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A hybrid β Cephei-SPB star in a binary system: γ Pegasi[⋆,⋆⋆,⋆⋆⋆]

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ABSTRACT

High resolution and high signal to noise ratio spectroscopic observations of the classical β Cephei star γ Peg were obtained between 1991 and 2005. The analysis of these data combined with previously published results shows that γ Peg is a spectroscopic binary with an orbital period of 370.5 d. We discovered three new frequencies in addition to the well-known 6.5897 d^{-1} (0.15175 d) one. That at 6.01 d^{-1} is a typical β Cephei frequency. The two others at 0.68 and 0.87 d^{-1} are similar to the high degree g-mode frequencies found in SPB stars. Thus, γ Peg is a hybrid β Cephei-SPB star. Its position in the HR diagram is compatible with such a status.
In addition, a small increase of the main period has been detected between the 1995 and 2005 observations.

Key words. stars: binaries: spectroscopic – stars: oscillations – stars: individual: β Cephei – stars: variables: general

1. Introduction

γ Peg (HD 886, $B2$ IV, $m_v = 2.83$) is one of the so-called "classical" β Cephei stars. It has been assigned to this group by McNamara (1953) who demonstrated its variability in radial velocity with a single period of 0.1517 d and an amplitude of 3.5 km s^{-1}. Its photometric variability, with the same period as the spectroscopic one and corresponding to an amplitude of 15 mmag in yellow light, was detected by Williams (1954). He showed that, as in the other stars of the group, the light curve lags about 90° behind the radial velocity one. Jerzykiewicz (1970), observing the star through UBV Johnson's filters, derived the amplitudes $U = 27$ mmag, $B = 18$ mmag and $V = 17$ mmag. He also observed that the $U - B$ colour index was smallest around light maxima. A more precise determination of the period was obtained by Sareyan et al. (1975) and its constancy was confirmed by Valtier et al. (1985). Smith & McCall (1978) and Cugier et al. (1994) attributed this pulsation to a radial mode. From high time and high spectral resolution observations obtained with an electronographic camera, Duchesne et al. (1967) showed that line profile and equivalent width variations were associated with the light and radial velocity period.

Harmanec et al. (1979) proposed a binary period of 6.83 d which has not been confirmed yet.

We have obtained new spectroscopic observations from which new results could be derived both on the binary nature and on the pulsation of γ Peg. Section 2 presents the observations, Sect. 3 examines the binarity and the pulsation characteristics of the star. The results are discussed in Sect. 4.

2. Observations

A total of 1079 spectra were obtained in 1991, 1992, 1993, 1995 and 2005 at the Haute-Provence Observatory using the Aurelie spectrograph attached to the 152 cm telescope. Three wavelength domains were considered: the first one centered on the Si III triplet at 4552 Å, 4567 Å and 4574 Å, the second one centered on Si II at 5320 Å and the third one centered on S II 5453 Å. The journal of the observations is given in Table 1. The resolution of the spectra is 30 000 and the signal to noise ratio is always above 200. Reductions were done using the IRAF[1] software. In order to limit the dispersion in the data, only the Si III 4567 Å (not affected by any blend) radial velocities were considered. When this line was not observed, we used the Si III 4828 Å, S II 5320 Å or S II 5453 Å lines.

3. Data analysis

3.1. Binary elements

The spectroscopic binary nature of γ Peg is still debated: while McNamara (1955) pointed out that the γ-velocity of the curves relative to the 0.15175 d period might vary, Abt & Levy (1978) claimed that their observations did not present any variation

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[⋆] Based on observations obtained at the Observatoire de Haute-Provence.

[⋆⋆] Radial velocity data are available in electronic form at the CDS via anonymous ftp to `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/448/697`

[⋆⋆⋆] Table 1 is only available in electronic form at `http://www.edpsciences.org`

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

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Table 2. Elements of the orbit.

P = 370.5 ± 0.5 d
T = 2449215.69 ± 1.94 d
e = 0.62 ± 0.04
v = -0.52 ± 0.36 km s^{-1}
ω_1 = 191.7 ± 5.4^o
K = 11.35 ± 0.81 km s^{-1}
$a \sin i$ = $(45.2 \pm 5.4)\,10^6$ km
f_m = $0.0268 \pm 0.0095\,M_\odot$
σ = 2.24 km s^{-1}

in relation to a possible orbital period. Harmanec et al. (1979) analyzed all the published data and announced an orbital period equal to 6.83 d with a low amplitude ($K = 1.34$ km s^{-1}) and a zero eccentricity. This result was contradicted by Ducatel et al. (1981) on the basis of new data indicating that the weak variations of the γ axis in their data were not in agreement with the period of Harmanec et al. (1979). Our new observations exhibit clear variations in the γ values from –22 km s^{-1} to +7 km s^{-1} and suggest a longer orbital period and an amplitude much larger than the Harmanec et al. (1979) ones. These new data and all the published radial velocities since 1931 (McNamara 1953, 1955, 1956; Sandberg & McNamara 1960; Abt & Levy 1978; Lane & Percy 1979; Harmanec et al. 1979; Ducatel et al. 1981) have been used to study the binary nature of γ Peg. We did not use the radial velocities published before 1931 because they are too highly scattered. Using the Phase Dispersion Minimization (PDM) method (Stellingwerf 1978), we derived a period of 370.5 d. However, at this stage of the analysis, because this value of the period was close to one year, and because large gaps exist in the data, we could not completely exclude the half value (185 d). To reduce the influence of pulsation, we then determined for every night the γ velocity derived from a sine-fit with the 0.15175 d pulsation period. The result of the PDM analysis supports unambiguously the 370.5 d value. Table 2 provides the main elements of the orbit and Fig. 1 shows the adjustment throughout the data. There is no indication of a period around 6.83 d as proposed by Harmanec et al. (1979). In the 1993 and 1995 data, the detection thresholds are respectively 0.22 and 0.28 km s^{-1}, five times lower than the amplitude claimed by Harmanec et al. (1979). The small night to night variations in the mean radial velocity found by various authors can be easily explained by the SPBs pulsation (see Sect. 3.2).

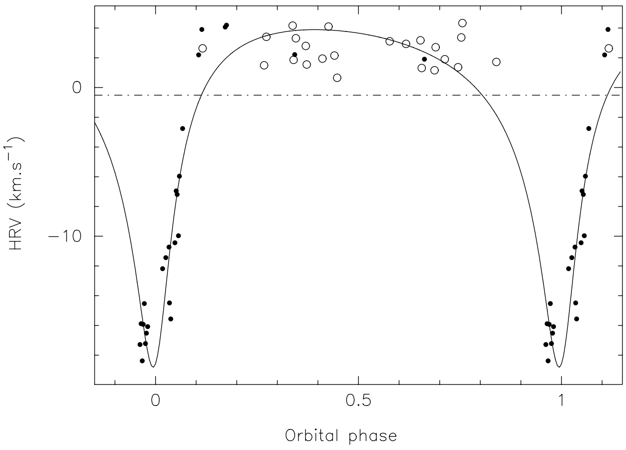

Fig. 1. Fit of γ heliocentric radial velocities (HRV) with the 370.5 d orbital period. Open circles represent old observations; dots correspond to our new observations.

Table 3. Results of the Fourier analysis performed on the 1993 and 1995 data. The frequencies f_i are in d^{-1}, the amplitude K_i in km s^{-1} and the phases φ_i in fractions of a day. The zero points are HJD 2 449 201.4558 for the 1993 data and HJD 2 449 969.3337 in 1995. The residuals are respectively 0.47 and 0.40 km s^{-1}.

	1993			1995		
	f_i	K_i	φ_i	f_i	K_i	φ_i
f_1	6.591	3.57	0.896	6.589	3.31	0.059
	±3	±11	±5	±1	±9	±4
f_2	0.659	1.60	0.452	0.670	1.37	0.231
	±6	±11	±11	±3	±9	±10
f_3	0.840	0.80	0.213	0.872	1.57	0.704
	±11	±11	±22	±3	±9	±9
f_4	5.993	0.41	0.331	6.019	0.47	0.584
	±21	±11	±44	±8	±9	±29

3.2. Pulsation

3.2.1. Frequency analysis

Our data set consists of 5 series of observations, i.e., 2 consecutive nights in 1991, 5 nights spread over 36 days in 1992, 8 consecutive nights in 1993, 8 nights spread over 12 days in 1995 and 2 nights in 2005 (Table 1). The radial velocity curves show that the variations cannot be accounted for by a single frequency contrary to what has been claimed up to now. We searched for new frequencies in the two most abundant series of data obtained in 1993 and 1995 using the Period04[2] software (Lenz & Breger 2005). We have not prewhitened the data for orbital motion because the uncertainties on the shape of the curve are still too large. We first analyzed the data year by year. In 1993, four frequencies are detected at respectively 6.591, 0.659, 0.840 and 5.99 d^{-1} (Table 3). Figure 2 shows the corresponding Fourier spectra.

In 1995 our data lie on the steep ascending branch of the orbital curve and the γ velocity increases by more than 10 km s^{-1} in 12 days. Consequently in our periodogram a low non-pulsational frequency appears with a large amplitude. After prewhitening these data for this frequency, we are able to compensate for the orbital movement and then look for pulsation frequencies. The same four frequencies are again present at 6.589, 0.670, 0.872 and 6.02 d^{-1} (Table 3). Figure 3 presents the corresponding Fourier spectra. To make the figure clearer, only the periodograms corresponding to the pulsations

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[2] Period04 is a software package designed for sophisticated time series analysis available at
`http://www.astro.univie.ac.at/~dsn/`

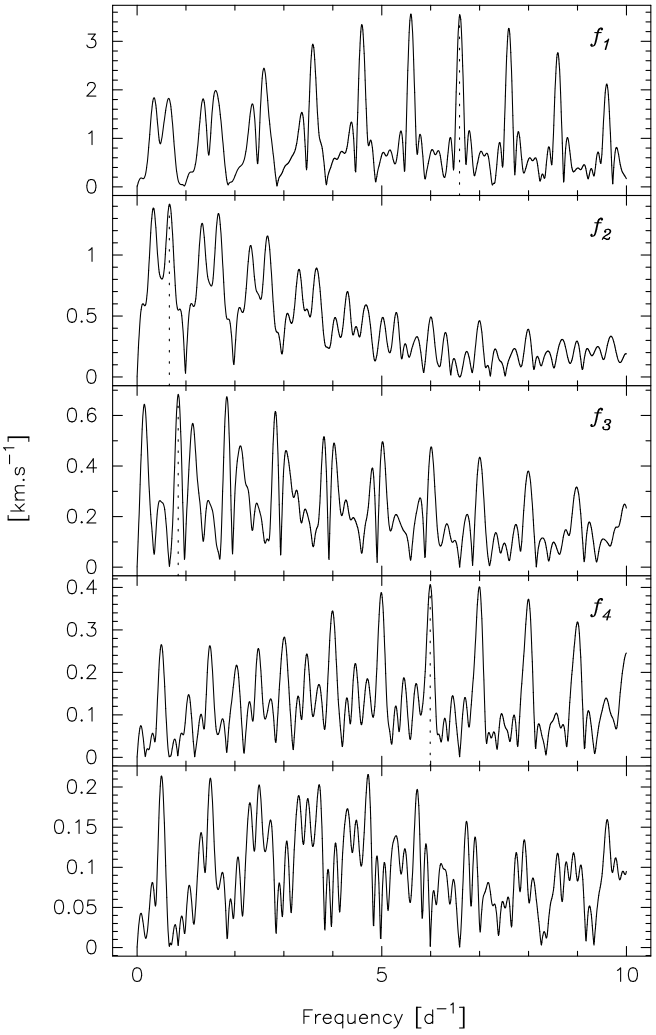

Fig. 2. Amplitude spectra for the 1993 data. The successive panels show the periodograms after different stages of prewhitening. The dotted line indicates the position of the detected frequency given in the upper right corner. The bottom one shows the periodogram for the residuals.

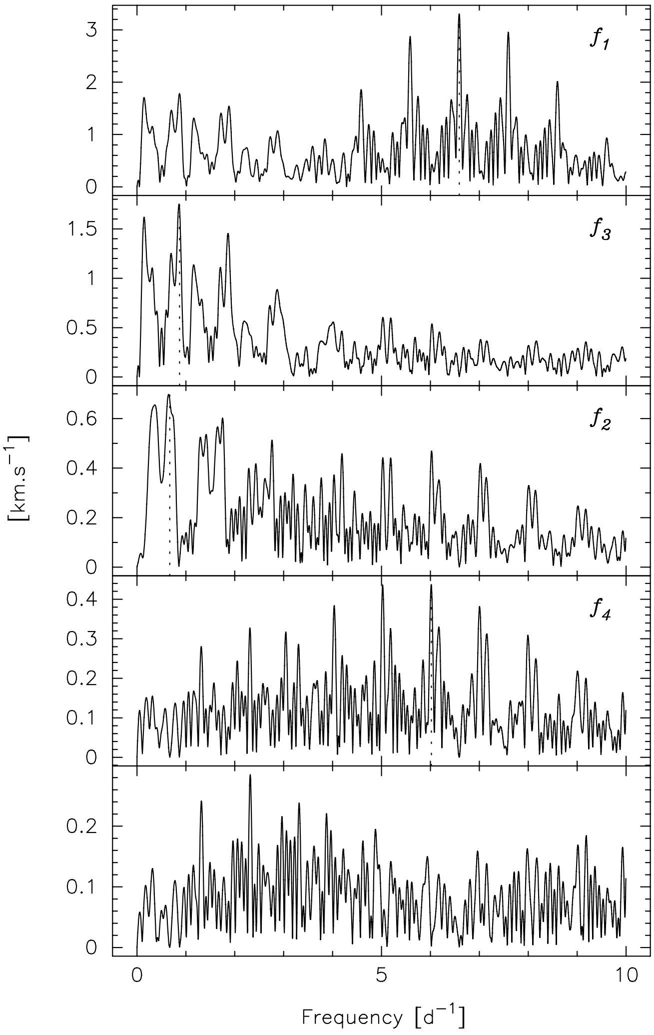

Fig. 3. Amplitude spectra for the 1995 data (see Fig. 2). Note that f_3 is detected before f_2.

frequencies are presented. Using a straight line to prewhiten the 1995 data for the orbital motion, we find the same four frequencies but with small differences for the two low ones: $f_2 = 0.701\,\mathrm{d}^{-1}$, $K_2 = 1.65\,\mathrm{km\ s}^{-1}$ and $f_3 = 0.892\,\mathrm{d}^{-1}$, $K_3 = 0.82\,\mathrm{km\ s}^{-1}$. Note that we also tried to prewhiten the data for the orbital curve calculated in Sect. 3.1. Unfortunately, this curve is not accurate enough and a slight slope remains so the data had to be prewhitened again for a low frequency.

If we analyze together the two sets of data of 1993 and 1995 after prewhitening for a low frequency, we find again the four frequencies at $f_1 = 6.5898$, $f_2 = 0.686$, $f_3 = 0.866$ and $f_4 = 6.01\,\mathrm{d}^{-1}$, with respective amplitudes $K_1 = 3.46$, $K_2 = 1.41$, $K_3 = 1.12$ and $K_4 = 0.43\,\mathrm{km\ s}^{-1}$. The number of cycles between the two sets is so large that large uncertainties in the cycle count occur.

Considering the results of the two data sets and the different methods used to remove the orbital movement, we finally adopt the main values $f_2 = 0.68 \pm 0.03\,\mathrm{d}^{-1}$, $f_3 = 0.87 \pm 0.03\,\mathrm{d}^{-1}$ and $f_4 = 6.01 \pm 0.03\,\mathrm{d}^{-1}$ for the pulsation frequencies. For f_1, we retained the $6.5897763\,\mathrm{d}^{-1}$ value given by Valtier et al. (1985). Figures 4 and 5 display the adjustment of the observational data using the values provided in Table 3.

3.2.2. Equivalent widths and profile variations

The variability of equivalent widths and line profiles discovered by Duchesne et al. (1967) were confirmed by Le Contel (1968, 1975) and by Smith & McCall (1978). Le Contel & Morel (1985) related the existence of weak components in the wings of the Si III lines to the development of shock waves in the atmosphere of γ Peg. In our new data, weak variations of the equivalent widths (at a level of 2%) and of the Full Widths at Half Maximum are observed, correctly folded with the f_1 frequency. However, the spectral resolution is not sufficient to allow a direct comparison with Le Contel's observations.

3.2.3. Main period variation

As in other β Cephei variables, the constancy of the main pulsation period ($6.5897\ \mathrm{d}^{-1}$; 0.15175 d) of γ Peg has been checked

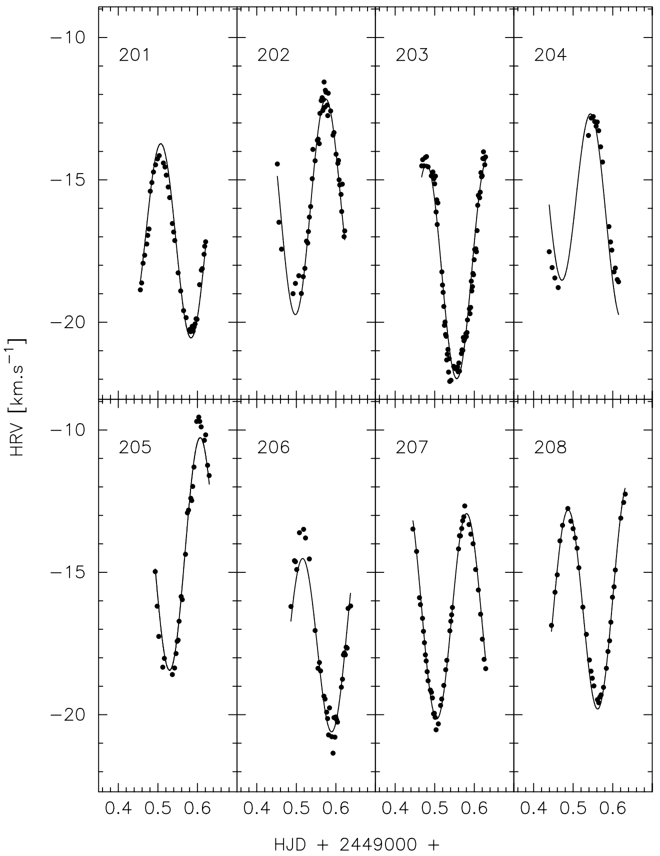

Fig. 4. Adjustment of the 1993 observational data with the frequencies, amplitudes and phases given in Table 3.

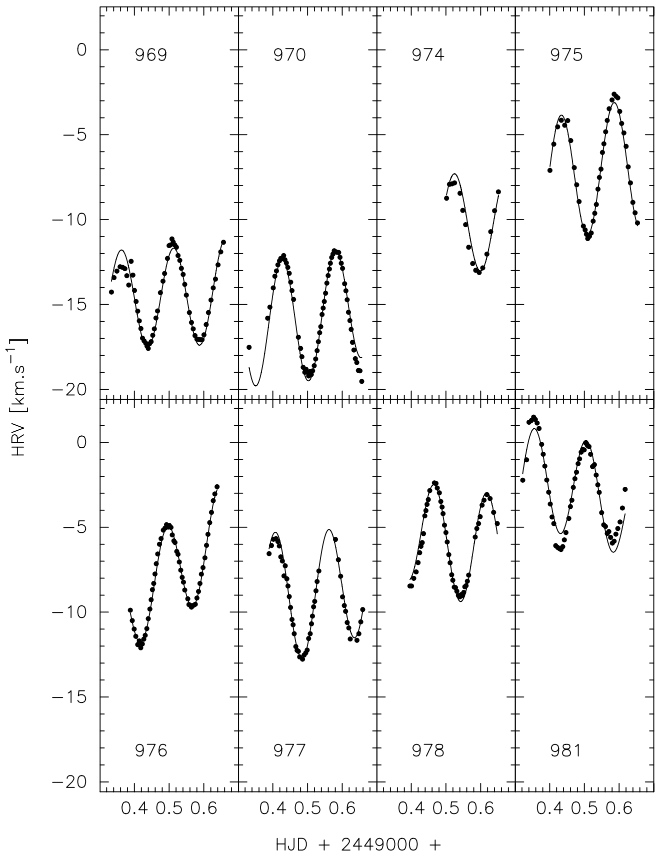

Fig. 5. Adjustment of the 1995 observational data with the frequencies, amplitudes and phases given in Table 3.

by different authors (Van Hoof 1970; Sareyan et al. 1975; Smith & McCall 1978; Lane & Percy 1979; Valtier et al. 1985). They all confirmed that the pulsation period remained constant from 1931 to 1985. Conversely, Koubsky et al. (1981), including in their analysis old data from 1899 to 1931, suggested that the period might have increased at a rate of 0.06 s century^{-1}. Our present data obtained between 1991 and 1995 agree with the Valtier et al. (1985) ephemeris. However, our two 2005 data sets show a phase lag of +0.021 and +0.024 d with respect to this last ephemeris which corresponds to an increase in the main period of at least 0.08 s between 1995 and 2005.

Such abrupt variations have been detected in several other β Cephei stars (Chapellier 1985). In some of these stars such a phenomenon has been explained by the light-time effect associated with a long period (several tens of years) companion (Mendenhall 1930; Odell 1985; Chapellier 1990; Pigulski 1992; Pigulski & Boratyn 1992; Pigulski 1993). In the case of γ Peg, since no other companion was observed by McAlister et al. (1989) and since no observation has been obtained between 1995 and 2005, no interpretation of this period variation can be given.

4. Discussion

The first result arising from our study is the discovery of the binarity of γ Peg. The length of the orbital period (about one year) and the shape of the orbital curve explain why it had not been detected earlier. The value of the orbital elements should be improved by new data obtained during the descending branch of the curve.

The second important result is that γ Peg is a multi-periodic variable: in addition to the well-known f_1 frequency, three new frequencies were detected in two independent data sets as well as in the whole data set. Moreover, we cannot exclude the existence of other frequencies associated with smaller amplitudes. The two high frequencies, i.e. f_1 and f_4, are related to the classical β Cephei instability while f_2 and f_3 are too low, but are well in the range of the SPBs typical frequencies.

The β Cephei type variations in γ Peg were detected more than fifty years ago while the SPBs variations are detected in our data sets separated by about 2 years. They are also observed in our 1992 data set although there are not enough data points to perform a separate detailed analysis. If we reanalyze all the previously published data between 1952 and 1978 and if we prewhiten them for the well-known f_1 frequency, a dominant peak appears at 0.69 d^{-1} corresponding to f_2. Therefore we consider that the two types of variations are always present in γ Peg.

Since the mechanism responsible for the instability of β Cephei and SPB stars has been discovered, theoretical models indicate the existence of a small region in the HR Diagram where the two types of variations can coexist

(Pamyatnykh 1999). This region coincides with the extreme cool limit of the β Cephei instability zone of slightly evolved stars. From its classification (B2IV) and its temperature, γ Peg is among the coldest β Cephei stars and is very close to the hotter limit of the SPBs instability zone as determined by Pamyatnykh (1999). Thus, it is not surprising that γ Peg appears to be a hybrid star. Such SPBs pulsations have been observed in another β Cephei star, ν Eri, by Handler et al. (2005). Using the data from a very large observational campaign in 2002–2003, they detected a low amplitude frequency at $0.432\,\mathrm{d}^{-1}$ in photometry. This frequency has not been detected in spectroscopy (Aerts et al. 2004), but was found again in the 2003–2004 photometric campaign (Jerzykiewicz et al. 2005). On the other hand, high frequency variations have also been observed in two SPB stars, 53 Psc (Wolf 1987; Mathias & Waelkens 1995; Le Contel et al. 2001) and ι Her (Chapellier et al. 1987, 2000) but the phenomenon is spurious.

From a theoretical point of view, the existence of excited p and g modes should allow the simultaneous study of both the external and the internal zones of the star. It may also help to refine the limits of the SPBs instability zone. Our data do not allow mode identification but if f_1 is actually radial, f_2 is necessarily non-radial. Simultaneous photometric and high resolution spectroscopic observations are requested to give more precise frequency values, mode parameters and a better determination of the orbital elements.

5. Conclusion

We presented high-resolution spectroscopic observations, performed over 14 years, of the classical β Cephei star γ Peg. Two new important results are obtained. The first is that γ Peg is an eccentric binary with a period of 370.5 d and an amplitude of $11\,\mathrm{km\,s}^{-1}$. The second result is that this star, considered as one of the rare mono-periodic β Cephei, is actually multi-periodic. In the two largest data sets (1993 and 1995), we detected a second high-frequency pulsation at $6.01\,\mathrm{d}^{-1}$ as well as two low frequencies at 0.68 and $0.87\,\mathrm{d}^{-1}$. These latter frequencies are similar to the high degree g mode frequencies found in SPB stars. Being one of the coldest β Cephei star, γ Peg is the second star after ν Eri in which both types of variations are clearly observed. This shows that the superposition zone of the two phenomena is probably larger than is described by present theoretical models. New accurate photometric and spectroscopic observations of the colder β Cephei stars are needed to clarify this point.

In addition, a small increase in the main period was detected between the 1995 and 2005 observations.

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Online Material

Table 1. Journal of the spectroscopic observations. The columns display the Heliocentric Julian Day, the exposure time (min), the length of the observation (d), the number of spectra and the spectral line used for the radial velocities measurements.

2 400 000+	exposure	length	spectra	line
48 538.4071	8.0–15.0	0.08	9	SiIII 4567 Å
48 539.5095	15.0	0.15	11	SiIII 4567 Å
48 851.5500	1.0	0.16	103	SiIII 4567 Å
48 854.7287	2.5–3.3	0.18	55	SiIII 4567 Å
48 857.5272	2.0–8.3	0.22	57	SiIII 4567 Å
48 884.5563	3.0–6.0	0.23	56	SiIII 4567 Å
48 887.4727	3.3–10.0	0.11	5	SiIII 4567 Å
49 201.5383	1.7–10.0	0.16	40	SiIII 4567 Å
49 202.5371	0.8–10.0	0.17	45	SiIII 4828 Å
49 203.5476	1.2–7.5	0.17	73	SII 5320 Å
49 204.5271	2.8–10.0	0.17	19	SiIII 4567 Å
49 205.5616	1.7–10.0	0.14	29	SiIII 4828 Å
49 206.5616	1.7–10.0	0.15	34	SiIII 4828 Å
49 207.5367	2.0–6.7	0.18	44	SII 5453 Å
49 208.5383	3.2–10.0	0.19	32	SiIII 4567 Å
49 969.4953	4.5–10.8	0.32	59	SiIII 4567 Å
49 970.4938	3.3–8.0	0.32	64	SiIII 4567 Å
49 974.5765	9.0–15.0	0.33	16	SiIII 4567 Å
49 975.5270	3.8–15.0	0.25	40	SiIII 4567 Å
49 976.5134	3.7–7.2	0.25	56	SiIII 4567 Å
49 977.5239	3.3–8.3	0.27	47	SiIII 4567 Å
49 978.5221	3.3–11.7	0.25	50	SiIII 4567 Å
49 981.4696	5.4–11.7	0.29	56	SiIII 4567 Å
53 418.2773	5.0–6.0	0.05	12	SiIII 4567 Å
53 536.5505	1.7	0.08	66	SiIII 4567 Å