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The classical β Cephei star γ Pegasi: study of pulsation, binarity and magnetic field

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Abstract. In this work the results of study of magnetic field variability of the classical β Cep-type star γ Peg are presented. The 370.5-day orbital period detected recently by Chapellier et al. (2006) is not confirmed. Weak magnetic field has been detected on the star. The longitudinal component of the field varies from $-8\,$G to $34\,$G with the rotational period $P_{\rm rot} = 6.653$ days. Variation of the longitudinal magnetic field during the pulsation period with an amplitude of about $7\,$G has been detected.

Key words: stars: magnetic fields – stars: early-type – stars: oscillations – stars: binaries: spectroscopic – stars: individual: β Cephei

1 Introduction

γ Peg (HD 886, HR 39, Sp B2 IV) is a classical β Cep-type star which pulsates in a low-order purely radial mode. It has one of the weakest amplitude variation in radial velocity, $2K = 7$ km s^{-1}, light $\Delta m_{\rm V} = 0.017$ with a short pulsation period of 0.15 day. de Jager et al. (1982) concluded that γ Peg has a virtually zero rotational velocity component.

McNamara (1955) pointed out a possibility that the γ-axis of the 0.15-day velocity curve of γ Peg varies. Harmanec et al. (1979) have determined a 6.83-day period for the variation of the γ-axis and have given the ephemeris:

$$JDh(RV_{\rm max}) = 2434675.620 + n \times 6.830713 \pm 0.000169\,. \qquad (1)$$

They have concluded that the star is a spectroscopic binary with a circular, slightly inclined orbit. Ducatel et al. (1981) have suggested that the day-to-day variations of the γ-axis are associated with stellar oscillations. Butkovskaya et al. (2006) have confirmed that γ Peg is a spectroscopic binary as it was suggested by Harmanec et al. (1979). Orbital elements calculated by them are consistent with those published by Harmanec et al. (1979). Recently, Chapellier et al. (2006) combining their radial velocity measurements with data from the literature also confirmed the binarity of this star but with another orbital period of 370 days.

The attempts to detect a magnetic field on γ Peg have been made by different researchers. Babcock (1958) found no evidence for the presence of the magnetic field in this sharp-line star. Rudy & Kemp (1978) detected no statistically significant magnetic field on γ Peg with the least error $\sigma = 30$ G. Landstreet (1982) found no any traces of a magnetic field on γ Peg with the least error $\sigma = 45$ G. Butkovskaya & Plachinda (2004) also detected no statistically significant values of the longitudinal magnetic field in this star. The detection level with error bars from 4 to 15 G was achieved by the authors in the course of ten observing nights.

By now, a weak dipole magnetic field with a polar strength of some hundred Gauss has been detected on a number of chemically normal early type stars: β Cep (B1 IV, Donati et al. 2001), θ^1 Ori C (O4-6 V, Donati et al. 2002; Wade et al. 2006) V 2052 Oph (B2 IV-V), ζ Cas (B2 IV), and ω Ori (B2 IIIe) (Neiner et al. 2003a,b,c).

Hubrig et al. (2006) have detected a longitudinal magnetic field of the order of a few hundred Gauss on the β Cep star ξ^1 CMa and 13 slowly pulsating B stars.

Discovery of a magnetic field with unusually complex topology on the young massive star τ Sco was reported by Donati et al. (2006).

Two hot stars which host magnetic field, β Cep and V 2052 Oph, pulsate mainly in a radial mode. No results of study of magnetic field modulation due to the pulsations were published for these stars.

On the other hand, the presence and pulsational modulation of magnetic field in the cool pulsating supergiants RR Lyr and η Aql have been widely discussed in literature (Babcock 1958; Preston 1967; Romanov et al. 1987, 1994; Chadid et al. 2004; Borra et al. 1981; Plachinda 2000; Wade et al. 2002).

In the Section 2 the spectropolarimetric observations are presented. In the Section 3 the reality of the 370-day orbital period is tested. Discovery of the presence of magnetic field on γ Peg is reported in the Section 4. Also, in the Section 4 the results of a detail study of the longitudinal magnetic field variation due to the radial pulsations of the star are presented. All obtained results are summarized in the Section 5.

2 Observations and data reduction

An intensive study of γ Peg was performed in the He I 6678 line in the course of 23 nights from 1997 to 2005. A total of 405 exposures were obtained using the coude spectrograph of the 2.6-m Shajn telescope of the Crimean Astrophysical Observatory (in particular, 262 exposures were obtained using a polarimeter). The signal-to-noise ratios for a single spectrum were typically 350–600 with a spectral resolving power of approximately 2.2×10^4.

The study of the magnetic field of the star was carried out with the same equipment and 'Flip-Flop' procedure discussed in the paper by Plachinda (2004). In this case an internal polarimeter capability allows us to control the presence or absence of significant stochastic or spurious time-dependent Stokes signatures. When using more than one pair of exposures, spectra with identical circular polarization which are obtained at identical quarter-wave plate angles are projected on same location of the CCD. Therefore, we can calculate the value of the spurious 'magnetic field' that must be equal to zero if all spurious effects are negligible. In order to test the reliability of obtained results we evaluate the 'spurious field' $B_{\rm test} \pm \sigma_{\rm test}$.

3 Binarity

In this section the reality of the 370.5-day orbital period claimed by Chapellier et al. (2006) is tested. All γ-velocities and $2K$-amplitudes of the individual pulsation curves were recalculated using the least-square sinusoidal fitting of the data published by different authors. We found no peculiarity in the $2K$-amplitude of the pulsation velocity curves, whereas the behavior of the γ-velocity is more complicated.

In the upper panel of Figure 1 the γ-velocities obtained from data of McNamara (1955, 1956), Sandberg & McNamara (1960), Lane & Percy (1979), Ducatel et al. (1981), our data (filled circles), and data of Chapellier et al. (2006) (asterisks) are folded in phase with the 370.5-day period. Positive γ-velocities measured by us from 1998 to 2005 locate in a phase interval from 0.8 to 1.3. Extremely negative γ-velocities detected in 1992, 1993, and 1995 by Chapellier et al. (2006) occupy

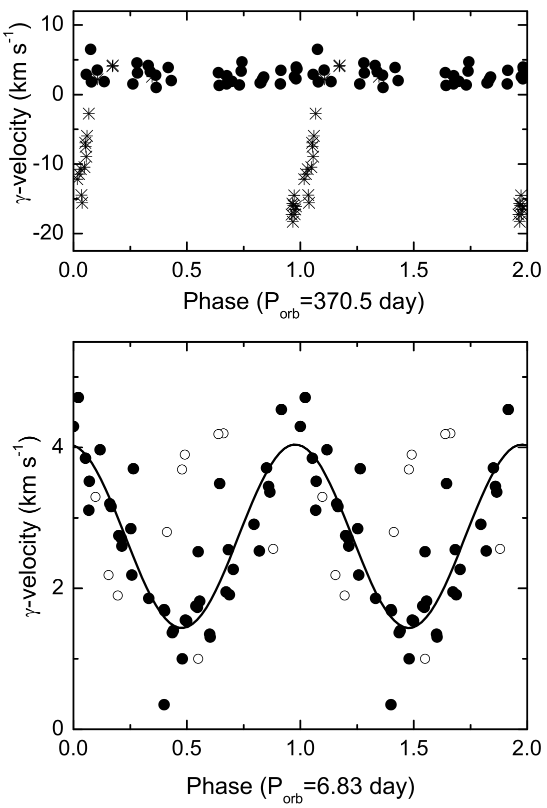

Figure 1: γ-velocities folded in phase with the 370-day (*top panel*) and 6.83-day (*bottom panel*) periods.

the same phase interval (0.9 – 1.1). We also detected an abnormally blueshifted γ-velocity of the star, -60.57 ± 0.29 km s^{-1}, during one observational night in 2005 (JDh 2453599). This value locates at phase 0.83 and it is not shown in Figure 1. In our opinion, these negative γ-velocities of the star are not produced by orbital motion. It may be an episodic mass loss that takes place during sporadic outbursts by analogy with the Be-stars.

In the bottom panel of Figure 1 all positive γ-velocities are folded with the 6.83-day period. The γ-velocities obtained from data of McNamara (1955, 1956), Sandberg & McNamara (1960), Harmanec et al. (1979), Lane & Percy (1979) and our γ-velocities are in good agreement with each other. They are shown as filled circles. However, some data of Ducatel et al. (1981), and Chapellier et al. (2006) demonstrate significant scatter (open circles in Fig. 1). The sinusoidal least-square fit of the filled circles is shown by the solid line. In our opinion, the star is a spectroscopic binary and the 6.83-day orbital period suggested by Harmanec et al. (1979) can be used as the initial guess. To improve the orbital period and orbital elements, additional time-series of the radial velocity are required.

4 Magnetic field

We used our averaged-per-night values of the longitudinal magnetic field to search for a periodicity in variation of the field strength. To determine the period we applied "Period98" program (Sperl, 1998). Computations were performed on the assumption that the rotation period of γ Peg is close

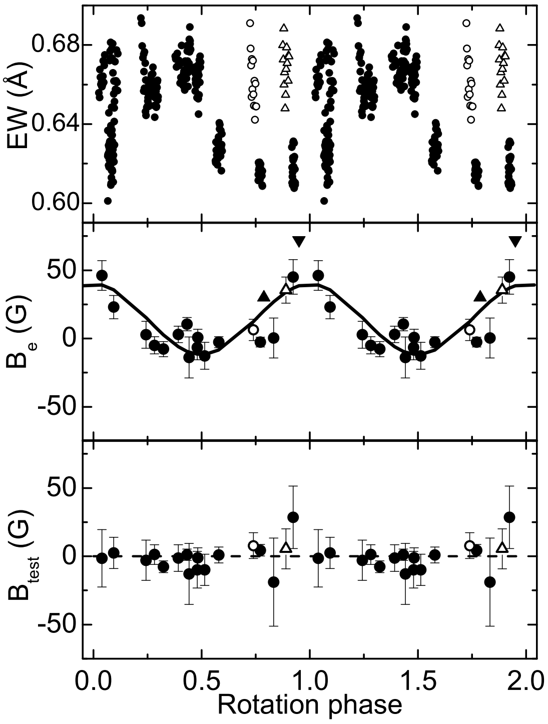

Figure 2: EW, $B_{\rm e}$, and zero field $B_{\rm test}$ folded in phase with the 6.653-day axial rotation period.

to its orbital period. Analysis of the power spectrum of the data revealed a period of 6.653 ± 0.001 days as the most probable. We suggest that this period corresponds to the rotation period of the star. The following ephemeris was calculated:

$$JDh(B_{\rm max}) = 2450679.364 + n \times 6.653 \pm 0.001\,. \qquad (2)$$

In Figure 2 the Equivalent Width (EW) of the He I line, mean-per-night longitudinal magnetic field $B_{\rm e}$ and zero field $B_{\rm test}$ (see Section 2) are folded in phase with the axial rotation period. Zero field $B_{\rm test}$ measurements (see Figure 2) indicate that no spurious circular polarization signals are observed.

The EW and magnetic field obtained during two nights of observations, JDh 2453599 (when γ-velocity of the star was unusually blueshifted), and previous night JDh 2453598 (when the γ-velocity was yet normal but the increase of the EW were detected) are plotted as opened triangles and circles. Our other data are shown as filled circles.

Equivalent widths of the He I line exhibit two maxima at phases 0.05 and 0.45 (i.e. near the phases of maximal positive and negative field, respectively), and two minima at phases 0.25 and 0.75. The rotational modulation of the EW is most likely produced by the temperature variations which occur when the magnetic poles pass across the line of sight.

In total, 9 measurements of magnetic field on γ Peg were also performed by Rudy & Kemp (1978) and 3 measurements were made by Landstreet (1982). In spite of large errors, two more precise values obtained by Rudy & Kemp (30 ± 90 G) and Landstreet (72 ± 45 G) are in good agreement with our data (filled up- and down-directed triangles in Figure 2). We do not illustrate the other results of these authors because of unacceptable error bars (more than one hundred Gauss).

The best sinusoidal fit of the magnetic data is presented by the solid line in Figure 2. Around the average value of $B_0 = 13 \pm 4$ G, the amplitude of $B_{\rm e} = 21 \pm 4$ G was found. The longitudinal magnetic field varies from -8 G to $+34$ G. Using Fisher's F-test, a confidence level of statistical

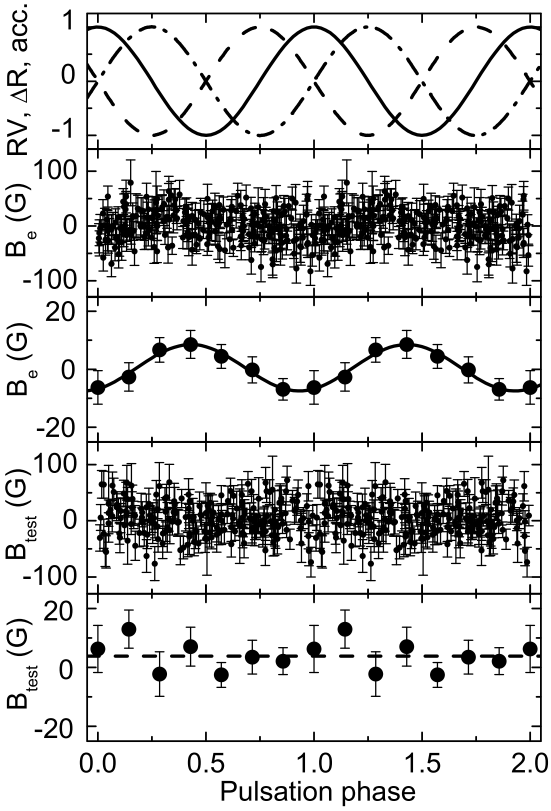

Figure 3: *Top panel*: radial velocity curve (solid line), acceleration curve (dash-dotted line), and radius variation curve (dashed line); *two middle panels*: individual magnetic field values folded in phase with the 0.15-day pulsation period and magnetic field B_{e} binned and averaged within 7 bins; *two bottom panels*: as well as middle panels but for 'zero' field B_{test}.

assurance of the field variation with rotation is evaluated to be 99.7%. Therefore, the centered dipole is a good initial approximation to describe the magnetic field geometry of γ Peg.

Assuming the limb darkening coefficient $u = 0.350$, we simulated the dipole magnetic field of γ Peg using the 'Magnetic Charge Distribution' method presented and described by Lebedev (1980) and Gerth & Glagolevskij (2000). The best fit to the observational data gives the following results: the polar field strength $B_{\mathrm{pol}} = 570$ G, the angle between the spin axis and the line of sight $i = 9°$, and the angle between both the spin and dipole axes $\beta = 85°$.

A study of the magnetic field behavior due to the radial pulsations of the star has been performed using individual longitudinal magnetic field values. The mean-per-night magnetic fields were subtracted from the individual values to eliminate the axial rotation effect. Therefore, we can not claim that the effective magnetic field of γ Peg changes its sign during the pulsation. The phases of the 0.15-day pulsation period were computed according to the ephemeris presented by Butkovskaya & Plachinda (2004):

$$P(RV_{\mathrm{max}}) = 2451060.461 + n \times 0.151750393 \pm 6.4 \times 10^{-8}\,. \qquad (3)$$

In the upper panel of Figure 3 the acceleration (dash-dotted curve) and the radius variation (dashed curve) calculated in a standard manner are presented with the radial velocity (solid curve) in the stellar rest frame. The curves are normalized by their extreme values, which are 1.41 m s^{-2}

for the acceleration, 2.98 km s^{-1} for the velocity, and 0.004 R_* for the peak-to-peak amplitude of the radius variation. Smooth sinusoidal form of all these curves indicates the absence of significant non-linear motions in the photosphere layer where the He I line is formed.

The longitudinal magnetic field phased with the pulsation period is represented in the middle panel of Figure 3. The B_e shows periodic variations due to the stellar radial pulsation and reaches its maximal and minimal values near phases of 0.45 and 0.95, respectively, i.e. the longitudinal component of the magnetic field varies almost in antiphase with the radial velocity. The behavior of the magnetic field with the pulsation period can be seen more clearly for averaged data, therefore in the third panel of Figure 3 the data are binned and averaged within 7 bins. The least-square sinusoidal fit is shown by the solid line. Each bin consists of about 30 field measurements. The magnetic field varies with the amplitude of $B_e = 7.2 \pm 0.6$ G around the average value of $B_0 = 0.5 \pm 0.4$ G.

In order to test the reliability of the pulsational variation of the magnetic field, in the two bottom panels 'zero' field B_{test} (see Section 2) folded in the same manner as B_e is presented. The average value is $< B_{test} >= 3.86 \pm 2.07$ G.

The origin of the observed pulsational variations of the longitudinal magnetic field will be discussed below.

1. *Homothetic pulsations of the whole dipole.* Owing to the fact that the magnetic field is frozen into the plasma, the initial hypothesis is that the radial pulsations of the star result in the homothetic variation of the magnetic dipole. Numerical simulations have been performed to evaluate the amplitude of the longitudinal component variation in this case. For given configuration of the dipole ($B_{pol} = 570$ G, $i = 9°$, $\beta = 85°$) the observed amplitude of the longitudinal magnetic field variation must be some tenths of Gauss, that is order of magnitude lower than the measured amplitude. Furthermore, in the case of the dipole homothetic pulsations the magnetic field should be maximal when the star is compressed and minimal when the star is expanded. This model is not confirmed by our observations (see Figure 3).

2. *Distortion of the initial dipole configuration.* In reality, the variation of the stellar structure during the pulsation cycle is not homologous. The pulsational amplitude of the layers above helium ionization zone is significantly larger than the pulsational amplitude of the layers below. Therefore, while under the helium ionization zone the magnetic field geometry is virtually stable, the pulsational motion of the atmosphere matter can appreciably distort the initial configuration of the magnetic dipole. On the other hand, in the presence of a magnetic field, pulsational motion of the upper layers of a star may lead to the generation of the magnetohydrodynamic waves. In that case the initial shape and density of magnetic field lines would also be disturbed.

3. *An artificial effect produced by variable velocity field.* A possible signature of the velocity field is the presence of line asymmetries, usually described in terms of the shape of the line bisector. Figure 4 shows the asymmetries for He I 6678, as delineated by the line bisectors.

All above-mentioned mechanisms are probably capable to give the observed pulsational variation of the longitudinal magnetic field. Therefore magnetohydrodynamic simulations are needed for studying the relation between stellar pulsations and magnetic field behavior. In addition, numerical simulations of the synthetic spectra of a star in the presence of magnetic field and variable velocity field are also needed.

5 Summary

The results of the spectropolarimetric study of the classical β Cep-type star γ Peg is presented.

The 370.5-day orbital period has not been confirmed. We have concluded that the star is a spectroscopic binary, and the 6.83-day orbital period suggested by Harmanec et al. (1979) can be used as an initial guess.

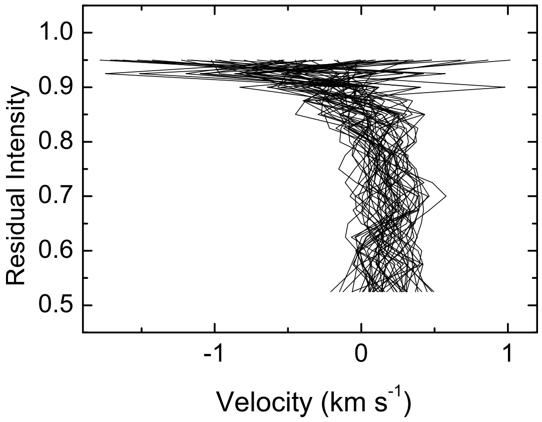

Figure 4: Bisectors of the He I 6678 line obtained during 4.93 h (47 exposures; JDh 2451172). The zero point of velocity scale corresponds to a center of gravity of the line.

During one night (JDh 2453599) the abnormally blueshifted radial velocities were detected in the He I 6678 line ($\gamma = -60.57 \pm 0.29$ km s^{-1}).

The presence of weak magnetic field has been detected in γ Peg. The longitudinal component of the field varies from -8 G to 34 G in phase with the stellar rotation period $P_{\rm rot} = 6.653 \pm 0.001$ day. Assuming the magnetic field of γ Peg to be dipole, we have estimated the polar field strength $B_{\rm pol} = 570$ G. The angle between the rotational axis and line of sight $i = 9°$. The angle between the rotational and magnetic dipole axes $\beta = 85°$.

The longitudinal component of the magnetic field is found to be variable during 0.15-day pulsation period of the star with an amplitude of $\sim$ 7 G. The maximum and minimum of the magnetic field variation locate at phases 0.45 and 0.95, respectively (i.e. near those phases where the radial velocities demonstrate their maximum outward- and inward-directed projections).

The origin of the observed pulsational variations of the longitudinal magnetic field is discussed. It is concluded that magnetohydrodynamic simulations are needed for studying the relation between stellar pulsations and magnetic field behavior, and numerical simulations of the synthetic spectra of a star in the presence of both magnetic field and variable velocity field are also needed.

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