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PG 1618+563B: A new bright pulsating sdB star*

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Abstract. The results of two runs of time-series photometry made at the Nordic Optical Telescope clearly show that the sdB star PG 1618+563B is a new member of the EC 14026 class of sdB pulsators. Its power spectrum shows a doublet of frequencies at about 6.95 and 7.18 mHz (P $\sim$ 144 and 139 s respectively), which produce a modulation effect in the light curve with a beat period of about 1.2 hours. The amplitudes of the two signals are very low, not more than 2 mma. Thanks to its brightness (B=13.4), which makes PG 1618+563B one of the brightest objects of its class, we were able to observe the star also in different colours and measure its UBV pulsation amplitudes and phases. The comparison of these “nonadiabatic observables” with models may help the identification of the oscillation modes. The spectral analysis of the sdB star and the spectral classification of PG 1618+563A suggest that both stars form a wide visual binary ($\sim$ 2500 A.U. separation), at a distance of about 680 pc from the sun.

Key words: subdwarfs – stars: oscillations – stars: individual: PG 1618+563

1. Introduction

The hot subdwarf B (sdB) stars are evolved objects with typical helium (He) burning cores of $\sim 0.5\,M_\odot$, surrounded by a thin H surface layer ($\sim$ 2% by mass or less). In the HR diagram they are located near the extreme horizontal branch (EHB). Their evolution is still not well known; in the past they should have experienced a core He flash and substantial mass loss during or after the giant branch phase. How such unusually large mass loss can occur it is still not clear. In the future they are expected to form white dwarfs (WDs) with lower than average masses.

The recent discovery that 15 of them are multimode pulsators (O’Donoghue et al. 1999; Billeres et al. 2000; Piccioni et al. 2000) has opened a new attracting possibility of probing their interior using seismological tools. The sdB pulsators, known also as sdB Variable=sdBV or EC 14026 stars from the prototype (Kilkenny et al. 1997), have short pulsation periods ($\sim$ 1–10 min) and low amplitudes (few mma up to a few hundredths of ma). Five out of 13 are in binary systems with F-G stars (Koen et al. 1999a).

Charpinet et al. (1996, 1997) have shown that the pulsations of the sdB stars can be driven by an opacity bump associated with iron ionization. Moreover both radial and nonradial modes are expected to have the same range of frequencies, making more difficult the mode identification. For this reason it would be important to find some signature of the nonradial modes given by the stellar rotation, which produces multiplets of $2l+1$ equally (or almost equally) spaced frequencies. This could be the case of PG 1605+072, whose very rich temporal spectrum (more than 50 frequencies, Kilkenny et al. 1999) can be partially explained by the frequency splitting due to a fast stellar rotation (Kawaler 1999). Heber et al. (1999a) have found indeed a large line broadening in the Keck 1 high resolution spectrum of PG 1605+072, which is probably caused by a fast rotation velocity v $\sin i$=39km/s ($\Rightarrow$ P_{rot}<8.7 h). On the other hand, the same authors did not find rotation at all within the observational limits for three other sdBV stars (Heber et al. 2000).

2. PG 1618+563: A new spectral analysis

The binary star PG 1618+563 (hereafter PG 1618) was observed at the Calar Alto Observatory in July 2, 1988; the medium resolution (2.5 Å) spectra obtained cover the range 4100 to 5000 Å. Details on the observations and data reduction were presented by Moehler et al. (1990). The (relatively) flux calibrated spectra of PG 1618+563A and B (the sdB star), hereafter PG 1618A and B, are displayed in Fig. 1. Weather conditions did not allow to derive a reliable absolute flux scale from our narrow slit spectra.

Both stars are equally bright at 4250 Å, which is consistent with their B magnitudes being similar (see Table 1 in the next section). We classify PG 1618A as a F3 star according to the ratio of the G-band and Hγ line strengths. In the spectrum of

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[*] Based on observations obtained at the Nordic Optical Telescope, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. And on observations obtained at the German-Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy

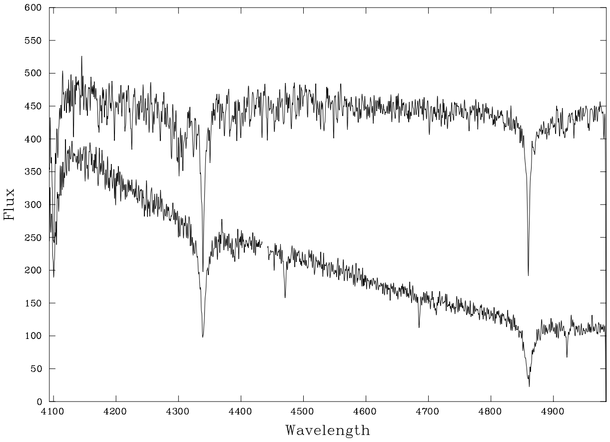

Fig. 1. Medium resolution (2.5 Å) spectrum of PG 1618A (top) and B (bottom). The spectrum of PG 1618B (the sdB star) has been offset by -150 counts and an artifact near 4450Å has been removed for clarity.

Table 1. UBVR$_c$ magnitudes

Star	Band	Mag
PG 1618A+B	U	11.96 ± 0.11
	B	12.54 ± 0.05
	V	12.32 ± 0.03
	R$_c$	12.01 ± 0.05
PG 1618A	U	13.12 ± 0.13
(F3)	B	13.22 ± 0.07
	V	12.75 ± 0.04
	R$_c$	12.30 ± 0.06
PG 1618B	U	12.41 ± 0.12
(sdB)	B	13.36 ± 0.07
	V	13.52 ± 0.06
	R$_c$	13.57 ± 0.08

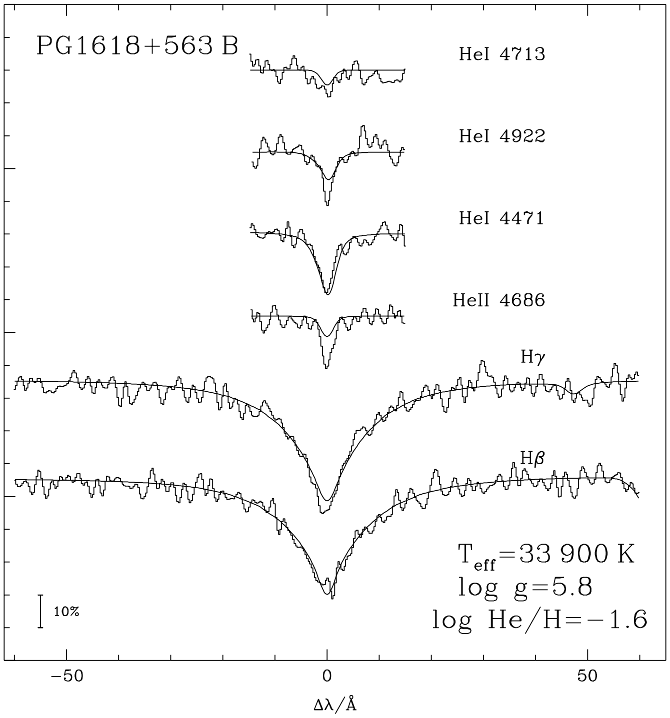

Fig. 2. Atmospheric parameters of the sdB star PG 1618+563B (details in the text).

the sdB star PG 1618B, the Balmer lines Hβ and Hγ can be measured (Hδ is at the edge of the spectrum) and the He I lines 4471 Å, 4713 Å, 4922 Å and He II 4686 Å are detectable. He I 4388 Å is marginally visible.

A grid of synthetic spectra derived from H-He line blanketed NLTE model atmospheres (Napiwotzki 1997) was matched to the data (see Fig. 2) to simultaneously determine effective temperature, gravity and helium abundance (Heber et al. 1999b). The results are: T$_{\rm eff}$=33 900 K, log g=5.80, log (N(He)/N(H))=–1.6. While the formal statistical (1σ) errors of the fitting procedure are relatively small (Δ(T$_{\rm eff}$)=500 K, Δ(log g)=0.09 dex, Δ(log (N(He)/N(H))=0.1 dex), the fit is not perfect. Hβ and Hγ, as well as He I 4471 Å , are well reproduced by the model spectrum; but He I 4922 Å and He II 4686 Å are weaker than observed. Therefore systematic errors (e.g. flat fielding, continuum placement, neglect of metal line blanketing etc.) contribute significantly to the error budget and the total errors are estimated as: Δ(T$_{\rm eff}$)=±1500K, Δ(log g)=±0.2 dex, Δ(log(N(He)/N(H)))=±0.2 dex.

Comparing its atmospheric parameters to those of the other pulsating sdB stars, PG 1618B turns out to be almost a twin of PG 1219+534, discovered by Koen et al. (1999b). Heber et al. (2000) carried out a detailed quantitative spectral analysis of the latter, based on high resolution Keck spectra, and derived T$_{\rm eff}$=33200K, log g=5.93, log (N(He)/N(H))=–1.6 using the same technique and model atmospheres as applied here for PG 1618B. Besides their similar effective temperature and gravity, the helium abundance in both stars is higher than in all other known pulsators. Moreover, Heber et al. (2000) pointed out that there is a mismatch between the Balmer line profiles and the helium lines for PG 1219+534: from the helium ionization equilibrium T$_{\rm eff}$=35200K, log g=6.03, log (N(He)/N(H))=–1.41 were derived. For PG 1618B the mismatch of He I 4922 Å and He II 4686 Å in our model fit (see above) may point towards a similar problem and the comparison with PG 1219+534 is used to estimate systematic errors of our spectral analysis. However, a high resolution spectrum of PG 1618B is required to address this question.

The results of the spectroscopic analysis place the star well inside the region of the (T$_{\rm eff}$, log g) plane, for which pulsation instabilities are predicted (Charpinet et al. 1997) and where most of the known pulsating sdB stars, indeed, have been found (Koen et al. 1999a). Therefore, PG 1618B was selected for our time-series monitoring program from an ongoing spectroscopic study of hot subluminous stars drawn from the Palomar Green (Green, Schmidt & Liebert 1986) and the Hamburg Schmidt (Heber et al. 1999b) surveys.

3. Is PG 1618+563 a visual binary?

If the F3 star is a main sequence star, its absolute magnitude is M(V)=3.5 (Schmidt-Kaler 1982); hence, from its apparent

Table 2. Time-series Photometry

Date (1999)	Instr.	Observers	Start (UT)	Length (hours)	Filter	Res. (s)
Jul 19	PMT	JGP,RS,JES	21:56:10	1.5	V	5
Jul 20	PMT	JGP,RS,JES	21:19:20	2.3	NO	5
Jul 20	PMT	JGP,RS,JES	23:51:10	1.5	UBV	20
Jul 21	PMT	JGP,RS,JES	22:33:50	1.0	NO	5
Jul 22	PMT	JGP,RS,JES	22:34:00	1.4	NO	5
Oct 15	CCD	RØ,JES	20:18:27	1.4	R	20
Oct 16	CCD	RØ,JES	19:23:02	1.2	U	30
Oct 16	CCD	RØ,JES	20:37:20	1.0	B	30

magnitude V=12.75 (see Table 1), we derive a distance modulus m-M=9.25. For the sdB star, adopting a mass of M=0.5 $M_\odot$, we obtain an absolute magnitude M(V)=4.4 from the atmospheric parameters. Its apparent magnitude (V=13.52) places it roughly at the same distance (within the errors) as the F star (m-M=9.12). Also the radial velocities of both stars are identical to within observational limits. The radial velocity of the F star was measured directly to be –105 km/s. The radial velocity of the sdB stars is difficult to determine but a cross correlation of Hβ and Hγ line profiles in both stars indicates small differences of +2 km/s and –12 km/s only. Both results suggest that PG 1618 is probably a visual binary system. The distance of the system is about 680 pc (with a negligible interstellar extinction A_V=0.01, assuming A_V=3.1 × E(B-V) and E(B-V)=0.004 from Schlegel et al. 1998). Thus the separation of the two components by 3.7 arcsec corresponds to a linear distance of about 2500 A.U., i.e. PG 1618 is a very wide system.

4. PG 1618+563: photometry

PG 1618 was observed at the 2.5 m Nordic Optical Telescope (NOT) in two runs, July and October 1999[1], using respectively the Tromsø-Texas 3-channel photoelectric photometer with Hamamatsu R647 photomultipliers (PMTs), and the High Resolution Adaptive Camera (HiRAC) with Loral Lesser thinned 2048×2048 CCD chip, modified with our own control software to be able to run in high-speed multi-windowing mode.

4.1. Calibrations

In both runs we measured the magnitude of PG 1618, which are reported in Table 1; they are in agreement with the Strömgren b magnitude of 12.7 measured by Wesemael et al. (1992) for both stars together. The uncertainties are quite high because of the small number of Landolt standards used (3 with different colours in July, just one in October); moreover, the small separation between the two stars rendered the calibration of the single components more difficult.

4.2. Time-series: observations and data reductions

Table 2 contains all the information relative to the time-series observations. In the first run of July 1999 we used only 2 channels (target + sky) of the photoelectric photometer because of some focusing problems with the telescope. Nevertheless, the lack of comparison star did not significantly affect the quality of the results thanks to the high stability of the sky. The presence of the F3 star at 3.7 arcsec in the S-W direction forced us to use medium size apertures (10.3 and 14.7 arcsec), in order to include both stars in the diaphragm. Some attempts to exclude the F3 star using a 5.1 arcsec aperture did not give good results. In the CCD observations of October 1999, the sky area available for a reference star was limited by the chip area to about 3.7x3.7 square arcmin. Hence in the U and B bands we were forced to use PG 1618A only as comparison star; nevertheless, the high space resolution of HiRAC (0.1 arcsec/pix) permitted us to separate the two objects and obtain good results even in this situation. In the R band a further reference star with a brightness comparable to that of the target was observed. Moreover, in all bands the sky was monitored in two independent fields on each side of the target, at a reasonable distance from it.

The data were reduced on line using the standard WET (Whole Earth Telescope, Nather et al. 1990) software for the PMT data and the Real Time Photometry (RTP, Østensen & Solheim 2000) program for the CCD data, developed by one of us (R. Østensen) as part of his Ph.D.-project. Then all the data were reduced again with a more accurate procedure including smoothing of the sky, compensation of long time-scale trends, extinction corrections; and also better flat fields, optimization of the aperture size, and MAP[2] technique for the CCD data.

4.3. Amplitude spectrum

4.3.1. No-filter data

The light curve of July 20, which has the highest S/N ratio, shows a periodicity of about 140 s, with a $\sim$ 4300 s modulation (Fig. 3). The amplitude spectrum of the same observation presents a doublet of close frequencies at about 6.95 and 7.16 mHz (Fig. 4), which explains the modulation effect ($P_{beat} \simeq P^2/\Delta P \simeq 4800$ s). The two frequencies are also visible in the observation of July 22 (Fig. 4); in July 21 only one peak appears, but both the data quality and the frequency resolution are lower in this observation.

In order to obtain more accurate frequencies, we have joined together the three consecutive observations and calculated the amplitude spectrum of the entire set (Fig. 4). Then we have

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[1] PG 1618 was also observed with the CCD camera of the 1.23 m telescope at the German Spanish Astronomical Center, Calar Alto. The variability reported by Schuh et al. (2000) from a preliminary data reduction, however, could not be confirmed in the final analysis. Due to the smaller telescope and the poor weather conditions, the detection limit was much lower compared to the NOT data sets; therefore those results will not be used here.

[2] The moving aperture photometry (MAP) technique computes the centre of the target in each frame and recenters the aperture correspondingly. This corrects for small tracking errors, allowing to use much smaller apertures, between 2.6 and 3.5 arcsec in our case.

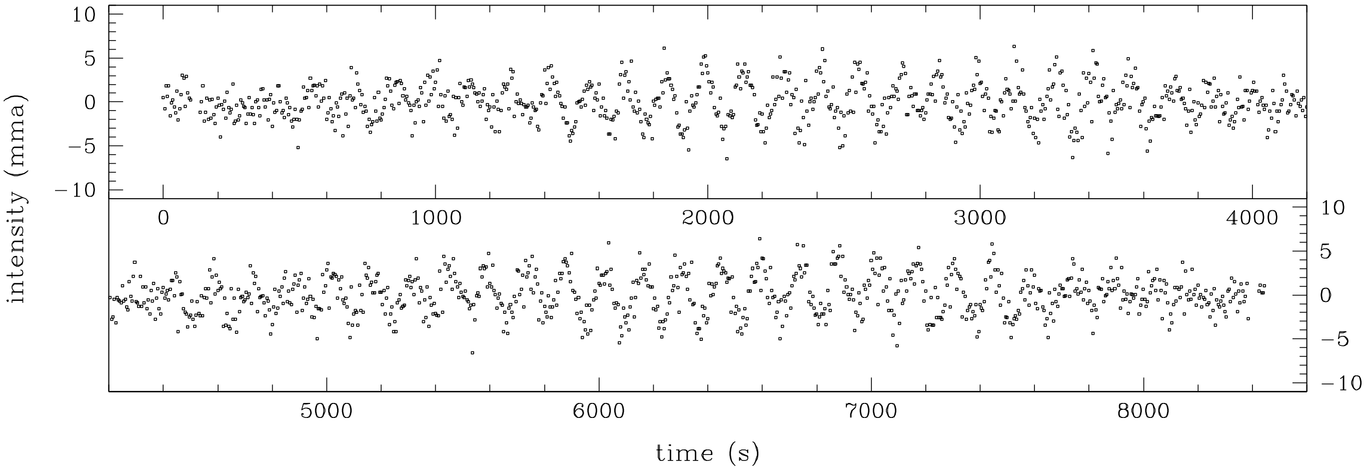

Fig. 3. No-filter light curve of July 20. Two beat periods are clearly visible.

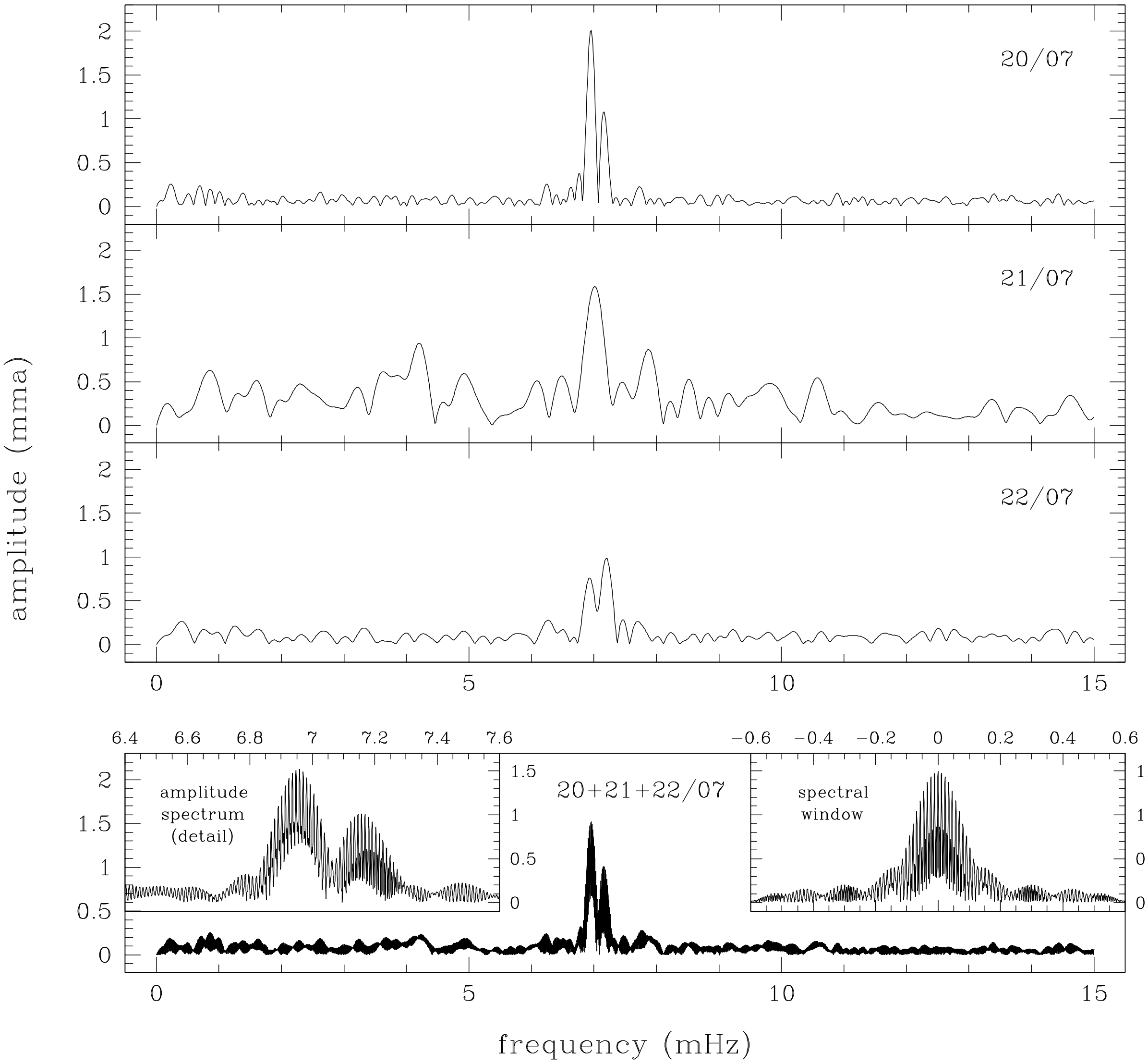

Fig. 4. Amplitude spectra of the no-filter data. The bottom plot shows the spectrum of the three consecutive nights together; the two smaller panels represent the same spectrum with a larger scale (left) and its spectral window (right).

applied a least-squares two-sinusoid fit to the data to optimize amplitudes and frequencies (and phases). The results are:

f_1=(6947.6 ± 0.1 ± n×11.6) μHz, a_1=(1.45 ± 0.04) mma;

f_2=(7180.3 ± 0.3 ± n×11.6) μHz, a_2=(0.86 ± 0.04) mma.

The first indetermination on the frequencies is the formal error of the fit, whereas the second one is due to the one-day aliases (11.6 μHz = 1 cycle/day) created by the lack of data between one night and another (see bottom panel of Fig. 4). The integer number n should not be larger than 2 or 3 in absolute value.

Looking at Fig. 4, the amplitudes of the two signals are different from one night to another; in the last night the ratio of the amplitudes is inverted respect to the first night. Because of the low frequency resolution, it is not clear whether the amplitudes variations are real or due to interference between unresolved close frequencies. For the same reason, to search for further small-amplitude signals can not produce definitive results. Nevertheless, in both the observations of July 20 and 22, one can note some power near 6.25 and 7.73 mHz, which is not due to windowing effects, as we checked subtracting the two main frequencies from the data.

To investigate this further, we have used the '*Delta* method', often used in the context of blazar variability (see Hagen-Thorn et al. 1997 and references therein). The *Delta* method is based on a 'pre-whitening' technique i.e., after each subtraction of a sinusoidal component, periodograms of the residuals are constructed and analyzed again. Since white noise has a constant spectral density, the dispersion Δ_n^2 of the residual series decreases *linearly* with increasing number n of subtracted harmonics:

$$\Delta_n^2 = \frac{1}{N-1} \sum_{k=1}^{N} [x(t_k) - \sum_{i=1}^{n} g_i(t_k)]^2 \qquad (1)$$

where $g_i(t_k)$ is a sinusoid of the form $A_i cos(\omega_i t_k + \phi_i)$, N is the total number of points in the time-series and $x(t_k)$ is the time-series itself.

Thus, in a sense, the very presence of noise establishes the optimum number of sinusoids required to characterize the maxima in the power spectrum. Having applied this method to our data results in Fig. 5, which shows the dependence of Δ_n^2 on the number of subtracted sinusoids. The figure shows that we cannot expect to fit more than 2 sinusoids (n=0 is a constant term) to the data, since we would be descending into white noise.

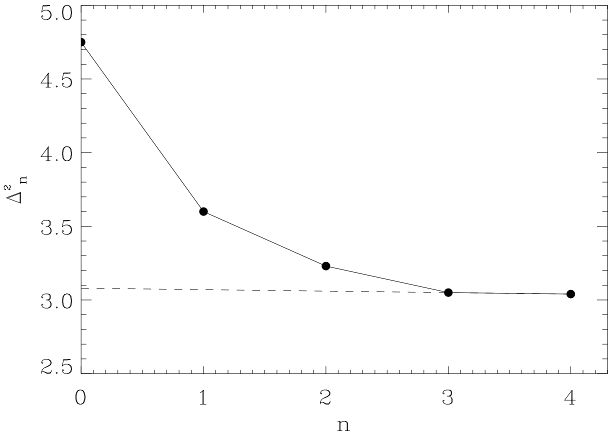

Fig. 5. Dependence of Δ_n^2 on the number of subtracted harmonics. n=0 refers to the subtraction of a constant term. The n=3 and n=4 sinusoids, fitted at 6937.7 and 7079.3 μHz respectively, are not significant and merely serve to demonstrate the linear dependence of Δ_n^2 on the number of subtracted frequencies when we approach the noise level, which is represented by a dotted line. Thus these frequencies are not used in our analysis.

Table 3. UBV Pulsation Amplitudes and Phases[1]

F	**A_1 (mma)**	**Φ_1 (0-1 units)**	**A_2 (mma)**	**Φ_2 (0-1 units)**
U	4.6 ± 0.7	0.21 ± 0.01	1.5 ± 0.5	0.92 ± 0.05
B	4.3 ± 0.8	0.17 ± 0.02	1.2 ± 0.6	0.10 ± 0.07
V	2.6 ± 1.0	0.27 ± 0.04	2.6 ± 0.9	0.91 ± 0.04
V[2]	2.6 ± 1.0	0.22 ± 0.03	0.6 ± 0.5	0.87 ± 0.13

Notes: [1] The normalized phases are referred to 0.0 UT of July 20, 1999.
[2] Amplitudes and phases of July 19 (see the text)

4.3.2. UBV data

On the 20th of July we observed PG 1618 in multifilter mode, i.e. with automatic filter changing between each measurement. The integration times of 9 s (U), 3 s (B) and 8 s (V) were chosen to have a similar S/N in the three bands. In this way we obtained three quasi-contemporary UBV light curves with an effective resolution time of 20 s in each band. The amplitude spectra of the UBV data are shown in Fig. 6. In order to obtain more precise amplitudes and phases, we applied a least-squares two-sinusoid fit to the data, using the frequencies derived from the no-filter observations (see previous section). The amplitudes have been then corrected taking into account the contribution of the F star; hence the values reported in Table 3 are relative to the flux of the sdB star only. The amplitude errors take into account both the fit errors and the flux indetermination due to the contamination of the F star. For completeness, Table 3 contains also the results of the V observation of July 19. One can note that the V amplitude of the secondary frequency in July 20 (2.6 mma) is much higher than that of July 19 (0.6 mma), whereas the amplitudes of the primary frequencies are the same. It is not clear weather this amplitude variation is real or due to the noise, which in the V band is almost at the same level of the signals. For this reason it might be more safe to scale the amplitude of the secondary frequency to that of the previous night and consider a value of 0.6 mma. The amplitude ratios and phase differences of PG 1618 can be a valuable contribution for the mode identification, as it has been demonstrated in the case of the β Cephei stars (see for example Cugier, Dziembowski & Pamyatnykh 1994; Heynderickx et al 1994; and ref. therein).

As already mentioned in Sect. 4.2, PG 1618 was also observed in U, B and R bands with the CCD photometer in October 1999. The amplitude spectra are shown in Fig. 7. In the R spectrum, which is the most noisy due to cirrus, both signals

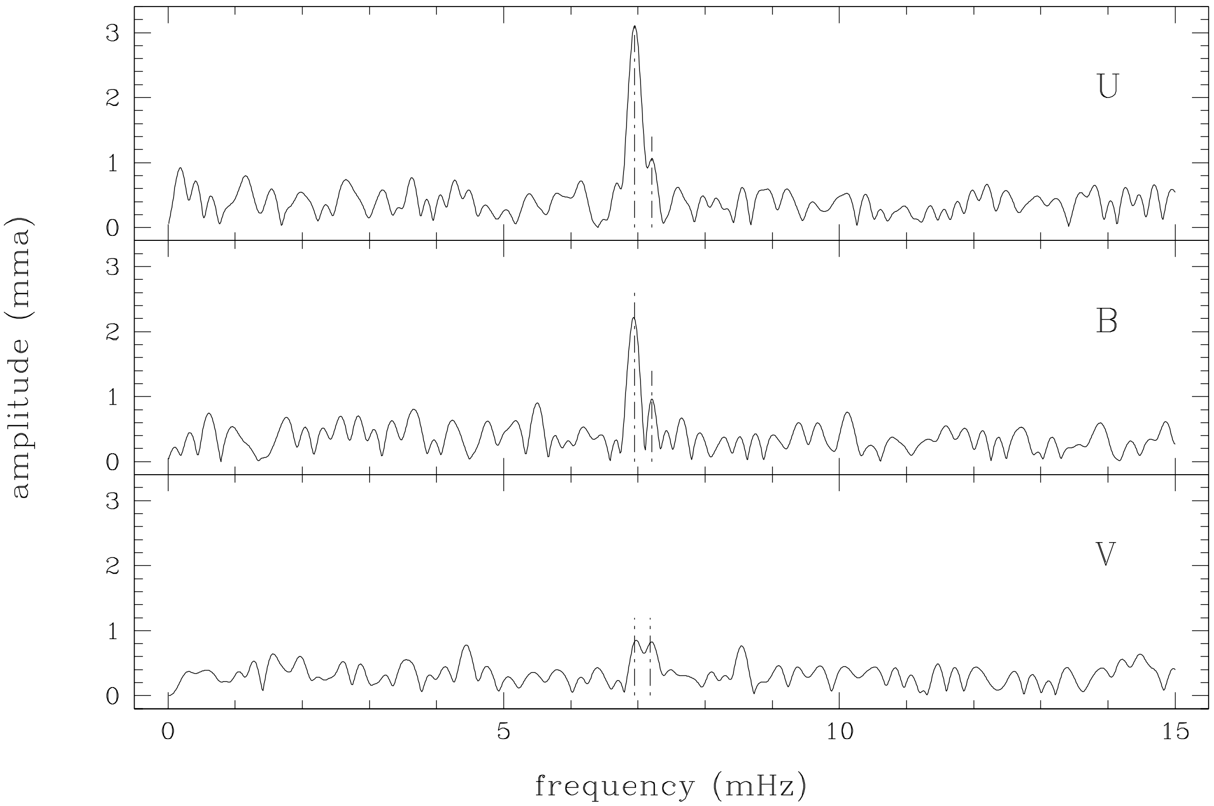

Fig. 6. UBV amplitude spectra of PG 1618, obtained from the PMT quasi-contemporary data of July 20, 1999. The vertical lines correspond to the main frequencies of the no-filter observations.

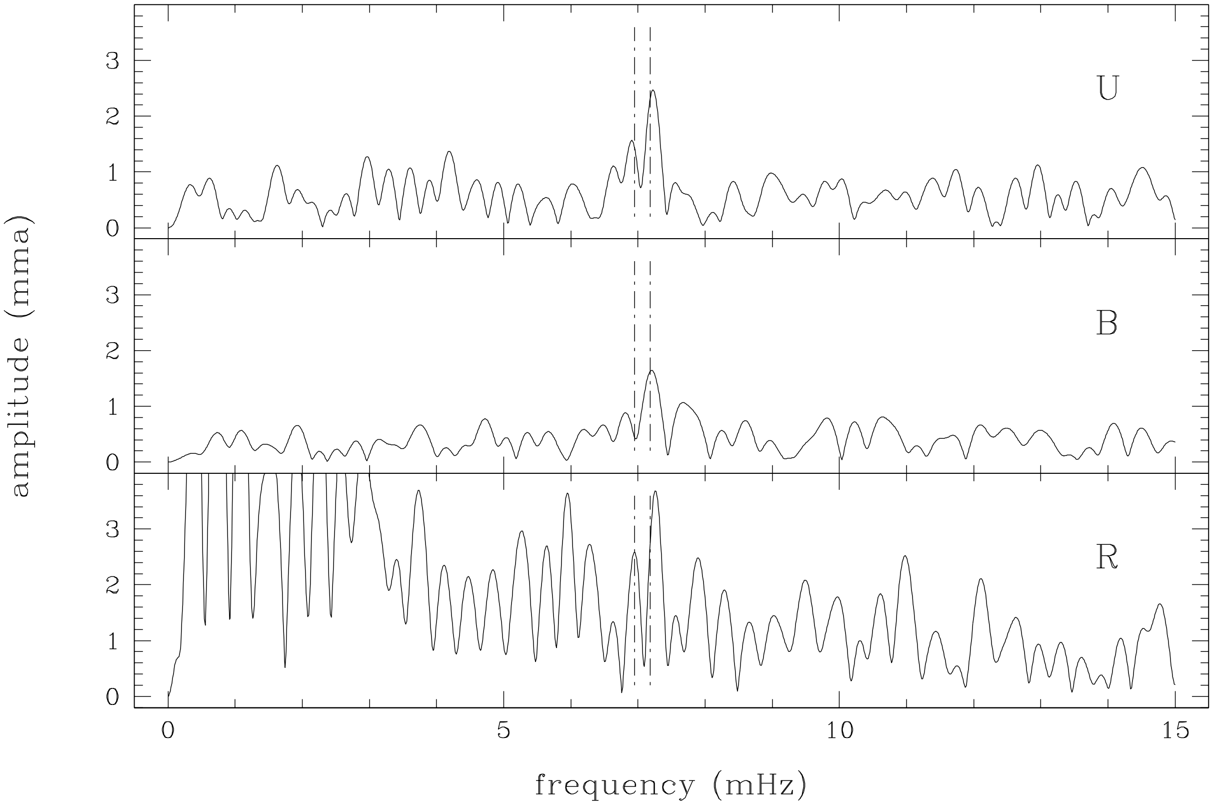

Fig. 7. UBR amplitude spectra of PG 1618B, obtained from the CCD data of October 1999. The vertical lines correspond to the main frequencies of the no-filter observations.

do not exceed the noise level. In the U and B bands the spectra are different from those of July[3]: the signal at 6.95 mHz, which was the strongest three months before, is close to the noise level, whereas the peak at 7.18 mHz has an amplitude increased by a factor of about 2. Hence the comparison between the results of July and October 1999 indicates that amplitude variations in time-scales of months could be present, in addition to the night to night changes observed in July.

5. Summary and discussion

The sdB star PG 1618B, which is located well inside the region of the ($T_{\rm eff}$, log g) plane where the sdB pulsators are expected to be, has a quite simple temporal spectrum, with two close peaks at about 6.95 and 7.18 mHz, and possibly some further low amplitude signals. Its brightness permits time-series observations not only in white light, but also in different colour bands, allowing possible nonadiabatic studies and mode identification. The UBV amplitudes and phases we measured are a first step in this direction. Comparing the amplitude spectra taken in different nights and a few months apart, we note a variability of the pulsation amplitudes which could be real, but could also be related to a more complicated spectrum with unresolved structures. More detailed observations with higher frequency resolution are needed to solve this question. At this level, we can only make some conjecture on the nature of the two peaks, which may have different spherical harmonic degrees and perhaps different radial indices too. Another possibility is that their separation is due to the rotational splitting, with the other components of the multiplet hidden in the noise or not excited at all; this hypothesis would imply a fast rotation velocity[4].

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[3] The differences are even larger if we consider that in Fig. 7 the flux of the sdB star only is used. Thus the amplitudes of Fig. 7 should be compared with those reported in Table 3, where the contribution of the F3 star has been excluded.

[4] Depending on the values of l and m, the (unprojected) rotational velocity would be included between a minimum of ~ 40 Km/s (l=2,Δm=4, quite unlikely) and a maximum of ~ 260 Km/s (l=1,Δm=1).