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ОБСЕРВАТОРИИ**

High-accuracy spectropolarimetric study of γ Pegasi in the line He I 6678 Å

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Abstract. Results of an intensive spectropolarimetric study of the small-amplitude purely radial pulsating β Cephei-type star γ Pegasi are presented.

It was found that residual intensity, full width at half maximum and equivalent width of the helium line vary during 0.15-day pulsation period and reach its maximal value when the temperature of the star is highest. The line parameter variations due to pulsation were explained as a temperature effect.

It was shown, that if the star has a dipole magnetic field then dipole axis would be situated near rotation equator plane. It was estimated, that owing to frizzing of magnetic field into plasma amplitude of the longitudinal magnetic field variation due to radial pulsation of the star is 0.4 Gauss.

Studying of a possible origin of 6.83-day period of γ-velocity variation has been made. It was concluded, that the star is a spectroscopic binary and improved orbital elements are presented. The orbit inclination angle was estimated as $i \le 7°$.

Key words: Stars: individual: γ Pegasi, magnetic field; (stars): binaries: spectroscopic; stars: atmospheres, early-type, oscillations; line: profiles

1 Introduction

The β Cephei-type star γ Pegasi (HR 39, B2 IV) has one of the smallest amplitude variations in radial velocity $2K = 7\ km\ sec^{-1}$ (McNamara, 1953), light $\Delta m_v = 0.017$ (Sareyan et al., 1975) and short pulsation period $P \sim 0.15$ day. The star is believed to pulsate in a low-order, purely radial mode. Jager et al. (1982) show that γ Pegasi has a virtually zero rotational velocity component i.e. the star is seem rotation pole-on.

Results of a number of attempts to detect significant magnetic field on this star (Babcock, 1958; Rudy and Kemp, 1978; Landstreet, 1982; Butkovskaya and Plachinda, 2004) left this problem unsolved. However, magnetic field with polar strength of several hundred gauss were detected on three early B-type pulsating stars: β Cep (Donati et al., 2001), ζ Cas (Neiner et al., 2003a), ω Ori (Neiner et al., 2003b) and V 2052 Oph (Neiner et al., 2003c).

In the supposition that γ Pegasi has a magnetic field, in this paper the magnetic dipole configuration has been modeled, and the amplitude of the longitudinal magnetic field variation due to radial pulsation of γ Pegasi was estimated.

Small-amplitude stars have not often been an object of intensive high-resolution study for variation of spectral line parameters due to pulsations. In this paper high-accuracy study of the variation of the

He I 6678 line parameters due to radial pulsation of γ Pegasi has been performed, and results of LTE and NLTE simulation of observed He I line profile are presented.

Harmanec et al. (1979) have determined the 6.83-day period of variation of the γ-axis of the pulsation velocity curves and concluded that the star is a spectroscopic binary. Ducatel et al. (1981) clearly detected day-to-day variation of the γ-velocity, but they assumed that the γ-axis probably varies due to stellar oscillations.

For resolving of this problem a number of possible origins of the 6.83-day period were examined in this study.

2 Observations

An intensive study of γ Pegasi has been performed in the line He I 6678.149 $\mathring{A}$ during 15 nights from 1997 to 2004, and 308 high-accuracy spectra were obtained using coude spectrograph of the 2.6-m Shajn telescope at the Crimean Astrophysical Observatory. Signal-to-noise ratios of a single spectrum were typically 350-600 with resolving power of spectra approximately 2.2 ± 10^4.

3 Discussion and conclusions

3.1 Pulsation

In Figure 1a,b,c,d radial velocity (RV), core residual intensity (RI), full width at half maximum (FWHM), and equivalent width (EW) curves as functions of the pulsation period phase are presented. The mean pulsation cycle values of both radial velocity and all three spectral line parameters were subtracted. Fitting curves obtained by least-square sinusoidal fitting are shown by solid lines.

In Figure 1e, the acceleration (dash-dot-dot curve) and radius variation (dashed curve), calculated in standard manner, are presented with the radial velocity (solid curve) in the stellar rest frame. The curves are normalized to unity at their extreme values 1.41 $m\ sec^{-2}$ for the acceleration, 2.98 $km\ sec^{-1}$ for velocity, and 0.004 R_* for peak-to-peak amplitude of the radius variation.

The FWHM and RI variations during pulsation cycle are around 2% and 1.2%, respectively. The EW curve exhibits a maximum at the phase 0.25 as well as in the cases of FWHM and RI, but the insurance is no statistically significant (statistical probability estimated using Fisher's F-test equal to F=0.765, while for FWHM and RI variations it found be 1.000 and 0.999).

In our opinion, in the case of γ Pegasi the variations of the line parameters due to pulsation would be explained as a temperature effect.

LTE and NLTE profiles of the He I line (Figure 2) were calculated for different pulsation phases by variation of T_{eff}. For this purpose, using LLModels code (Shulyak et al., 2004) the grid of atmosphere models was calculated in temperature diapason from 21000 K to 21250 K (Peters et al., 1987)), for log g = 4.25 (Pitando and Adelman, 1993) and solar chemical composition. LTE profiles were calculated using the SynthM code (Khan, 2004). NLTE modeling of the profile of the line was implemented by the codes DETAIL and SURFACE (Giddings, 1981; Butler, 1984; Butler, 1997). Because NLTE-profiles of the He I line are in well agreement with the observed ones, variation of the EW, FWHM and RI of the profiles due to pulsation has been studied. It was found, that the theoretical NLTE-profiles exhibit weaker by amplitude variation of the line parameters (EW of about 0.1%, FWHM of about 0.5%, and RI of about 0.3%) than observed. In our opinion, the discrepancy between amplitudes of the pulsation variation of the observed and calculated line parameters occurs because other line-broadening effects including non-isotropic motions in the pulsating atmosphere have been ignored in this study.

3.2 Magnetic field

The results of a number of previous attempts of different authors to detect significant magnetic field on γ Pegasi left this problem unsolved. But both rotation axis of γ Pegasi and line of sight are almost

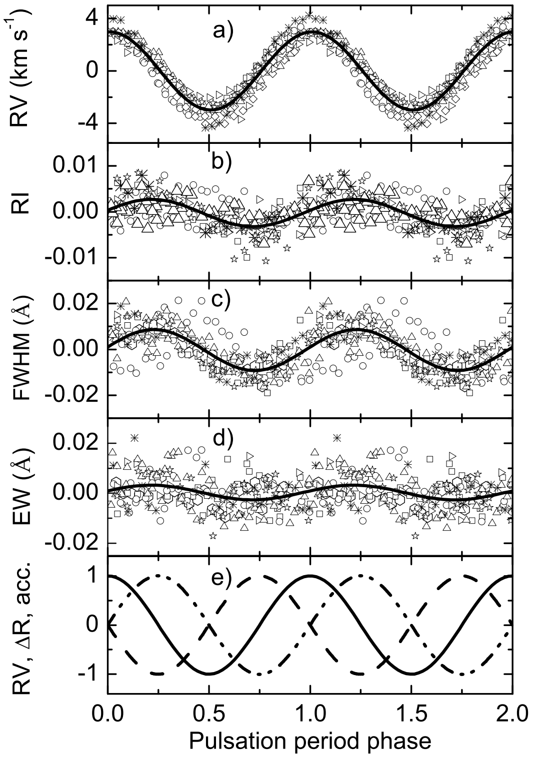

Fig. 1. Radial velocity (a), RI (b), FWHM (c), EW (d) of the He I line. The radial velocity (solid line), radius variation (dashed line) and acceleration (dash-dot-dot) curves (e)

coincide (see Introduction). So, if γ Pegasi has a dipole magnetic field with polar strength comparable to polar field strength of above-mentioned pulsating B-stars then magnetic dipole axis would be situated near rotational equator plane and the longitudinal magnetic field value can be less than some dozens Gauss.

Indeed, in our high accuracy magnetic field measurements the longitudinal magnetic field values are scattered from about -8 to 11 G. Assuming angle β between both rotation and dipole axes is 90° and polar field strength is 360 G (by analogy to β Cephei polar field strength), one can estimate the inclination angle i between the rotational axis and the line-of-sight for which the amplitude of the calculated curve would be coincided with range of scattering of observed data (20 G). For γ Pegasi inclination angle i estimated in such manner is less than 7°.

The radius variation due to pulsation of γ Pegasi is 0.004 R_*, so if the star has a magnetic field one can supposed that the pulsation variation of the frozen magnetic field exists. It was calculated, that for given central dipole configuration amplitude of the longitudinal magnetic field variation owing to stellar radius variation is of about 0.4 G.

3.3 Binarity

McNamara (1955) pointed out a possibility that γ-axis of the 0.15-day velocity curve of γ Pegasi varies. Harmanec et al. (1979) have determined the 6.83-day period for the variations of the γ-axis, indicating that the star is a spectroscopic binary, and gave the ephemeris:

$$RV_{max}(JD_0) = HJD2434675.620 + n \times 6.830713 \pm 0.000169 \qquad (1)$$

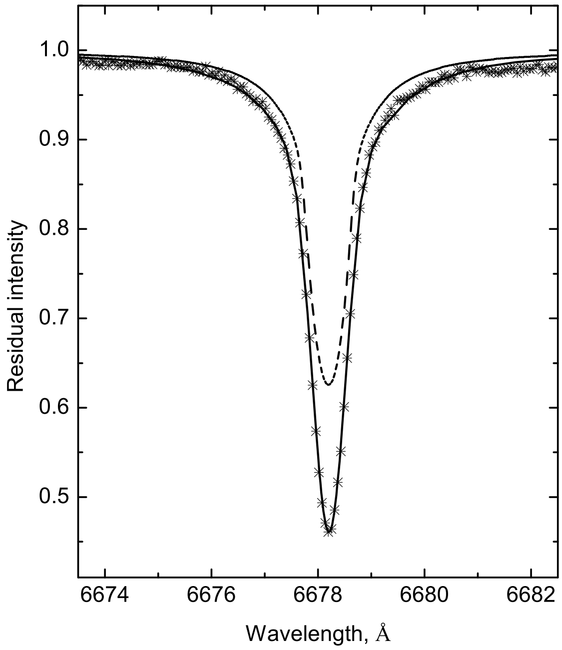

Fig. 2. The He I 6678 Å line. Observed profile (stars), NLTE profile (solid line), LTE profile (dashed line)

Ducatel et al. (1981) clearly detected day-to-day variations of the γ-velocity, but because many of their data points deviate from curve published by Harmanec et al. (1979), they supposed that the γ-axis probably varies due to the stellar oscillations.

Values of the γ-velocity as a function of the 6.83-day period phase are given in Figure 3a, where filled circles represent our γ-velocity data, filled squares are data taken from Figure 1 in paper of Harmanec et al. (1979), and crosses are data of Ducatel et al. (1981).

2K-amplitudes of the pulsation radial velocity curves as a function of the 6.83-day period phase are presented in Figure 3b.

Following possible origins of the 6.83-day period were examined in this study:

1. The 6.83-day period is produced by frequency superposition of the fundamental pulsation period and sideral day.

It was found, that fundamental pulsation mode for γ Peg is 0.730 day that significant less than 0.870-day period which frequency superposition with sidereal one could produce the 6.83-day beat period.

2. The 6.83-day period is a result of a superposition of a traveling wave and a stationary oscillation (Osaki, 1971). In this case the amplitude of the pulsation radial velocity curves must be modulated by the 6.83-day period.

Though 2K-amplitude of the pulsation radial velocity curves exhibits day-to-day variations (Figure 2b), but the periodicity is not statistically significant.

3. The 6.83-day period is a result of a superposition of a wave traveling in the rotation direction and a wave in the opposite direction that can give a beat in which the γ-velocity modulated. In this case variation in γ-velocity should be accompanied with those in the shape of the pulsation radial velocity curves with the same long period, while the orbital one should not (Osaki, 1971; Mathias et al., 1992).

In our case the shape of the pulsation radial velocity curves are the same for all pulsation cycles (see Figure 1a).

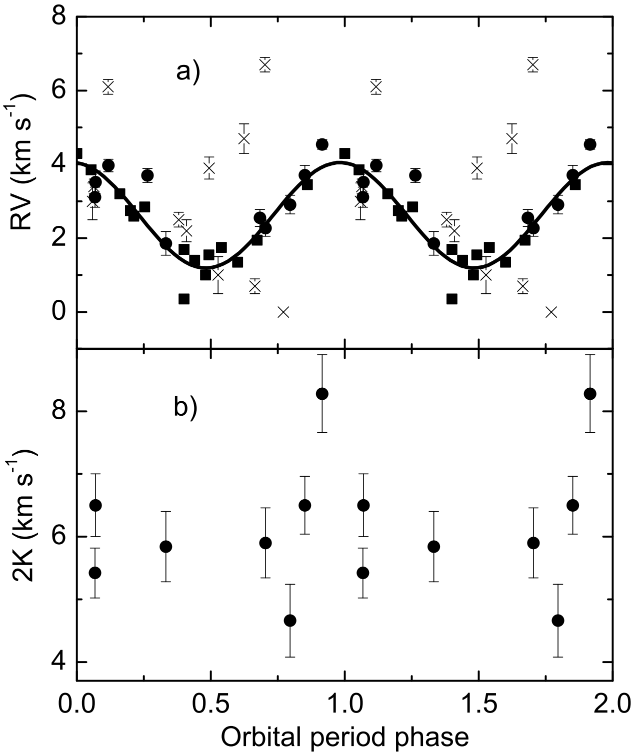

Fig. 3. γ-velocity (a) and $2K$-amplitude (b)

4. The 6.83-day period is a result of frequency superposition of 0.15-day pulsation period and a some neighbour period.

Search for period closed to 0.15-day was performed using program Period98 (Sperl, 1998). For this purpose our radial velocity data were supplemented by data of McNamara (1955), Sandberg and McNamara (1960), and Ducatel et al. (1981) and frequency resolution was 2.61×10^{-6}. We not found any period close to 0.15-day which could produce the 6.83-day beating.

In view of the aforesaid, it was concluded that 6.83-day period is orbital period as it was claimed by Harmanec et al. (1979). For more precise orbital element calculation our γ-velocity data were completed by data of Harmanec et al. (1979). Improved orbital elements are presented in Table 1.

`**Таблица 1.** Orbital elements of γ Pegasi

Orbital element	Harmanec et al. (1979)	This study
e	0	0
K	1.34±0.11	1.42±0.03
γ	2.50±0.09	2.62±0.03
$f(m)$	1.71×10^{-6} M$_\odot$	2.03×10^{-6} M$_\odot$
$a_1 sini$	0.181 R$_\odot$	0.192 R$_\odot$

Because γ Pegasi seems virtually rotational pole-on and assuming that the rotational axis of γ Pegasi is parallel to its orbital angular momentum vector then the orbit inclination of such binary system would be low. Indeed, for boundary condition of absence of mass transferring between the components, from mass function

$$f(m) = M_2^3 sin^3 i/(M_1 + M_2)^2 \tag{2}$$

(where $M_{1,2}$ - masses of primary and secondary components; i - orbit inclination angle), using primary component mass value 8.3 $M_\odot$ (Venn et al., 1996) and assuming that the secondary component is a latter B- or A-type Main sequence star, inclination angle was estimated as $i \ \leq 2°$.

On the other hand, in the Section 3.2 it was shown, that the inclination angle i between the rotational axis and the line-of-sight is $i \ \leq 7°$. Owing to our assumption that the rotation axis is close to perpendicular of the orbit plane, one can conclude that the orbit inclination would be really $i \ \leq 7°$.

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