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Modeling the Pulsating sdB Star PG 1605+072

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Abstract

In this paper, we exploit new photometric data for the short period pulsating sdB star PG 1605+072 gathered with the Canada-France-Hawaii Telescope. We identify some 65 frequency components, 19 of which are due to harmonics and nonlinear combinations of larger amplitude modes. We attempt to model the 46 remaining components in terms of a collection of rotationally-split frequency components in a relatively fast rotating pulsator and, thus, determine its rotation period. To do this, we must identify a priori the central ($m = 0$) components of multiplets since the comparison is carried out with purely spherical models. We find that this a priori approach is not satisfactory and that no clear signature of a specific rotation period emerges. In the light of this result, we investigate another approach where PG 1605+072 is instead seen as a "slow" rotator in which the (numerous) low amplitude frequency components can be interpreted not as rotationally-split features but as second- and third-order harmonics and nonlinear combinations of the ten highest amplitude frequencies. This new approach can partly be justified from the observation that the light curve of PG 1605+072 does not resemble any other light curve from short period sdB stars as it shows a highly nonlinear behavior. We present some preliminary results on the basis of this assumption.

Individual Objects: PG 1605+072

Introduction

PG 1605+072 has, since its discovery by Koen et al. (1998), puzzled many scientists. Its pulsation spectrum contains over 50 frequencies, and it is commonly believed that this complex structure in the Fourier domain is due to rotational splitting in a relatively fast rotator. Indeed, high resolution spectroscopic observations have revealed significant extra broadening in narrow metal

Table 1: Photometric observations on PG 1605+072

Run	Date dd/mm/1997	Start (UT)	Number of points
cfh-054	10/06	08:23:31	525
cfh-056	11/06	08:15:56	1800
cfh-059	12/06	07:57:33	2070
cfh-062	13/06	08:17:49	1945

lines which, attributed to rotation, leads to a projected equatorial velocity of $v \sin i =$ 39 km s^{-1} (see Heber et al. 1999). These characteristics are different from those commonly found in other pulsating sdB stars.

In an interesting development, Kuassivi et al. (2005) found that part of the line broadening in the spectrum of PG 1605+072 could originate from Doppler shifts (pulsational broadening) instead of a fast rotation. This could mean that the pulsation spectrum of PG 1605+072 does not contain significant frequency splitting due to rotation and that therefore another origin for its complexity needs to be found.

In this paper, we present new photometric data taken with the Canada-France-Hawaii Telescope (CFHT), as well as the results of some of our attempts to best fit the complex observed frequency spectrum of PG 1605+072 in terms of models generated by the Montréal second generation codes under the assumption that the dense spectrum originates from a fast rotation or that the star is not rotating rapidly and the spectrum has a different origin.

Observations

Photometric observations of PG 1605+072 were done during four successive nights in 1997, from June 10 to June 13, with the CFHT. For all kinds of reasons, these data had remained unexploited. Data points were taken with an integration time of 10 seconds in white light using the three-channel photometric instrument LAPOUNE. Table 1 gives some details about the four runs. The obtained light curves of the four nights can be found in Figures 1 and 2 in which one can see the complex luminosity changes as a function of time.

Frequency Analysis

For PG 1605+072, a total of 65 frequencies were found (see Table 2). The prewhitening process at different stages can be seen in Figure 3. As one can see, no peaks remain above the 3σ level in the residual of the modeled spectrum.

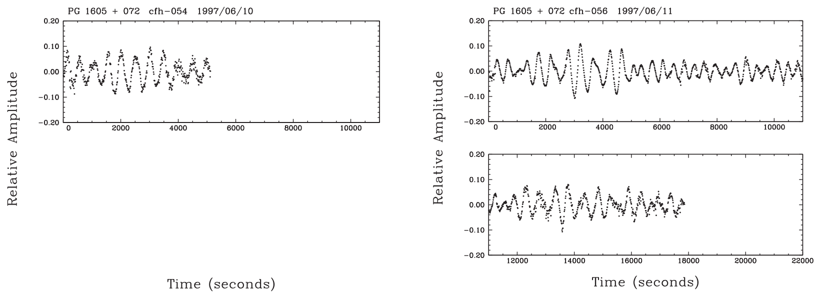

Figure 1: The lightcurve of PG 1605+072 for June 10 and 11 1997 at the Canada-France-Hawaii Telescope.

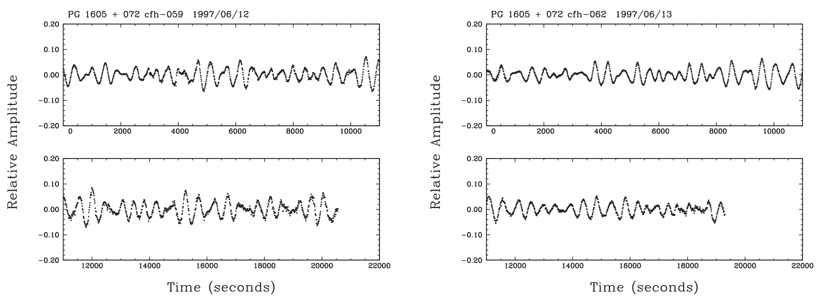

Figure 2: The lightcurve of PG 1605+072 for June 12 and 13 1997 at the Canada-France-Hawaii Telescope.

Given the relatively limited temporal resolution of our data set (our formal resolution is 3.6 μHz) in conjunction with the very dense frequency spectrum observed in PG 1605+072, some caution was necessary during the prewhitening exercise. In particular, if a peak was present around an identified mode in the data set of Kilkenny et al. (1999), that alias was chosen to participate in the process closest to the frequency from Kilkenny and company. This is because Kilkenny et al. have a much better resolution, $\sim$1/(14 days) as compared to $\sim$1/(4 days) in our case. From their 55 frequencies, a total of 38 could easily be located in our spectrum. Those common frequencies are indicated by asterisks in Table 2 and can be considered quite reliable. In both sets, the frequency with the largest amplitude is the same and the majority of the

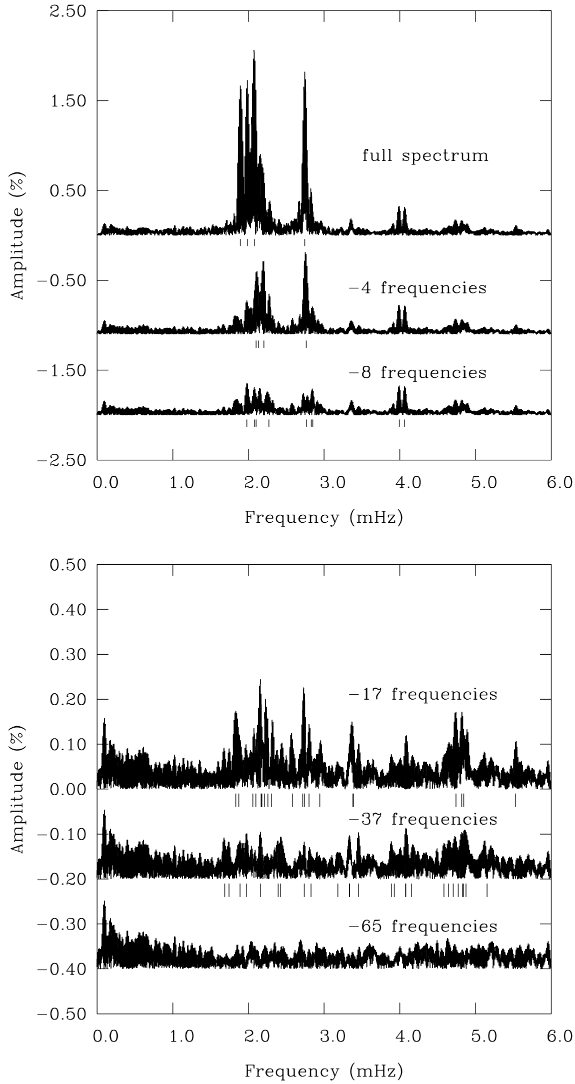

Figure 3: The prewhitening process of PG 1605+072. On the left, the full spectrum and the spectrum after subtraction of the first 4 and the first 8 frequencies. On the right, the spectrum after subtraction of the first 17 and the first 37 frequencies, and the residual spectrum after subtraction of some 65 frequencies.

Table 2: Found frequencies in the Fourier Transform of PG 1605+072

Rank n	P (s)	f (mHz)	Amplitude (%)	Rank n	P (s)	f (mHz)	Amplitude (%)
46	592.91	1.687	0.0882	5*	362.11	2.762	0.8217
52*	573.35	1.744	0.0780	16*	361.56	2.766	0.2187
20*	545.61	1.832	0.1869	27*	357.03	2.801	0.1374
24	534.61	1.871	0.1463	65*	353.73	2.827	0.5498
40	529.22	1.890	0.1463	12*	352.14	2.840	0.2683
3*	528.67	1.892	1.7856	14*	351.63	2.844	0.2600
60	518.01	1.930	0.0651	32*	339.86	2.942	0.1128
64	507.19	1.972	0.0610	61	314.30	3.182	0.0641
9*	505.82	1.977	0.3600	58	300.16	3.332	0.0874
39	505.29	1.980	0.1004	45	299.60	3.338	0.0946
4*	503.59	1.986	1.5229	26*	295.95	3.379	0.1394
28*	485.74	2.059	0.1253	37*	295.34	3.385	0.1023
1*	481.79	2.076	2.0640	42	289.69	3.452	0.0990
11*	481.71	2.076	0.2963	51	257.23	3.889	0.0801
29*	476.73	2.098	0.1244	63	254.76	3.925	0.0623
7*	475.95	2.101	0.6601	13*	246.25	4.061	0.2635
15*	475.85	2.102	0.2250	10*	250.44	3.993	0.3248
8*	475.27	2.104	0.5450	38	245.40	4.075	0.0679
46	463.44	2.158	0.0926	48	245.25	4.077	0.1008
18*	461.37	2.167	0.1980	56*	240.58	4.156	0.0724
33	459.61	2.176	0.1118	52*	218.23	4.582	0.0790
6*	454.19	2.202	0.8106	54	215.36	4.643	0.0777
19	451.84	2.213	0.1943	49	212.63	4.703	0.0838
25	443.28	2.256	0.1397	21	210.99	4.740	0.1710
17*	440.32	2.271	0.2134	55	209.58	4.771	0.0763
30*	434.30	2.303	0.1172	23*	207.54	4.818	0.1612
57*	418.00	2.392	0.0713	44	207.16	4.827	0.0984
43	412.87	2.422	0.0989	41*	206.52	4.842	0.0999
36*	387.45	2.581	0.1025	35*	206.38	4.845	1.0489
22*	368.16	2.716	0.1698	59	205.11	4.875	0.0671
62*	365.28	2.738	0.0635	50	195.14	5.125	0.0824
31*	364.72	2.741	0.1159	34	180.96	5.526	0.1071
2*	364.60	2.743	1.8283				

Table 3: The equally spaced multiplets present in the observed spectrum. Multiplets 1, 2, 3, and 4 have a spacing of $\sim$ 90 μHz. Multiplets 5, 6, 7, and 8 are have a spacing of $\sim$ 40 μHz.

Nr.	f_{center} mHz	m	$f \pm \Delta\nu$ mHz	$\Delta\nu$ μHz	Nr.	f_{center} mH z	m	$f \pm \Delta\nu$ mHz	$\Delta\nu$ μHz
		-1	1.744	88			-1	1.890	40
1	1.832	0	-	-	5	1.930	0		-
		1	1.930	98			1	1.972	42
		-2	1.892	184			-2	2.716	85
		-1	1.986	90			-1	2.762	39
2	2.076	0	-	-	6	2.801	0		-
		1	2.167	91			1	2.844	43
		2	2.256	180					
							-2	2.176	80
		-1	2.213	90			-1	2.213	43
3	2.303	0	-	-	7	2.256	0		-
		1	2.392	89			1	2.303	47
		-2	2.582	180			-2	1.892	85
4	2.762	0	-	-	8	1.977	0		-
		2	2.942	180			2	2.059	82
							3	2.102	125

10 highest amplitude frequencies is the same, although not in the same order. The other frequencies in Table 2 are less reliable, but we nevertheless believe them to be real although possibly less accurate. Given the limitations of current models in reproducing the observed frequencies at their observational precision, this question of frequency accuracy is of secondary importance in the context of this exploratory work.

Models

Using the list of frequencies given in Table 2, we tried to construct acceptable seismic models for PG 1605+072 using the Montréal second generation model building codes (see, e.g., Brassard et al. 2001). We searched parameter space in the ranges $T_{\text{eff}} = 31,500{-}33,500$ K (with a resolution of 10 K), $\log g = 5.200{-}5.300(0.001)$, $M_*/M_\odot$ = 0.300−0.800 (0.001), and $\log q(\mathrm{H})$ from −3.00 to −6.00 in steps of 0.01. The search domains for the effective temperature and the surface gravity were defined by independent spectroscopic constraints.

Fast Rotation Models

Kawaler (1999) was the first to try to find an asteroseismological model for PG 1605+072. He only used the five frequencies with the highest amplitudes within the dense Fourier spectrum reported by Kilkenny et al. containing at least 55 frequencies, and found that three of these frequencies could possibly make up a rotational triplet if the velocity at the equator of PG 1605+072 is 130 km s^{-1}. Taken at face value, and assuming log g = 5.25 and a representative mass of 0.5 $M_\odot$ for PG 1605+072, this implies a rotation period of about 2.6 h. This is quite short for a single star such as PG 1605+072. At the same time, this also implies that the temporal resolution achieved during our 4-night observing run is amply sufficient to resolve rotationally-split multiplets, if present (not withstanding the difficulty of overlapping frequency components in the dense spectrum as briefly alluded to above). Subsequent spectral analysis by Heber et al. (1999) indicated that PG 1605+072 could indeed be a fast rotator, with a projected rotational velocity of $V \sin i = 39$ km s^{-1}, a rather high value by sdB standards. Starting from these findings, we tried to find a rotation period for PG 1605+072 by looking for nearly equally spaced components within frequency multiplets caused by the fast rotation as expected from first-order perturbation theory. The different multiplets found are listed in Table 3. Next, we retained what appeared to us as the central (m = 0) components of the multiplets for detailed comparison with the predictions of spherical models in the same spirit as in Brassard et al. (2001).

Model 1

In this first model, a reference one, we assume no rotation at all, and we try to fit all observed frequencies as independent modes with different values of k and l. It should be pointed out, however, that in the original list of 65 frequencies only 46 can be considered a priori as independent modes, the others (those with periods less than 260 s) being harmonics and nonlinear combinations of the highest amplitude modes. Hence, we tried to fit only 46 frequencies. As expected for this reference model, the best fit is really not good, showing a rather large goodness-of-fit value of χ^2 = 741. This indicates that our original assumption that all 46 frequencies are modes with different individual values of k and l is incorrect. For a graphical representation of the model fit, see Figure 4.

Model 2

In this second model, we removed the 10 frequency components associated with the m components of the four multiplets characterized by a common spacing of 90 μHz in Table 3. We thus retained only the m = 0 components of these multiplets, limiting our list of retained frequencies to 36. Again, we searched in parameter space for the best fit model. We found that the resulting merit function for that optimal model is still very high at $\chi^2 = 349$. Taking into account the reduced number of frequencies to fit, this is no significant improvement over the previous case. See Figure 4 for a graphical representation of the model fit.

Model 3

Our third search exercise is similar to our previous attempt, except that we removed 10 other frequencies, this time associated with the four multiplets in Table 3 showing a possible common spacing of 40 μHz, the other possibility for such splitting in our original list of 46 frequencies. Hence, we tried again to fit 36 frequencies, but 10 of which are different from before. We then found a significant improvement in the merit function over the previous cases, a value of $\chi^2 = 215$, but this still remains an unacceptable fit as can be seen in Figure 4. The observed distribution of periods is simply not well reproduced by our approach.

If PG 1605+072 is rotating fast enough to split the modes into equally spaced multiplets, the subtraction of these components should significantly improve the best fit to spherical models. As this is not the case, one could conclude that perhaps PG 1605+072 is rotating so rapidly that second-order solid-body rotation or differential rotation effects would set in, resulting in non-equally spaced multiplets for which the search is beyond the scope of this work. Alternatively, one could instead conclude that perhaps PG 1605+072 is, in fact, rotating slowly, and rotational multiplets can no longer be found with our frequency resolution. At this stage, we prefer to think that the weakness of our approach rests currently with our a priori identification of the $m = 0$ components of the multiplets. We suggest that the period-matching exercise in parameter space should be redone in the future, but using models that specifically include rotation so that no a priori identification needs to be made. This would allow all the 46 observed frequencies to be treated on the same footing. An example of such an approach has been presented recently by Van Grootel et al. (2008) for the short-period pulsating sdB star Feige 48.

Slow Rotation Models

The idea that PG 1605+072 may not be, after all, a fast rotator comes from the work of Kuassivi et al. (2005) who showed that pulsational broadening could account for up to 34 km s^{-1} (twice the measured fluid displacement velocity of 17 km s^{-1}) in terms of line broadening in that star. If true, it may be that the rotation period of PG 1605+072 is rather long. Of course, if this is the case, another mechanism needs to be found for the large number of visible modes in the spectrum. Comparing the looks of the light curves in Figure 1 and

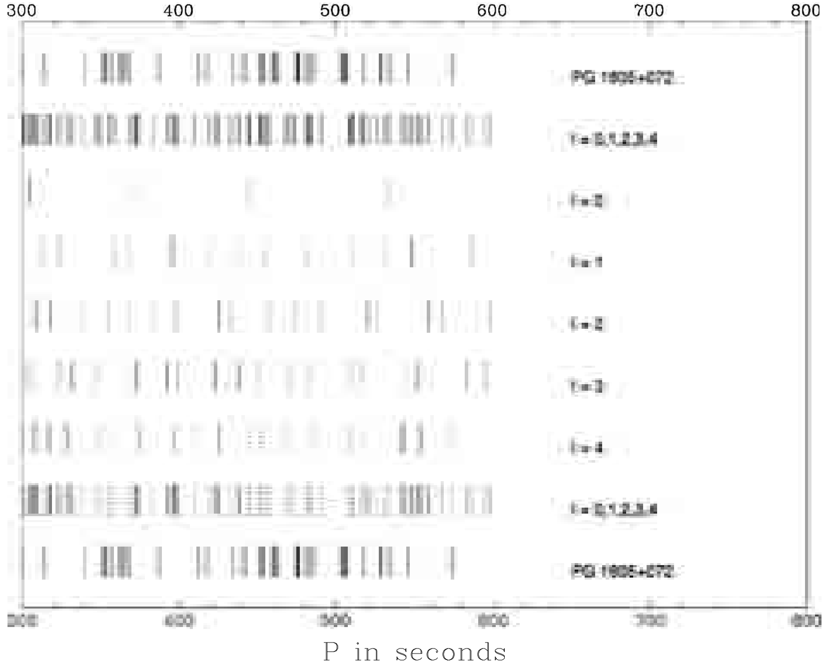

Figure 4: Graphical representations of the best-fit models for a fast rotating PG 1605+072: Model 1

The first line of each graph is the observed spectrum of PG 1605+072, the second line represents the spectrum for the best fit model, the next four lines split this spectrum into the different l-values, and the last two lines are similar to the first two lines. Dashed lines represent the modes in the modeled spectrum identified with modes in the observed spectrum.

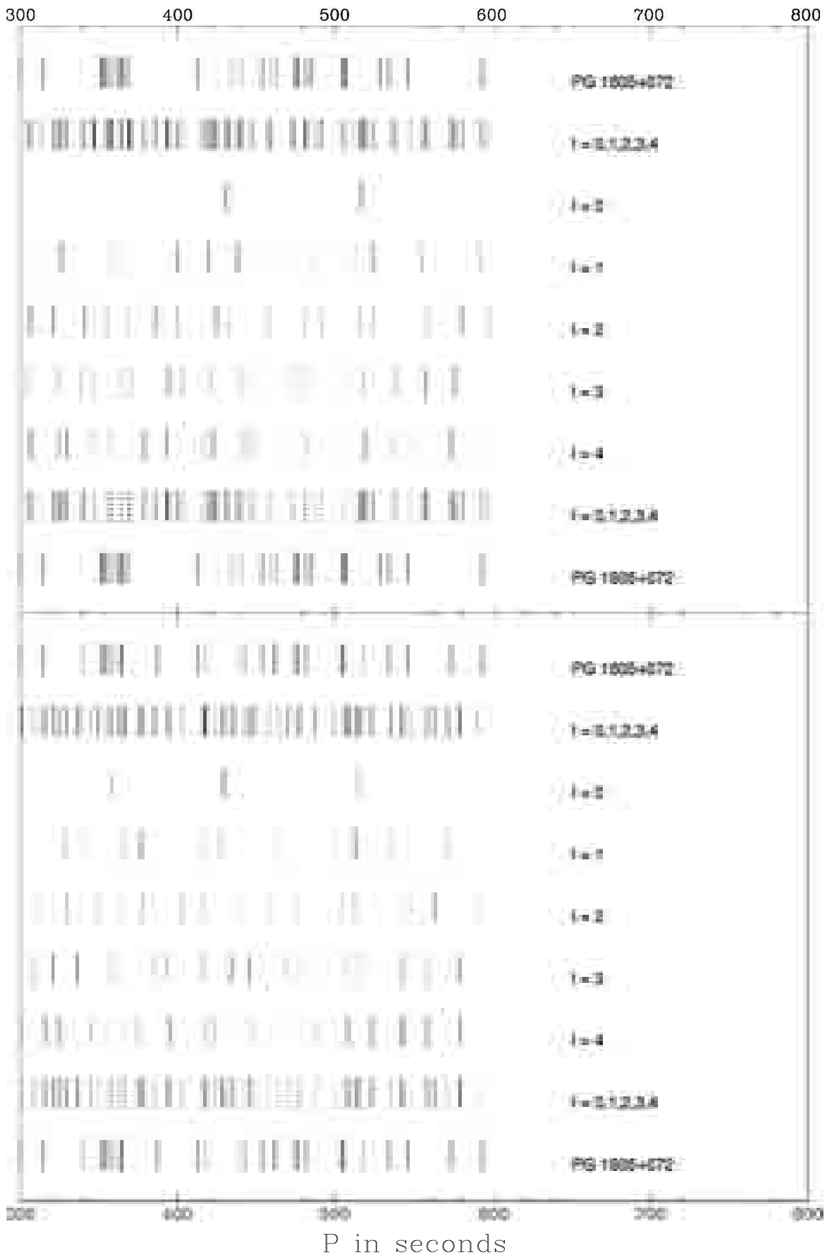

Figure 5: Graphical representations of the best-fit models for a fast rotating PG 1605+072. The configuration in the figure is the same as in Figure 4.
Top panel: Model 2. Bottom panel: Model 3.

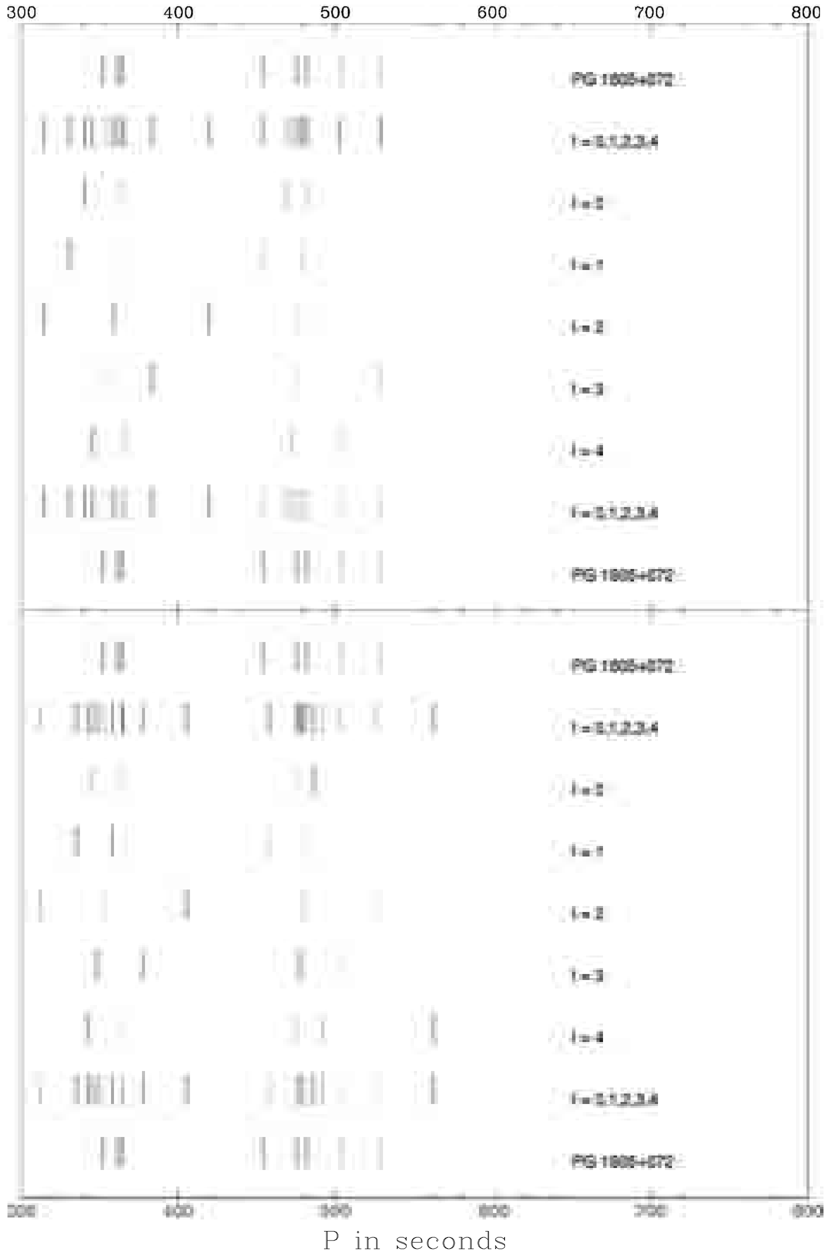

Figure 6: Figure 6 (below) The best fit models for PG 1605+072, including only the ten highest amplitude modes. The configuration in the figure is the same as in Fig. 4. Top panel: Model 4. Bottom panel: Model 5.

Figure 2 with other sdB light curves suggests that, for PG 1605+072, a highly nonlinear oscillation process could be at the origin of the many frequencies in the spectrum. The result of this is that a large number of 2nd- and 3rd-order harmonics and cross frequencies can be invoked to make up the rich spectrum of PG 1605+072. In fact, among our list of 65 frequencies, it only takes the ones with the ten highest amplitudes to construct the remaining 55 frequencies with second- or third-order combinations within our resolution.

Model 4

Using these 10 modes only, another search in parameter space results in a best fit model defined by $T_{\rm eff} = 32\,300$ K, $M = 0.707 M_{\odot}$, $\log g = 5.248$, and $\log q({\rm H}) = -5.78$. The merit function for this model is $\chi^2 = 15.3$. Not only is the formal fit better than in the previous models (taking into account the much reduced number of observed frequencies in the fit), but the distribution of the modeled modes is now very similar to the distribution of the observed modes as can be seen in Figure 5. Furthermore, the highest amplitude mode is either an $l = 0$ or an $l = 1$ mode, as can be expected. Although the mass of this model is rather high (and therefore the hydrogen envelope rather thin), it is still within the predicted mass range by Dorman et al. (1993), Han et al. (2002), and Han et al. (2003).

Model 5

Another good fit for the 10 highest amplitude modes is found at $T_{\rm eff} = 32\,300\,K$, $M = 0.561 M_{\odot}$, $\log g = 5.217$ and log q(H) = -6.22 (see Figure 5). The fit for this model is slightly worse than for Model 4 at $\chi^2 = 24.3$, but still noteworthy because of the lower mass. The l value for the highest amplitude mode in this model is either 1 or 2.

Conclusion

New data for the pulsating sdB star PG 1605+072 have been presented. After analysis, a pulsation spectrum containing at least 65 frequencies emerges. During the prewhitening process, we used, when appropriate, the mode identification of Kilkenny et al. (1999), and we recovered 38 of their frequencies.

Under the assumption that the dense spectrum is caused by a relatively fast rotation of the star which produces a splitting of modes into equally spaced multiplet components, we found two possible frequency spacings at ~ 90 μHz and $\sim 40\mu$Hz. The subtraction of the m components from the spectrum did not improve the quality of the fit between the observed values and the model frequency spectrum, however, as could have been expected. We suspect that this failure is caused by our a priori identification of the $m = 0$ components, and we suggest that the period-matching exercise in parameter space should be redone but, this time, with models incorporating rotation explicitly.

If the dense spectrum is assumed instead to consist of a large number of second- and third-order harmonics and cross frequencies, and only the highest amplitude modes are genuine modes, we then find two acceptable models at $M_* = 0.561 M_\odot$ and $M_* = 0.707 M_\odot$. Further investigations along this line of nonlinear frequency peaks should certainly be pursued in more detail than presented here, particularly in view of the unique, highly nonlinear light curve observed for PG 1605+072.

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