In Fig. 6, unstable modes with $\ell = 0, 1$, and 2 for models with a mass of $12 M_{\odot}$, evolving from ZAMS to TAMS, are shown. The initial hydrogen abundance was $X = 0.7$ and the heavy element abundance $Z = 0.02$. We consider two values of the rotational velocity, $v_{\text{rot}} = 0$ and 200 km s^{-1} . The vertical lines mark the range of effective

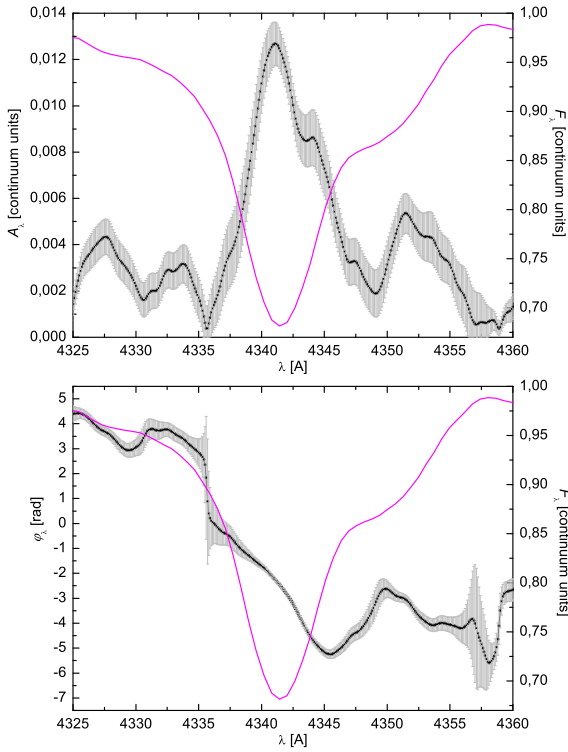


Figure 5. The monochromatic amplitude (top) and phase (bottom) diagrams for $H\gamma$. The line profile is plotted with a thin line and the amplitudes and phases with a thick one. Errors are shown as grey shadows. Right ordinate is given in flux units and refers to the line profile.

temperatures determined from the IUE spectra. The rotational velocity of SY Equ is equal to at least 200 km s^{-1} , which gives rotational frequency of $\sim 0.6 \text{ d}^{-1}$ assuming the stellar radius of about $6.5 R_{\odot}$. If the frequency of 6.029 d^{-1} (solid horizontal line) is a sectoral prograde mode, we have to compare theoretical values with the centroid of the $\ell = 2$ mode which should be placed at about 4.8 d^{-1} (dotted horizontal line). As one can see from Fig. 6, for $Z = 0.02$ the pulsation instability begins at $\log T_{\text{eff}}$ of about 4.41 dex, which is much lower than the effective temperature of SY Equ used by some authors, e.g. [2] and [7]. Moreover, we checked the metallicity and mass effects on the instability domain considering several values of Z and M . Changing Z from 0.015 to 0.025 shifts the hottest unstable mode from $\log T_{\text{eff}} \approx 4.40$ to 4.42 dex. Changing mass from 11 to $13 M_{\odot}$ gives exactly the same effect on the hot edge of instability.

6. CONCLUSIONS

We presented the results of the frequency analysis of both the photometric and spectroscopic time series of SY Equ. In both datasets, we found the dominant mode at $f_1 = 6.029 \text{ d}^{-1}$, and several new candidate frequencies. More-

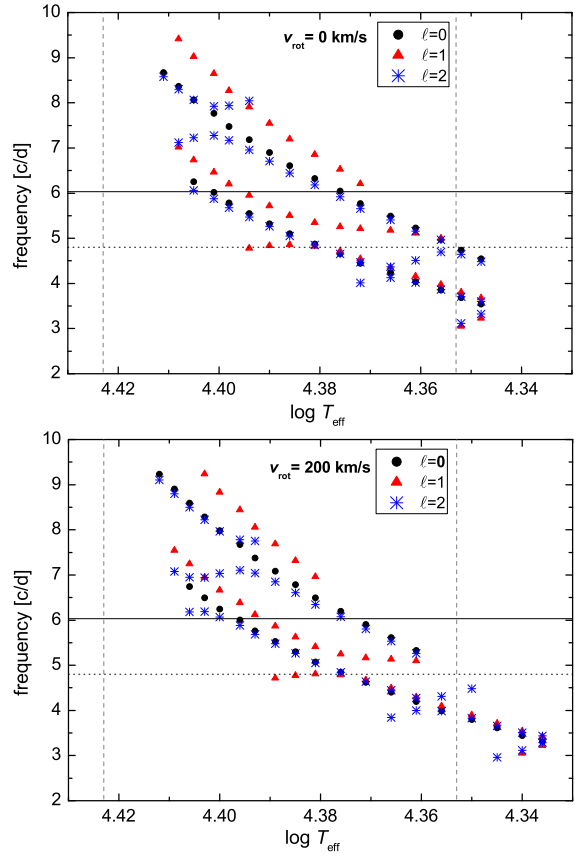


Figure 6. Evolution of unstable modes with $\ell = 0, 1$, and 2 in a sequence of β Cephei star models with mass of $12 M_{\odot}$, assuming $Z = 0.02$. The models cover the phase from ZAMS to TAMS. The two panels show the effects of rotational velocity (0 and 200 km s^{-1}) on the pulsation frequencies.

over, there is a low-frequency variation at $f_a = 0.197 \text{ d}^{-1}$ detected in radial velocities, which can be an evidence of the binary motion or the excitation of a gravity mode. For the dominant mode we confirmed the $\ell = 2$ identification of [2] and identified the azimuthal order, $m = +2$. It means that the dominant frequency is a sectoral prograde mode with $\ell = 2$. However, one has to be aware that at $v_{\text{rot}} \approx 200 \text{ km s}^{-1}$, the rotational mode coupling can take place, if the frequency difference between modes j and k is of the order of angular velocity of rotation, and if the spherical harmonic indices satisfy the relation $l_j = l_k \pm 2$, see [3].

Recently, [2] made an attempt of comparisons of theoretical frequencies with the observed value of the dominant mode, but the authors totally ignored the effects of rotation and the instability condition. Our analysis showed that only for lower effective temperatures we enter the instability domain. These temperature values agree very well with the range determined from the ultraviolet IUE spectra. Moreover the rotation effects on frequencies cannot be neglected for such rapid rotator as SY Equ.

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