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R. Silvotti

R. Janulis

S. L. Schuh

S. Charpinet

T. Oswalt

See next page for additional authors

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R. Silvotti[1], R. Janulis[2,3], S. L. Schuh[4], S. Charpinet[5], T. Oswalt[6], N. Silvestri[6], J. M. Gonzalez Perez[7], R. Kalytis[3], E. Meištas[3,2], D.註ališauskas[3], S. Marinoni[8], X. J. Jiang[9], M. D. Reed[10], R. L. Riddle[11], S. Bernabei[12], U. Heber[13], O. Bärnbantner[14], O. Cordes[15], S. Dreizler[4], E. Goehler[4], R. Østensen[16,7], J. Bochanski[17], and G. Carlson[6]

1 Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Napoli, Italy
2 Institute of Theoretical Physics and Astronomy, Goštauto 12, Vilnius 2600, Lithuania
e-mail: jr@itpa.msrev.lt
3 Astronomical Observatory of Vilnius University, Čiurlionio 29, Vilnius 2009, Lithuania
e-mail: romualdas.kalytis@ff.vu.lt, edmund@ktl.mii.lt, darius.alisauskas@mtmi.vu.lt
4 Institut für Astronomie und Astrophysik, Sand 1, 72076 Tübingen, Germany
e-mail: schuh@astro.uni-tuebingen.de, dreizler@astro.uni-tuebingen.de, goehler@astro.uni-tuebingen.de
5 Observatoire Midi-Pyrénées, 14 avenue E. Belin, 31400 Toulouse, France
e-mail: scharpin@ast.obs-mip.fr
6 Department of Physics and Space Sciences and the SARA Observatory, Florida Institute of Technology, Melbourne, FL 32901-6975, USA
e-mail: oswalt@astro.fit.edu, nicole@astro.fit.edu, hlidskialf@juno.com
7 Institutt for Fysikk, Universitetet i Tromsø, 9037 Tromsø, Norway
e-mail: Jose-Miguel.Gonzalez@phys.uit.no
8 Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, 40127 Bologna, Italy
e-mail: s_marinoni@astbo4.bo.astro.it
9 National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, PR China
e-mail: jiang@nova.bao.ac.cn
10 Southwest Missouri State University, Department of Physics, Astronomy, and Material Science, 901 S. National, Springfield, MO. 65804, USA
e-mail: mreed@iastate.edu
11 Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
e-mail: riddle@iastate.edu
12 Osservatorio Astronomico di Bologna, via Ranzani 1, 40127 Bologna, Italy
e-mail: s_bernabei@astbo4.bo.astro.it
13 Dr. Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, 96049 Bamberg, Germany
e-mail: heber@sternwarte.uni-erlangen.de
14 Universitäts-Sternwarte München, Scheinerstrasse 1, 81679 München, Germany
e-mail: obaern@usm.uni-muenchen.de
15 Sternwarte der Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany
e-mail: ocordes@astro.uni-bonn.de
16 Isaac Newton Group of Telescopes, 37800 Santa Cruz de La Palma, Canary Islands, Spain
e-mail: roy@ing.iac.es
17 Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085, USA
e-mail: john.bochanski@villanova.edu

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Send offprint requests to: R. Silvotti,
e-mail: silvotti@na.astro.it

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Abstract. In this article we present the results of more than 180 hours of time-series photometry on the low gravity ($\log g = 5.4$, $T_{\rm eff} = 29\,300$ K, $\log {\rm He/H} = -3.0$ by number) sdB pulsating star HS 2201+2610, obtained between September 2000 and August 2001. The temporal spectrum is resolved and shows 5 close frequencies: three main signals at 2860.94, 2824.10 and 2880.69 μHz, with amplitudes of about 1%, 0.5% and 0.1% respectively, are detected from single run observations; two further peaks with very low amplitude (<0.07%) at 2738.01 and 2921.82 μHz are confirmed by phase analysis on several independent runs. Due to the small number of detected frequencies, it is not possible to obtain a univocal identification of the excited modes and perform a detailed seismological analysis of the star. No clear signatures of rotational splitting are seen. Nevertheless, the observed period spectrum is well inside the excited period window obtained from pulsation calculations with nonadiabatic models having effective temperature and surface gravity close to the spectroscopic estimates. Due to its relatively simple temporal spectrum, HS 2201+2610 is a very good candidate for trying to measure the secular variation of the pulsation periods in time. With this purpose a long-term monitoring of the star was started. The results of the first 11 months show amplitude variations up to ∼20% on time-scales of months, which are probably real, and allow us to measure the pulsation frequencies with an unprecedented 0.02 μHz resolution.

Key words. stars: subdwarfs – stars: oscillations – stars: individual: HS 2201+2610

1. Introduction

Subluminous B (sdB) stars dominate the populations of faint blue stars of our own Galaxy and are found in both the disk (field sdBs) and the halo populations as blue tails to the horizontal branches of globular clusters (Ferraro et al. 1997). Observations of elliptical galaxies with the Ultraviolet Imaging Telescope (Brown et al. 1997) and the Hubble Space Telescope (Brown et al. 2000) have shown that these stars are sufficiently common to be the dominant source for the "UV upturn phenomenon" observed in elliptical galaxies and galaxy bulges (see also Dorman et al. 1995; Greggio & Renzini 1999). However, important questions remain over the exact evolutionary paths and the appropriate time-scales.

It is now generally accepted that the sdB stars can be identified with models for Extreme Horizontal Branch (EHB) stars burning He in their core, but with a very tiny (<1% by mass) inert hydrogen envelope (Heber 1986; Saffer et al. 1994). An EHB star bears great resemblance to a helium main-sequence star of half a solar mass and its further evolution should proceed similarly (i.e. directly to the white dwarf graveyard), as confirmed by recent calculations (Dorman et al. 1993). Therefore sdB stars are certainly important as the immediate progenitors of low mass white dwarfs.

How they evolve to the EHB configuration is controversial. The problem is how the mass loss mechanism in the progenitor manages to remove all but a tiny fraction of the hydrogen envelope at *precisely* the same time as the He core has attained the mass (∼0.5 $M_\odot$) required for the He flash. Whether this is primarily due to enhanced mass loss in single stars or to common envelope ejection in binaries is still not clear. Although many authors consider sdBs a result of single star evolution (see for example D'Cruz et al. 1996), considerable evidence is accumulating that many sdB stars reside in close binaries. Saffer et al. (2001) found that 45% out of more than 70 sdBs have periods of hours-days, i.e. are clearly post-common envelope binaries; another 20% show spectral lines from a cool turnoff or subgiant companion and have long periods of 1 year or more; the remaining 35% might be actually single sdBs but might also be wide binaries with undetected faint companions. Maxted et al. (2001) found that at least 60% in a sample of 36 sdBs are binaries with short periods (0.7 hours $\lesssim P_{\rm orb} \lesssim$ 10 days). A scenario of sdB formation from binary interactions is suggested by these results and predicts that a small fraction should be post-common envelope sdB + cool MS (Main Sequence) binaries (Heber et al. 2002), whereas another larger fraction should be post-common envelope sdB+WD (white dwarf) binaries (Green et al. 2001). The latter have been proposed as possible progenitors for type Ia supernovae, which makes them extremely interesting in a cosmological perspective. Five of these systems have been recently found by Saffer et al. (1998); other two of particular interest are KPD 0422+5421, an eclipsing binary (Orosz & Wade 1999), and KPD 1930+2752, whose sdB component is a known pulsator (Maxted et al. 2000; Billères et al. 2000).

The discovery of multimode pulsators among the sdB stars has opened a new attractive possibility of probing their interiors using seismological methods. The sdB pulsators (sdB Variables = sdBVs or EC 14026 stars after the prototype, Kilkenny et al. 1997), are characterized by short pulsation periods ranging between ∼1 and 10 min and low pulsation amplitudes, of the order of a few percent or less. The values of the pulsation periods suggest that all or almost all the observed modes are due to low-order acoustic waves. Radial modes alone are not able to explain the complex light curves of these stars, hence nonradial modes must be also present (see for example Kawaler 1999; Kilkenny et al. 1999; Charpinet et al. 2000).

The pulsations of the sdB stars are driven by an opacity bump associated with iron ionization (Charpinet et al. 1996). The enhancement of iron abundance in the driving layers is probably caused by radiative levitation (Charpinet et al. 1997; see also Unglaub & Bues 2001 for a discussion on the influence of diffusion and mass loss in sdB stars). Surface abundances have been determined recently for more than a dozen sdB stars, including four pulsators (Heber et al. 2000; Edelmann et al. 2001; Napiwotzki et al. 2001), demonstrating that in most cases the atmospheric iron abundance is solar. This is consistent with the predictions of the diffusion calculations

(Charpinet et al. 1997). The iron enrichment in the driving layer below the atmosphere is caused by material being pushed up by radiative acceleration from deeper layers.

The sdBV instability strip is predicted to occur at effective temperatures between about 29 000 K and 37 000 K, in good agreement with the observations. However, only less than one tenth of the sdB stars in this temperature interval show periodic luminosity variations (see for example Silvotti et al. 2002). It is not clear whether this is simply due to our insufficient detection limit or if actually not all the sdB stars in the strip do pulsate due to some physical reasons.

Presently data on 31 sdB pulsators are known: 28 are summarized in the review by Kilkenny (2002); additional discoveries are from Dreizler et al. (2002) and Silvotti et al. (2002). For three of them, PB 8783 (O'Donoghue et al. 1998), PG 1605+072 (Kilkenny et al. 1999) and PG 1336–018 (Reed et al. 2000), large time-series campaigns have permitted to reach a frequency resolution of the order of 1 μHz, which is typically needed for seismological analysis. For five sdB pulsators, PB 8783, KPD 1930+2752 (Billères et al. 2000), PG 1336–018, PG 0014+067 (Brassard et al. 2001) and PG 1047+003 (Charpinet et al. 2002a), some mode identification was obtained and/or some seismological results were derived.

In this article we describe the temporal behavior of the sdB pulsator HS 2201+2610 (hereafter HS 2201) at a very high frequency resolution. HS 2201 is located near the low gravity boundary of the sdBV instability strip, having $\log g = 5.4 \pm 0.1$, $T_{\rm eff} = (29\,300 \pm 500)$ K and $\log {\rm He/H} = -3.0 \pm 0.3$ by number (Østensen et al. 2001a). Its variability was discovered by the same authors in the framework of a search program at the Nordic Optical Telescope (NOT), which has already produced 10 new sdB pulsators (Silvotti et al. 2000, 2002; Østensen et al. 2001a,b) from a set of targets selected spectroscopically from the Hamburg Schmidt (Hagen et al. 1995) and the Palomar Green (Green et al. 1986) surveys.

2. Observations and observation strategy

In September–October 2000 a multisite time-series campaign was organized in order to study in detail the temporal spectrum of HS 2201. The telescopes and instruments used are listed in Table 1, together with the observers at each site and the duration of each run. The observations were carried out using two kind of instruments: photoelectric photometers with B-peaked photomultipliers (PMTs) and without filter, as well as CCDs with standard B filters. The integration time was set to 10 s for all the PMTs and to 10 or 20 s for the CCDs (with a cycle time of about 30–40 s). As it was not possible in that period to observe HS 2201 for the whole night, the cataclysmic variable RXJ 0028+59 was also observed as a secondary target (de Martino et al. 2002).

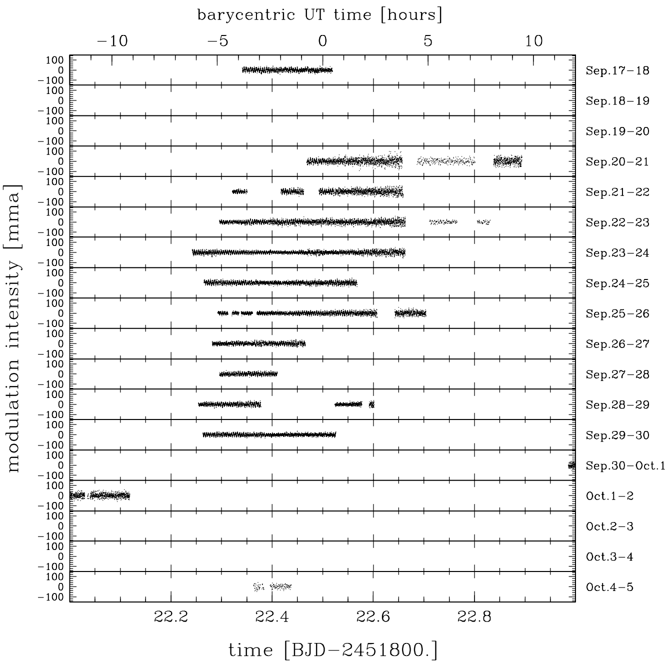

Fig. 1. Light curve of HS 2201 obtained during the multisite campaign of September–October 2000. Each panel represents 24 hours.

The complete light curve obtained for HS 2201 is shown in Fig. 1[1]. The central part of the same light curve is also represented with more detail in Silvotti et al. (2001). As one can see, the coverage is quite good at European longitudes and much poorer in America and Asia because of the smaller number of telescopes involved and some technical problems, leading to a duty cycle of 23% on the whole run, which increases up to 39% when we consider only the central part (from September 20 to 30). Nevertheless, thanks to the preliminary on-line data reductions and analysis that were done for the PMT data, it was clear soon that the coverage was probably sufficient to resolve the light curve. All the power in the spectrum of HS 2201 was concentrated in a relatively small region around 2850 μHz; a preliminary prewhitening of the spectrum at the end of the campaign resulted in only three frequencies detected. The relative simplicity of the spectrum convinced us to concentrate our interest on the temporal stability of the pulsations (see next sections). We then decided to start a long-term monitoring program on HS 2201, with the main purpose of measuring the secular variation of the pulsation periods.

Several short runs (at least 3 nights each) were planned and performed with the goal of having at least the two main frequencies resolved. The filters and integration times were the same as those used for the multi-site campaign described above. From November 2000 to July 2001, HS 2201 was observed in each month, apart from the

[1] In this figure, as well as in all the other graphs of this paper, the amplitudes are represented in milli modulation amplitude (mma) units, i.e. [(relative amplitude – 1) × 1000], as defined by Winget et al. (1994).

Table 1. Observing log.

Epoch	BJD^*_{start}	BJD^*_{end}	Telescope	Instr.	# nights	# **hours**	Observers
Sep.–Oct. 2000	1805.34	1822.44	Beijing 0.85 m	3ch.PMT	1	3.2	XJJ
			Moletai 1.65 m	3ch.PMT	7	33.3	EM, DA
			Wendelstein 0.8 m	CCD	1	1.8	OB
			Loiano 1.5 m	3ch.PMT	7	23.3	RS, RK, RJ
			Tenerife 0.8 m	3ch.PMT	4	25.0	JMGP
			Fick 0.6 m	2ch.PMT	2	2.8	MDR, RLR
			SARA 0.9 m	CCD	2	5.6	TO, NS
Nov. 2000	1850.28	1854.35	Calar Alto 2.2 m	CCD	4	9.0	SS
Dec. 2000	1890.21	1896.35	Loiano 1.5 m	3ch.PMT	3	6.5	RS, SB
May 2001	2051.95	2057.60	Loiano 1.5 m	3ch.PMT	3	3.3	RS
			SARA 0.9 m	CCD	4	4.7	TO, NS, JB, GC
Jun. 2001	2074.49	2077.59	Loiano 1.5 m	3ch.PMT	4	6.3	RS
Jul. 2001	2107.46	2119.60	Calar Alto 1.2 m	CCD	5	6.4	SS, EG
			NOT 2.6 m	CCD	4	5.6	RS, RØ
Aug. 2001	2131.46	2144.64	Loiano 1.5 m	3ch.PMT	9	49.5	RS, SM

* Referred to the whole run, after having subtracted 2450000.0.

period January–April 2001, when it was not observable. Then, in August 2001, a longer run was performed in order to check in detail the stability of the spectrum over a time-scale of almost one year. All the observations are listed in Table 1. The light curve obtained in August 2001 at Loiano is shown in Fig. 2, together with the longest high-quality observation performed in July 2001 at the Nordic Optical Telescope (NOT).

3. Data reduction

The data were reduced following standard procedures. For the PMT data, the sky was subtracted on a point-by-point basis when 3 channels were available; for the 2 channel data from Fick Observatory, a sky interpolation was applied to the sky measurements that were done every 30–60 min. We then calculated the flux ratio between target and comparison star in order to compensate for the sky transparency variations. For the CCD data, bias and flat fielding corrections were applied; then aperture photometry was performed subtracting the sky counts. The flux ratio was obtained dividing the counts of the target by the best combination of the available reference stars (between one and four). Finally, for both PMT and CCD data, the flux ratio was converted to relative amplitude; residual extinction and further large time-scale variations were then removed by means of large cubic spline interpolation, after having verified that no real long-period variations due to the target were present. When data from more than one site were available at the same time, a weighted average was applied. As a last step, the times of all data were converted to barycentric Julian date (BJD) using the algorithm of Stumpff (1980).

4. Temporal spectrum and analysis

4.1. Resolving the light curve

In order to check if the data set obtained in September–October 2000 was large enough to resolve the light curve, we divided the data into two equal parts and calculated the Fourier Transform (FT) of each subset. The two spectra, which are shown in Fig. 3 together with the spectrum of the whole data set, are very similar, suggesting that the main pulsation frequencies are resolved. This is confirmed by the results obtained independently one year later, in August 2001; the same behavior is found also from larger data sets including several months of observation (see next section).

4.2. Pulsation frequencies

A prewhitening technique was applied to the largest data sets of September–October 2000 and August 2001: we subtracted the main pulsation frequency from the data, calculated the Fourier Transform of the residuals, found out the secondary frequency and repeated the procedure until the residuals were close to the noise level. The results are shown in Fig. 4, together with the spectral window of each run (upper panels), i.e. the spectrum of a single sinusoid having the same time coverage as the data. If we compare the results of September–October 2000 (left panels) with those of August 2001 (right panels), we note that the frequencies detected are the same; the only difference is given by the amplitudes which are all larger by 10–20% in August 2001. This particular point is discussed in the next section.

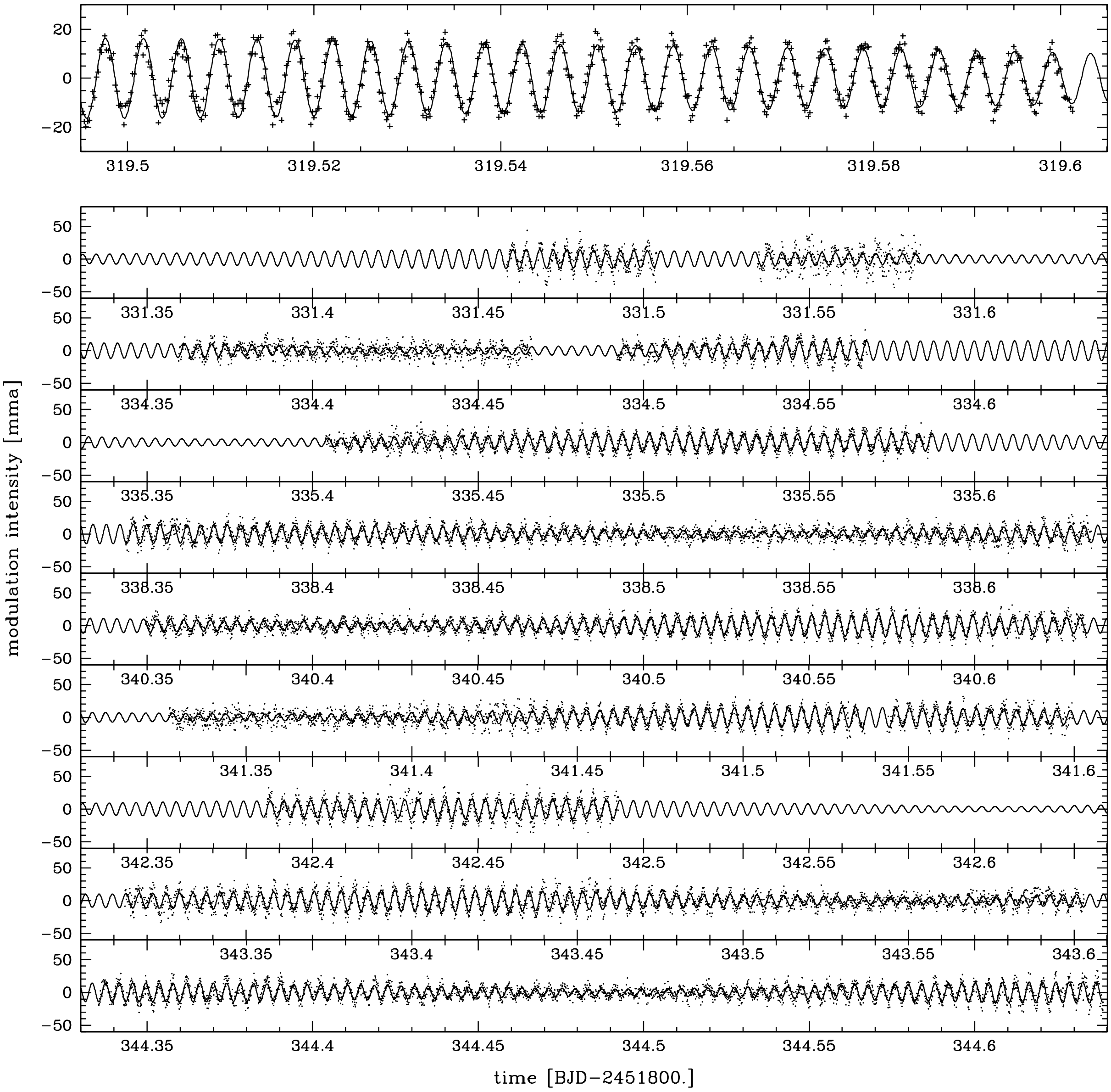

Fig. 2. Light curve of HS 2201 obtained during the run of August 2001 at Loiano. Each panel is 7.44 hours long. The continuous line represents a synthetic light curve obtained with the best fit parameters from the lower section of Table 2. The upper panel shows the quality of the fit compared with the longest (2.6 hours) high-quality observation performed at the NOT in July 2001.

In order to increase the frequency resolution, we then constructed two independent sets of data containing all the time-series measurements obtained in 2000 (from September to December) and in 2001 (from May to August). We applied again the prewhitening technique to these larger data sets and the frequencies obtained were then used in a non-linear least-square sinusoidal fit that gave us the best frequencies and amplitudes (and phases). The results are shown in Table 2. As one may expect, the three main signals have exactly the same frequencies (within the errors) in the two independent data sets of ∼3 months each. Moreover two low amplitude peaks at about 2922 and 2738 μHz have very similar frequencies despite their low S/N ratio. In order to check if they are real or not, we measured their phase in each single data set from September 2000 to August 2001. The results, shown in Fig. 5, demonstrate that the phases are in perfect agreement. Thus we conclude that also these two low amplitude peaks are real.

As a last step, we joined together the data of 2000 and 2001, thus obtaining a data set spanning over 11 months (from September 2000 to August 2001), and we applied to it the same prewhitening and sinusoidal fit technique as described before. This permitted us to reach an accuracy of the order of 0.01 μHz on the measured frequencies, as reported in the lower section of Table 2. The high-precision spectra obtained with the large data sets spanning 3 or 11 months are shown in Fig. 6, together with their spectral windows. Due to the very high resolution, only the main signal at 2860.94 μHz is represented.

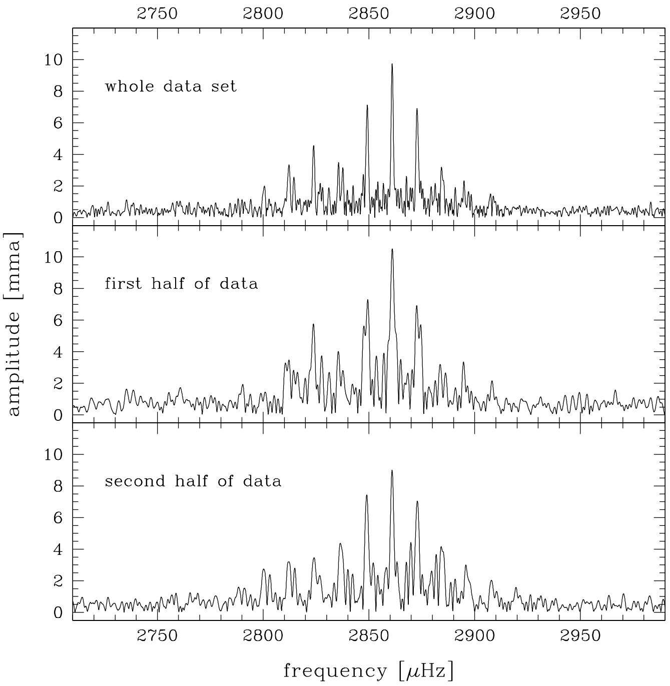

Fig. 3. Amplitude spectrum of the whole data set collected during the multi-site campaign of September–October 2000 (top panel), compared with the spectrum of the first and second half of data.

Note that despite the indetermination due to the spectral window, the highest peak in the two independent data sets of September–December 2000 and May–August 2001 is the same. Finally, in Fig. 7 the pulse shape of each of the five frequencies is shown; in each phase bin the average of the data over 11 months is represented.

4.3. Amplitude variations

Many authors report that amplitude variations on time-scales of weeks-months (or even less) were registered in some sdB pulsators. These variations may be explained in terms of non-linear interactions between the different frequencies. Nevertheless, this question is hard to study because in many cases the amplitude variations may be only apparent and due to an insufficient coverage, i.e. poor frequency resolution (that does not allow to separate all the single frequencies) and/or low duty cycle (that creates spurious frequencies referred to as "aliases").

Thanks to the relatively simple temporal spectrum of HS 2201 and to the large data set collected over several months, we then tried to study this aspect. With the high-precision frequencies obtained from the whole data set spanning 11 months (see previous section), we performed linear least-square sinusoidal fits (i.e. with fixed frequencies) to the single data sets obtained in the different months, in order to measure the pulsation amplitudes (and their errors) in that particular epoch. The behavior over eleven months, which is shown in Fig. 8, demonstrates that amplitudes variations up to ∼20% may occur in time-scales of the order of 30–40 days. Note that if the amplitudes were perfectly constant in time and these variations were only apparent, it would be difficult to explain why do they reach a 3–4 σ level in some cases. Therefore it is likely that these amplitude variations are at least partially real. But on the other hand, if this is true, then the hypothesis that the amplitude variations are negligible during each single run may start to be critical for the longest (∼2 weeks) runs, which are only two times shorter than the typical time-scales of the variations. This implies that the small error bars of the longest runs in Fig. 8 may be underestimated.

Another way to face this issue is to consider the main sources of noise in the measurement of the pulsation amplitudes. As mentioned before, one source of noise is certainly poor coverage. Another one is related to the different effective wavelengths at which the pulsation amplitudes are measured when different instruments are used (photoelectric photometers versus CCDs in our case). For both these phenomena we tried to quantify the errors for the two longest runs of September–October 2000 and August 2001 and we came to the conclusion that the differences in amplitude should not be higher than about 4% from one run tho the other, whereas the observed differences for the main pulsation frequency at 2860.94 μHz (the one less contaminated by the FT noise) are three times larger. Hence, also from this point of view, it seems difficult to explain the differences observed without admitting that real amplitude variations take place in the temporal spectrum of HS 2201.

5. Temporal spectrum of HS 2201 vs. models

Figure 9 provides a comparison between the five detected periods of HS 2201 and the computed nonadiabatic pulsation spectrum of a model with parameters $T_{\rm eff} = 30\,000$ K, $\log g = 5.36$, $M_{\rm tot} = 0.50\ M_\odot$, and $\log(M_{\rm env}/M_{\rm tot}) = -2.77$ (see Charpinet et al. 2001 for a short description of the so-called second generation models used for pulsation computations). All the modes of degree $\ell = 0$ up to $\ell = 3$ with periods between 150 and 550 s are represented. This particular model was isolated as one that can best reproduce the observed periods of HS 2201 within the parameter space region defined by the spectroscopic estimates of $T_{\rm eff}$ and $\log g$ and their corresponding uncertainties. We stress, however, that this is by no mean a firm seismological derivation of the fundamental parameters of the star, since other sets of values can provide equally good fits within that parameter space domain. There are simply not enough modes (and therefore not enough constraints on the models) to perform a detailed asteroseismological analysis of this star, as it has been done for PG 0014+067 (Brassard et al. 2001) and for PG 1047+003 (Charpinet et al. 2002a). Nevertheless, the comparison is still instructive in showing that it is in fact possible to reproduce the observed period spectrum with a model having parameters close to the spectroscopic estimates of $T_{\rm eff}$ and $\log g$. Moreover, the periods of HS 2201 are found well inside the excited period window obtained from the nonadiabatic

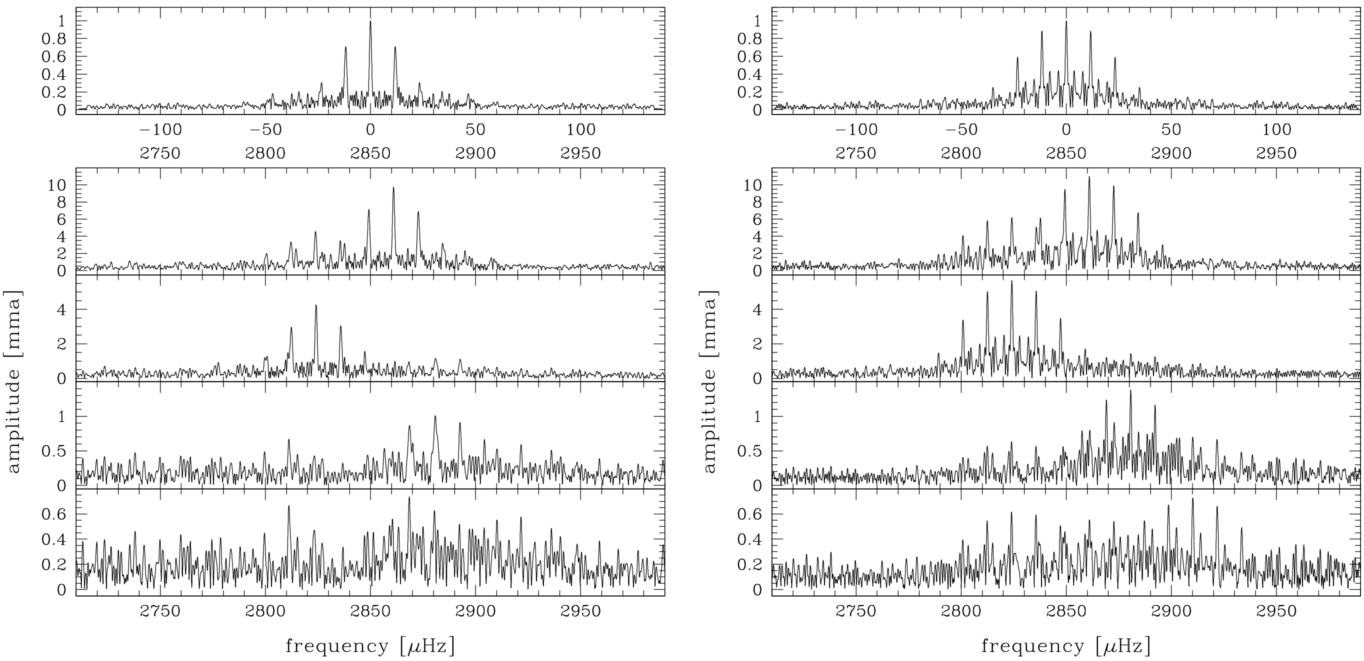

Fig. 4. Prewhitening of the set of data obtained in September–October 2000 (left) and August 2001 (right). The upper panels show the respective spectral windows. See the text for more details.

calculations applied to the model. This brings further support to the underlying pulsation mode driving mechanism that, we believe, is at work in pulsating sdB stars. With the model presented in Fig. 9, the 5 periods of HS 2201 correspond to low-order ($k \sim 1$–2) radial ($\ell = 0$) and non-radial ($\ell = 1$ and $\ell = 2$) acoustic modes, which is typical of most – if not all – sdBV stars (but again, this is not a firm mode identification due to the lack of constraints on the models). We find however that some *mixed* modes (i.e., modes with both p and g-mode properties) as well as several low-order g-modes are present in the theoretical spectrum, especially among the highest degree (mostly $\ell = 3$) modes. This is expected for a relatively low gravity object such as HS 2201 (see Charpinet et al. 2002b).

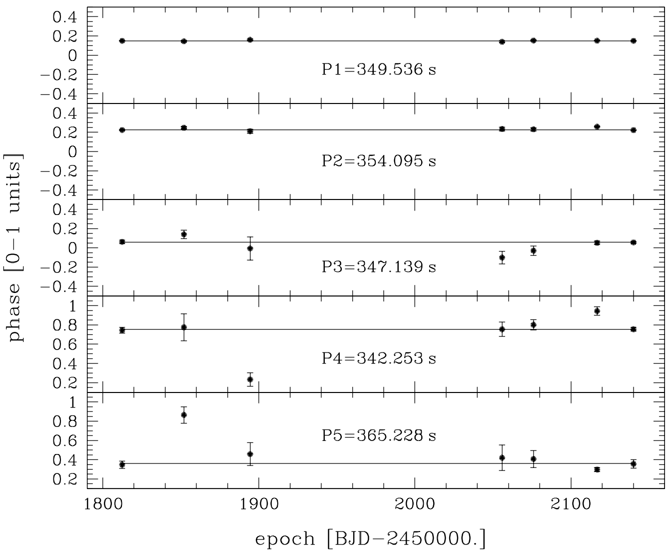

Fig. 5. Phases of all the detected pulsation modes determined from each single run during the period September 2000–August 2001. The phases are normalized to 1 (i.e. 1 corresponds to 2π) and are referred to BJD 24511800.0. The error bars are the formal errors obtained from the sinusoidal fits. Note that even in the worst cases of very low amplitude (P4 and P5), the phases of at least five out of seven independent observations are in agreement within the errors.

6. Summary and discussion

The pulsational spectrum of HS 2201 is compatible with the hypothesis of low-order p-modes, as in many – if not all – other sdBV stars. Nevertheless, the relatively long pulsation periods of HS 2201 are also compatible with the hypothesis of low-order g-modes (or *mixed* modes, i.e. modes with both p and g properties), as in a few other sdBV stars, in particular PG 1605+072 (Kilkenny et al. 1999). The small number of excited modes, equal to five with amplitudes larger than about 0.35 mma, renders more difficult the mode identification, which therefore is not univocally determined.

Although it is possible to explain the temporal spectrum of HS 2201 without invoking any rotational splitting of the frequencies, as shown in the previous section, on the other hand the presence of rotational splitting can not be completely ruled out. A separation of n times 20 μHz is relatively frequent: we get 41.1, 19.8, 36.8 and 86.1 μHz plus the combinations. If the separation of $\sim$20 (or $\sim$40) μHz was due to rotational splitting, the star would have a rotational period of about 14–18 (or 7–9) hours, the indetermination being related to a constant which depends on the stellar structure. Considering a stellar mass of 0.5 $M_\odot$ and $\log g = 5.4$, we would obtain an equatorial

Table 2. Results of the least-square sinusoidal fits.

Time–base	Frequency [μHz]	Period [s]	A [mma]
Sep.–Oct. 2000	2860.944 ± 0.20	349.5350 ± 0.024	9.77
	2824.124 ± 0.20	354.0920 ± 0.025	4.23
	2880.811 ± 0.20	347.1245 ± 0.024	1.04
Aug. 2001	2860.941 ± 0.25	349.5353 ± 0.031	10.88
	2824.076 ± 0.25	354.0981 ± 0.031	5.65
	2880.660 ± 0.25	347.1427 ± 0.030	1.34
Sep.–Dec. 2000	2860.941 ± 0.04	349.5354 ± 0.005	9.80
	2824.100 ± 0.04	354.0951 ± 0.005	4.24
	2880.678 ± 0.04	347.1405 ± 0.005	1.00
	2921.594 ± 0.04	342.2789 ± 0.005	0.60
	2737.889 ± 0.04	365.2449 ± 0.005	0.48
May–Aug. 2001	2860.940 ± 0.04	349.5355 ± 0.005	10.83
	2824.094 ± 0.04	354.0959 ± 0.005	5.40
	2880.704 ± 0.04	347.1373 ± 0.005	1.31
	2921.804 ± 0.04	342.2543 ± 0.005	0.64
	2738.009 ± 0.04	365.2289 ± 0.005	0.34
Sep. 2000–Aug. 2001	2860.939 ± 0.01	349.5356 ± 0.001	10.25
	2824.097 ± 0.01	354.0955 ± 0.001	4.74
	2880.690 ± 0.01	347.1390 ± 0.001	1.12
	2921.816 ± 0.01	342.2528 ± 0.001	0.56
	2738.015 ± 0.01	365.2281 ± 0.001	0.35

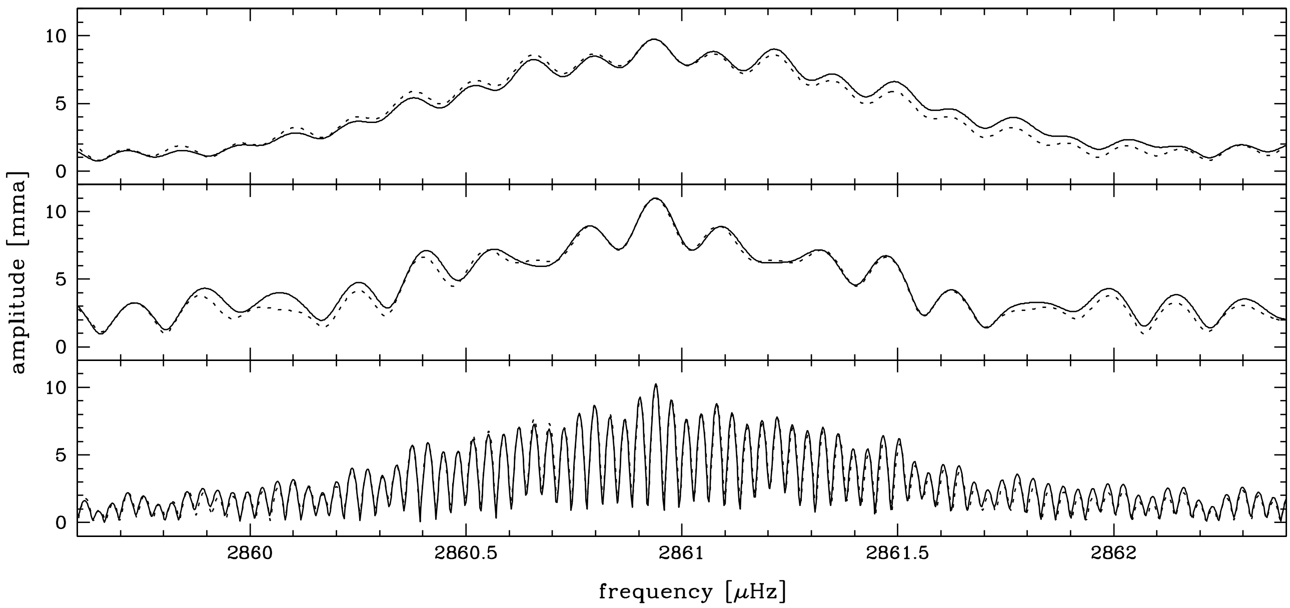

Fig. 6. The high-precision spectrum of HS 2201 obtained by joining together the data of September–December 2000 (up), May–August 2001 (center) and September 2000 to August 2001 (bottom). Only the main frequency at 2860.94 μHz is shown. The dotted lines represent the spectra of a pure sinusoid with same frequency and amplitude (spectral windows).

unprojected velocity of about 18 or 36 km s^{-1}. This hypothesis can be verified through spectroscopy. Unfortunately the spectrum reported by Østensen et al. (2001a, Fig. 1) does not allow to draw any conclusion because of the insufficient resolution; new higher resolution spectroscopy would be needed.

The relatively simple temporal spectrum of HS 2201 makes it an ideal candidate for trying to measure for the first time the secular variation of the pulsation periods ($\dot{P}$) in an sdBV star. This measurement is of great interest as it gives direct evidence of how the internal structure of the star is changing in time. The ratio $P/\dot{P}$ is related to the evolutionary time-scale needed to cross the instability strip and may be used to constrain the evolutionary models of EHB stars, helping to improve the general understanding of the sdB phenomenon.

If we consider the two other low gravity evolved pulsators similar to HS 2201 (long pulsation periods, not far

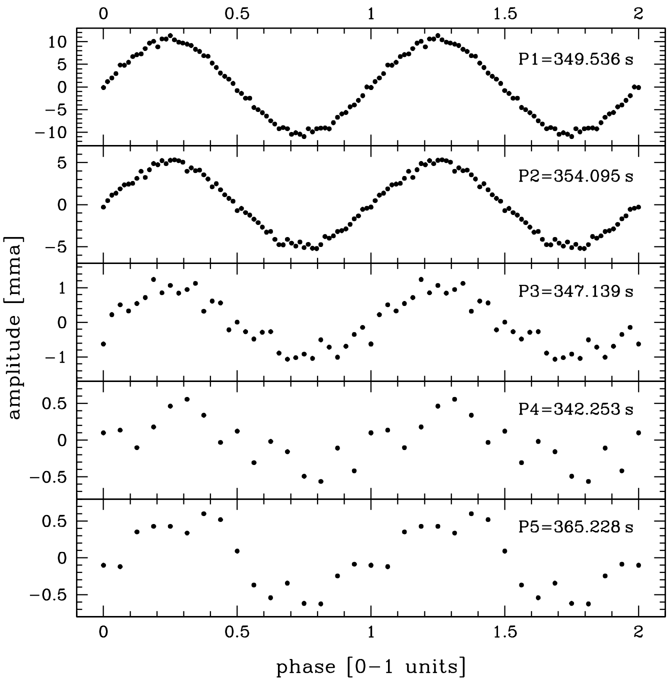

Fig. 7. The pulse shape of the five detected frequencies. The amplitude is averaged over 64 (P1 and P2), 32 (P3) or 16 (P4 and P5) phase bins, in order to reduce the noise.

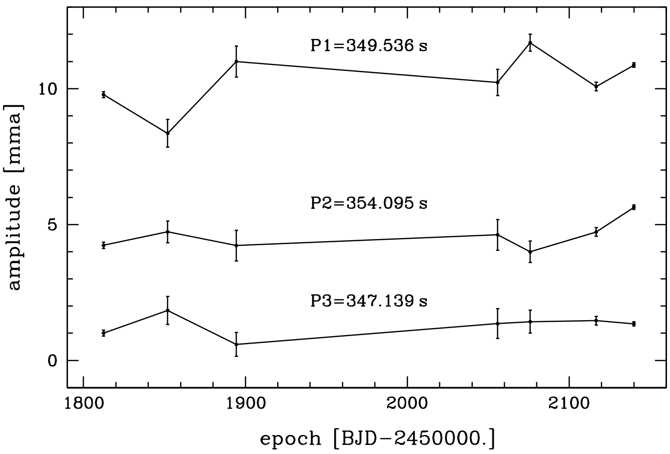

Fig. 8. Variation of the pulsation amplitudes of the three main frequencies of HS 2201 during the period September 2000–August 2001. The error bars represent the formal errors obtained from the sinusoidal fits.

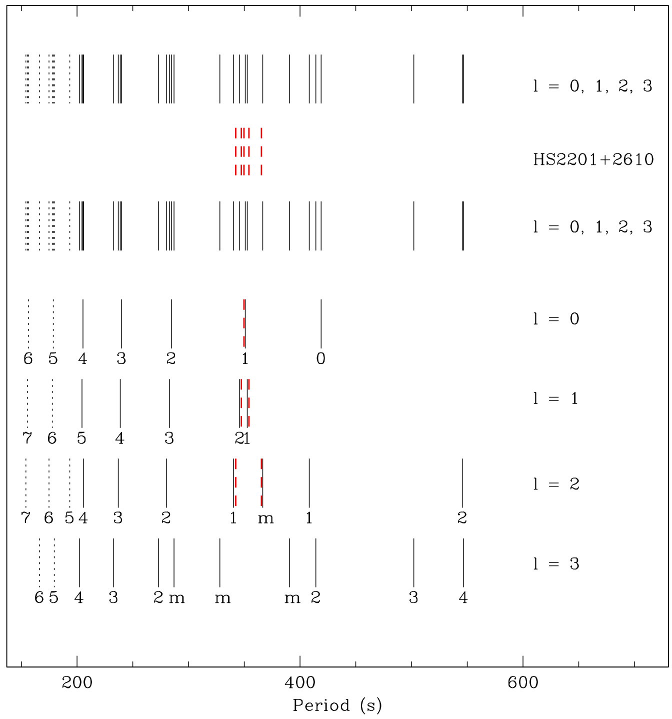

Fig. 9. Comparisons between the pulsation periods of HS 2201 and the computed spectrum of a model with $T_{\rm eff} = 30\,000$ K, $\log g = 5.36$, $M_{\rm tot} = 0.50\ M_{\odot}$, and $\log(M_{\rm env}/M_{\rm tot}) = -2.77$ (see text for details). Thick dashed line segments show the observed periods, while plain (dotted) line segments represent the computed periods of the unstable (stable) modes for $\ell = 0$ up to $\ell = 3$. Numbers below each segment correspond to the radial order (k) of the mode, while a m index indicates a mixed mode. Note that the radial order index decreases (increases) with increasing period for p-(g-)modes.

from HS 2201 in the [$\log T_{\rm eff}\ \log g$] plane), PG 1605+072 and Feige 48, the first one has a very rich but complex spectrum, with more than 50 excited modes (Kilkenny et al. 1999). Therefore, for trying to measure $\dot{P}$, several long runs (∼10 days or more each) would be needed in order to resolve the single frequencies, rendering this task much more difficult. On the other hand, Feige 48, which is more similar to HS 2201 with only 3 pulsation frequencies detected, shows very strong night-to-night amplitude variations (Koen et al. 1998). In the case of HS 2201, we have seen that the amplitudes variations do not exceed 20% in time-scales of months. Hence, also from this point of view, HS 2201 compares favorably with PG 1605+072 and Feige 48.

At this point the main question is: which value of $\dot{P}$ can we expect for HS 2201 and which time-basis will be required in order to measure $\dot{P}$? As this quantity has never been measured before for any sdB pulsator, it is hard to answer. A very crude estimate for $\dot{P}$ may be obtained dividing the pulsation period by half the evolutionary time required for crossing the sdBV instability strip. If we consider a crossing time of the order of 110 Myr, we derive a value of about 2×10^{-13} s s^{-1}. A much more reliable value may be obtained from a recent sample of p and g-mode evolution, referred to different evolutionary sequences of EHB stars (Charpinet et al. 2002c). Considering that HS 2201 should be near the phase of central helium exhaustion (the closest model gives an age of 106 Myr from the ZAEHB (Zero Age Extreme Horizontal Branch)), it is reasonable to expect a negative value for $\dot{P}$. Taking into account both p and g-modes, the best fits to the pulsation periods of HS 2201 are obtained by models with $\dot{P}$ between -1×10^{-11} and -1×10^{-13}, leading to a secular decrease of the periods of the order of 1 ms in about 4 to 400 years. This relatively large range of $\dot{P}$ is related to the

exact evolutionary status of HS 2201 close to, or just after, helium core exhaustion. Actually 1 ms every ∼400 yrs is a quite typical value for the models belonging to the EHB (He core burning), with the exception of a narrow region close to the low gravity tip, where $\dot{P}$ changes sign and may have lower values. On the other hand, 1 ms in ∼4 yrs reflects the much faster post-EHB evolution just after helium core exhaustion.

As this article clearly shows, it is possible to achieve an accuracy of the order of 1 ms with a 1-year monitoring. Therefore, a direct measurement of $\dot{P}$ can be achieved only in the most favorable hypothesis, with a data set spanning about 10 years. These numbers are confirmed by the example of the pre-white dwarf PG 1159–035 (Costa et al. 1999): Fig. 3 of this paper shows that with high-quality measurements one year of monitoring is sufficient to measure a value of 1.3×10^{-10}, i.e. about 10 times larger than the maximum value expected for HS 2201. On the other hand, to measure $\dot{P}$ with indirect methods (O–C diagram) seems to be possible also in the worst hypothesis. Two examples of such measurements are given by Kepler et al. (2000) and Mukadam et al. (2002), who derived very similar values of $(2.3 \pm 1.4) \times 10^{-15}$ and $(4.7 \pm 2.0) \times 10^{-15}$ for the two DAV white dwarfs G 117-B15A and R 548, from a large database spanning about 20 and 30 years respectively. We can then conclude that, if it appears unlikely that a direct measurement of $\dot{P}$ can be obtained in a few years, a time basis of 4–5 years might be long enough to perform an indirect measurement of (or at least to obtain an upper limit to) the secular variation of the pulsation periods of this star. For this reason we plan to continue our on-going time-series monitoring on HS 2201. This will allow us to obtain also more conclusive results on the amplitude variations of this star.

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References

Billères, M., Fontaine, G., Brassard, P., et al. 2000, ApJ, 530, 441
Brassard, P., Fontaine, G., Billères, M., et al. 2001, ApJ, 563, 1013
Brown, T. M., Ferguson, H. C., Davidsen, A. F., & Dorman, B. 1997, ApJ, 482, 685
Brown, T. M., Bowers, C. W., Kimble, R. A., Sweigart, A. V., & Ferguson, H. C. 2000, ApJ, 532, 308
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 1996, ApJ, 471, L106
Charpinet, S., Fontaine, G., Brassard, P., et al. 1997, ApJ, 483, L123
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 2000, ApJS, 131, 223
Charpinet, S., Fontaine, G., & Brassard, P. 2001, PASP, 113, 775
Charpinet, S., Fontaine, G., & Brassard, P. 2002a, Proc. of the IAU Colloq. 185, ASP Conf. Ser., in press
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 2002b, ApJS, in press
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 2002c, ApJS, in press
Costa, J. E. S., Kepler, S. O., & Winget, D. E. 1999, ApJ, 522, 973
D'Cruz, N. L., Dorman, B., Rood, R. T., & O'Connell, R. W. 1996, ApJ, 466, 359
de Martino, D., Silvotti, R., Gonzales-Perez, J. M., et al. 2002, ASP Conf. Ser., in press
Dorman, B., O'Connell, R. W., & Rood, R. T. 1993, ApJ, 419, 596
Dorman, B., O'Connell, R. W., & Rood, R. T. 1995, ApJ, 442, 105
Dreizler, S., Schuh, S., Deetjen, J. L., Edelmann, H., & Heber, U. 2002, A&A, 386, 249
Edelmann, H., Heber, U., & Napiwotzki, R. 2001, Proc. of the Joint European and German Astronomical Meeting JENAM 2001, Astronomische Nachrichten 322, 5, 401
Ferraro, F. R., Paltrinieri B., Fusi Pecci F., et al., 1997, ApJ, 484, L145
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Green, E. M., Liebert, J., & Saffer, R. A. 2001, Proc. of the 12th European Workshop on White Dwarfs, ed. H. L. Shipman, J. L. Provencal, J. Mac Donald, & S. Goodchild, ASP Conf. Ser., 226, 192
Greggio, L., & Renzini, A. 1999, Mem. S.A.It., 70, 691
Hagen, H.-J., Groote, D., Engels, D., & Reimers, D. 1995, A&AS, 111, 195
Heber, U. 1986, A&A, 155, 33
Heber, U., Reid, N., & Werner, K. 2000, A&A, 363, 198
Heber, U., Moehler, S., Napiwotzki, R., Thejll, P., & Green, E. M. 2002, A&A, 383, 938
Kawaler, S. D. 1999, Proc. of the 11th European Workshop on White Dwarfs, ed. J.-E. Solheim, & E. G. Meištas, ASP Conf. Ser., 169, 158
Kepler, S. O., Mukadam, A., Winget, D. E., et al. 2000, ApJ, 534, L185
Kilkenny, D., Koen, C., O'Donoghue, D., & Stobie, R. S. 1997, MNRAS, 285, 640
Kilkenny, D., Koen, C., O'Donoghue, D., et al. 1999, MNRAS, 303, 525

Kilkenny, D. 2002, Proc. of the IAU Colloq. 185, ASP Conf. Ser., in press
Koen, C., O'Donoghue, D., Pollacco, D. L., & Nitta, A. 1998, MNRAS, 300, 1105
Maxted, P. F. L., Marsh, T. R., & North, R. C. 2000, MNRAS, 317, L41
Maxted, P. F. L., Heber, U., Marsh, T. R., & North, R. C. 2001, MNRAS, 326, 1391
Mukadam, A., Kepler, S. O., Winget, D. E., et al. 2002, ApJ, submitted
O'Donoghue, D., Koen, C., Solheim, J.-E., et al. 1998, MNRAS, 296, 296
Napiwotzki, R., Edelmann, H., Heber, U., et al. 2001, A&A, 378, L17
Orosz, J. A., & Wade, R. A. 1999, MNRAS, 310, 773
Østensen, R., Solheim, J.-E., Heber, U., et al. 2001a, A&A, 368, 175
Østensen, R., Heber, U., Silvotti, R., et al. 2001b, A&A, 378, 466
Reed, M., Kilkenny, D., Kawaler, S. D., et al. 2000, Baltic Astron., 9, 183
Saffer, R. A., Bergeron, P., Koester, D., & Liebert, J. 1994, ApJ, 432, 351
Saffer, R. A., Livio, M., & Yungelson, L. R. 1998, ApJ, 502, 394
Saffer, R. A., Green, E. M., & Bowers, T. 2001, Proc. of the 12th European Workshop on White Dwarfs, ed. H. L. Shipman, J. L. Provencal, J. Mac Donald, & S. Goodchild, ASP Conf. Ser., 226, 408
Silvotti, R., Solheim, J.-E., Gonzalez-Perez, J. M., et al. 2000, A&A, 359, 1068
Silvotti, R., Janulis, R., Gonzalez-Perez, J. M., et al. 2001, Proc. of the Joint European and German Astronomical Meeting JENAM 2001, Astronomische Nachrichten 322, 5, 395
Silvotti, R., Østensen, R., Heber, U., et al. 2002, A&A, 383, 239
Stumpff, P. 1980, A&AS, 41, 1
Unglaub, K., & Bues, I. 2001, A&A, 374, 570
Winget, D. E., Nather, R. E., Clemens, J. C., et al. 1994, ApJ, 430, 839