Part 2.5. Pulsations in Compact Objects

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A Review of the Pulsating sdB Stars

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Abstract. A brief overview of the relatively new field of pulsating sdB stars is presented together with some recent observational and theoretical developments. A list of known pulsators is included.

1. Introduction

The first pulsating sdB stars were discovered at the SAAO in the mid-1990s (Kilkenny et al., 1997; Koen et al., 1997; O'Donoghue et al., 1997; Stobie et al., 1997). Since then, $\sim$30 stars have been found which belong to this class, largely by groups working at the SAAO, Montreal or with the Nordic Optical Telescope (see Table 1). A typical sdB pulsator varies with several frequencies in the range $\sim$ 5 – 10 mHz (100 – 200 seconds) with amplitudes of the order of 0.01 mag or less. Some show clear spectroscopic evidence for later-type (F or G) companions; others show no detectable companion.

The temperature and gravity ranges occupied by the sdB pulsators are 29000K $< T_{\rm eff} <$ 36000K and $5.2 < \log g < 6.1$ and, as yet, there is no obvious reason why some sdB stars pulsate and many others – in the same range of $T_{\rm eff}/\log g$ – do not. A list of pulsators known to the author at the time of writing (July 2001) is given in Table 1, along with some basic data.

At about the time the first sdB pulsators were being discovered at the SAAO, the Montreal group was showing theoretically that these stars should pulsate. Charpinet et al. (2001) have given an excellent review of this work, which found – before the discovery of any actual pulsators – that radial and non-radial pulsations can be driven in the range 29000K $< T_{\rm eff} <$ 36500K (almost exactly as observed) in representative models with M = $0.48 M_\odot$ and log g = 5.8. This is a clear *prediction* of the existence of a new class of pulsating stars – only the second time that such a successful theoretical prediction has been made (the first being the DB pulsators; see, for example Winget & Fontaine, 1982).

At present, there is no "official" name for these pulsators. Following the principle of naming a class of variables after the first such star discovered , they were initially called "EC14026 stars" (Kilkenny et al., 1997). Some authors have used "sdBV stars", by analogy with the DAV stars, but the question is still not settled. The 75th name list of variable stars (Kazarovets, Samus & Durlevich 2000) designates the class "RPHS" or "very rapidly pulsating hot (subdwarf B) stars" and notes that the variable star name V361 Hya has been given to the prototype star.

Table 1. List of the known pulsating sdB stars (~July 2001)

Star	$T_{\rm eff}$ (K)	log g	N_{freq}	P (s) (range)	ampl. (mmag)	Reference
EC14026-2647	34700	6.10	2	134-144	4-12	Kilkenny et al. (1997)
PB8783	35700	5.54	6	120-134	1-9	Koen et al. (1997)
			11†	94-136	0.3-2	O'Donoghue et al. (1998a)
EC10228-0905	34300	5.85	3	139-152	4-14	Stobie et al. (1997)
EC20117-4014	34800	5.87	3	137-159	1-4	O'Donoghue et al. (1997)
PG1047+003	34370	5.70	5	104-162	2-9	Billères et al.(1997)
	35000	5.90	9	104-162	1.5-10	O'Donoghue et al. (1998b)
			18†	104-175	0.4-7	Kilkenny et al. (in prep.)
PG1605+072	32100	5.25	>30	207-539	2-64	Koen et al. (1998a)
			55†	206-573	0.6-27	Kilkenny et al. (1999)
	30000	5.20	>50	290-601	1-25	Montreal group (in prep.)
PG1336-018	33000	5.70	2	141-184	5-10	Kilkenny et al. (1998)
			28‡	97-205	0.5-5	Kilkenny et al. (in prep.)
			‡			Reed et al. (in prep.)
KPD2109+4401	31200	5.84	5	182-198	2-9	Billères et al.(1998)
			5	182-198	1-6	Koen (1998)
			15	104-213	0.2-8	Montreal group (in prep.)
Feige 48	28900	5.45	4	340-380	1-7	Koen et al. (1998b)
			6	258-376	0.4-6	Montreal group (in prep.)
PG1219+534	32800	5.76	4	128-149	2-9	Koen et al. (1999a)
PG0911+456	31900	5.82	3	155-166	2-7	Koen et al. (1999a)
KUV0442+1416	30900	5.72	3	184-231	3-20	Koen et al. (1999b)
EC05217-3914	31300	5.76	3	213-218	2-7	Koen et al. (1999b)
KPD1930+2752	33280	5.61	44	146-332	0.2-3	Billères et al. (2000)
PG0856+121			2	315-436	3-3.5	Piccioni et al. (2000)
			3	303-503	2-3.6	Ulla et al. (2001)
PG1618+563B	33900	5.80	2	139-144	1-2	Silvotti et al. (2000)
KUV0815+4243	33700	5.95	1	126	7	Østensen et al. (2001)
HS2149+0847	33600	5.90	2	142-159	7-11	Østensen et al. (2001)
HS2201+2610	29300	5.40	1	350	11	Østensen et al. (2001)
PG0014+067	33310	5.79	13	80-169	0.4-2	Brassard et al. (in press)
HS0039+4302	32400	5.70	4	182-234	2-8	Østensen et al. (in press)
HS0444+0458	33800	5.60	1	137	12	Østensen et al. (in press)
HS1824+5745	33100	6.00	1	139	5	Østensen et al. (in press)
PG2151+089	34500	6.10	4	129-151	2-5	Østensen et al. (in press)
PG0048+091			7	106-190	2-8	Koen et al. (in prep.)
PG0154+181			1	164	10	Koen et al. (in prep.)
EC11583-2708			4	114-149	2-6	Kilkenny et al. (in prep.)
EC20338-1925			5	135-168	2-25	Kilkenny et al. (in prep.)

‡ = Whole Earth Telescope (WET) campaigns; † = other multi-site campaigns

2. Observational

2.1. Highlights

Most of the pulsating sdB stars have very small amplitudes, typically a few percent variation peak-to-peak. Indeed, the prototype, EC14026-2647, was not

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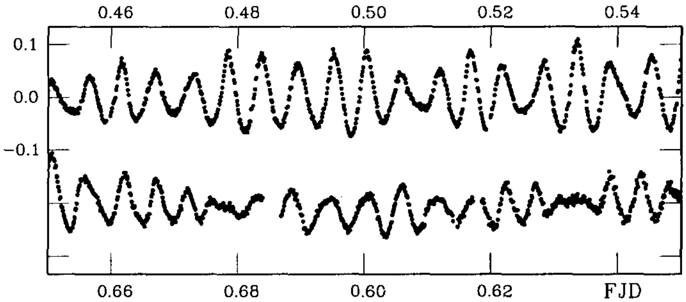

Figure 1. Part of the light curve of PG1605+072 from 1997 May 8 (Kilkenny et al., 1999). Ordinate units are fractional intensity.

seen to vary at the telescope; it was only when the Fourier analysis was carried out that variability was detected. It is worth mentioning a few unusual cases as these can lead to additional insights into the subject. That they happen to have the most spectacular light curves is a happy coincidence for the speaker.

PG1605+072 is the largest amplitude sdB pulsator known to date (~20% peak-to-peak) and has many modes of oscillation. It was discovered by Koen et al. (1998a) who found more than 30 frequencies. A multi-site campaign reported by Kilkenny et al. (1999) detected 55 frequencies, and whilst some of the higher frequencies could be identified as sums or harmonics of lower frequency signals, and others were of rather low amplitude, still about 40 frequencies are likely to be due to normal modes of pulsation. PG1605+072 has the lowest surface gravity ($\log g = 5.2$) and longest pulsation periods (up to $\sim$ 10 minutes) of any known sdB star – both items are consistent with the star being in the process of evolving away from the Zero-Age Horizontal-Branch. A short portion of a light curve is shown in Fig. 1.

PG1336-018 has, perhaps, the most striking light curve (Kilkenny et al. 1998). It is a short period ($\sim$ 0.1d) eclipsing binary and the companion is probably an M5 dwarf, so the system shows rapid eclipses and a large reflection effect with superposed fast pulsational variations. A sample light curve is shown in Fig. 2. In the discovery observations, two definite frequencies were detected (periods near 184s and 141s) although the existence of other weak frequencies was suspected. This star will be discussed further in the next section.

A beautiful light curve is exhibited by KPD1930+2752 (Billères et al., 2000). The star appears to have at least 44 frequencies in the period range 145 – 332 seconds, with amplitudes $\sim$ 0.06 to 0.45% of the mean stellar brightness. But the light curve is dominated by a nearly sinusoidal variation with a period of $\sim$ 4109s and amplitude of ~1.4%. This "slow" variation was interpreted as due to ellipsoidal variation, implying the star must have a cool companion. The rich pulsation spectrum is compatible with a low degree p-mode spectrum, rotationally split in a star rotating with a period of $\sim$ 8218s. Maxted, Marsh, & North (2000) have shown spectroscopically that the star is indeed binary (velocity amplitude ~350 km s^{-1}; orbital period $\sim$ 8218s) with a high probability that the companion is a high mass ($\sim 1 M_{\odot}$) white dwarf and the possibility that the system is a type Ia supernova progenitor.

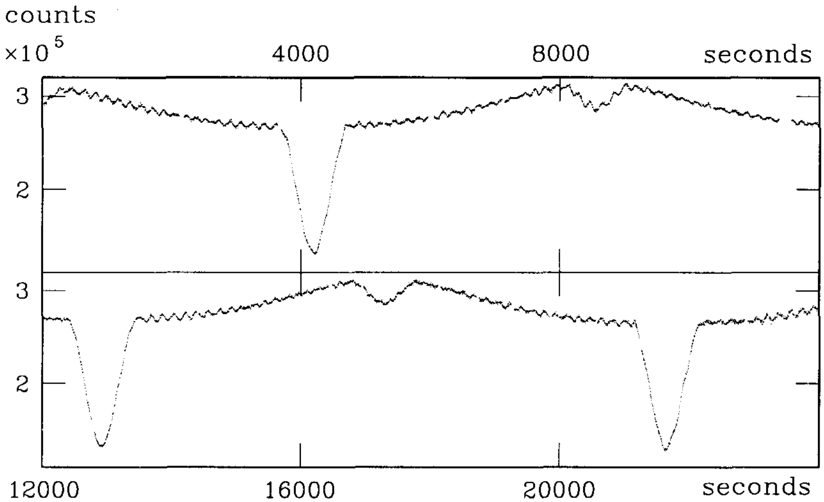

Figure 2. Most of a single light curve from WET campaign Xcov17 on PG1336-018. The ordinate is sky-subtracted, extinction-corrected counts. Note that pulsations can be seen during primary as well as secondary eclipse.

2.2. Multi-site campaigns

The value of multi-site campaigns is clear. Long data baselines increase the frequency resolution; the "window function" is simplified by uninterrupted data sets; and signal/noise is improved by having more data. For the pulsating sdB stars, these effects have resulted in many more frequencies being detected which means, for example, that it should be possible better to match observed frequencies to pulsation models and thus have more chance to determine the modes.

Two multi-site campaigns have been published so far; one on PB8783 which resulted in the number of known frequencies being increased from six to eleven (O'Donoghue et al., 1998a); and one on PG1605+072 which resulted in an increase from "more than 30" frequencies to "more than 50" (Kilkenny et al., 1999). In the latter case, it also became clear that most of the weak, high frequency terms were sums of two lower frequencies.

In 1997 a multi-site campaign was carried out for PG1047+003. It is interesting to note that even though the "duty cycle" of this campaign was only about 30% (compared with 53% and 43% for the two campaigns noted above), still the number of known frequencies was doubled from 9 to 18 (Kilkenny et al. in preparation).

The first "Whole Earth Telescope" (WET) campaign on a pulsating sdB star was Xcov17 on PG1336-018 (see *www.iitap.iastate.edu/xcov17/index.html* and Figs. 2 & 3). Apart from the usual aim of resolving the frequencies as completely as possible, it was also hoped to find rotational splitting of frequencies (by making the reasonable assumption that the binary components are phase-locked) and to model the light variations during primary (partial) eclipse as a way of identifying pulsation modes. Data coverage for this campaign was

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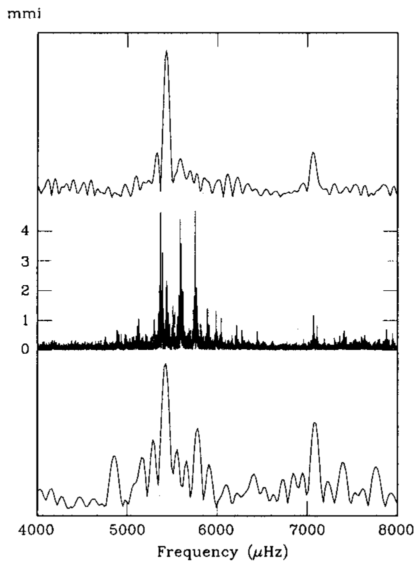

Figure 3. Comparison of periodograms for PG1336-018 from the discovery paper (Kilkenny et al., 1998) and from Xcov17. The upper and lower figures are, respectively, a $\sim$ 5 hr run with no filter and a $\sim$ 3 hr run with a U filter. The middle periodogram is from Xcov17. Note the vastly improved resolution and signal/noise of the middle periodogram.

about 47% and Fig. 3 shows a comparison of periodograms from the earlier "discovery" data with the much more extensive and more continuous data of Xcov17. Instead of two frequencies with the hint of more at the <0.3% level, we can now extract, with some confidence, over 20 frequencies down to about the 0.05% level. A complication is that it appears likely that the periodogram has changed significantly between 1996 and 1999. The search for rotationally split frequencies and attempts to model the in-eclipse pulsations were less successful than hoped, but a further WET campaign on the star was carried out in 2001 April and will be discussed by Mike Reed (these proceedings, see also *www.iitap.iastate.edu/xcov21/index.html*).

2.3. High-speed spectroscopy

An interesting development is the attempts to obtain spectroscopy at sufficient time resolution to provide pulsation information. However, the periods are short, the amplitudes are small, and most of the stars are faint, so that one might expect that only the largest telescopes would be able to produce useful results.

Jeffery & Pollacco (2000) used the 4.2m William Herschel Telescope to obtain spectroscopy of PB8783 and KPD2109+4401 at a time resolution of $\sim$ 10 seconds. In both stars they find peaks in the velocity periodograms which coincide with the photometric frequencies; amplitudes are around 2 km s^{-1}. For the spectroscopic binary PB8783 (sdB + F) they find that pulsation is confined to the sdB star and that the binary period is probably between 0.5 and 3.2d.

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The most obvious target for such studies is PG1605+072 because it has the longest pulsation periods ($\sim$ 8 min) and largest amplitudes ($\sim$ 20%). O'Toole et al. (2000) showed that it was possible to detect velocity variations in this star using quite modest sized telescopes (1.5 – 1.9m) and carried out further spectroscopic work with (nearly) simultaneous photometry which detected several variations in velocity at the same frequencies observed in the photometry. Simon O'Toole (these proceedings) describes this work in more detail.

3. Theoretical

3.1. Driving mechanism

The only seriously proposed model for driving sdB pulsations that I have seen is that initially proposed by Charpinet et al. (1996) and which predicted that some sdB stars should pulsate. The model, subsequently strengthened by Charpinet et al. (1997) requires that a balance between gravitational settling and radiational levitation is achieved which concentrates heavy elements, principally iron, at a level where the effect on the opacity can drive pulsations via the κ-mechanism. A very good review of this work is given by Charpinet et al. (2001).

3.2. Mode identification

Identification of actual pulsation modes in the pulsating sdB stars is decidedly non-trivial. As we have seen, some stars have many frequencies which indicates that there must be non-radial modes involved and means, as Brassard et al. (2002) have noted, that there may be billions of possible matches between observed and theoretical frequencies. In addition, there is an observational problem; since all multi-site campaigns have resulted in the detection of more frequencies than previously known, it is quite probable that for many of the stars we have not found anything like the full complement of frequencies. (In Table 1, for example, a number of stars are noted as singly-periodic. I would be surprised if detailed observation did not prove these to be multi-periodic.)

Qualitative matches have been made in several instances. These show that both the Kawaler and Montreal models predict pulsations in low-order, low-degree acoustic modes in the same sort of period ranges as pulsations are actually observed (see, for example, Fig. 8 of Kilkenny et al., 1999, and Figs. 10 and 11 of Koen et al., 1999a). Until recently, only one star has had any attempt at mode identification. Kawaler (1999) has identified the five strongest modes in PG1605+072 with the rotationally split ℓ=1, n=7 mode and "trapped" modes. This solution requires the star to be rotating at 130 km s^{-1} and Heber et al. (1999) have shown the star to have significant rotation with a $v \sin i$ = 39 km s^{-1}. An exciting new approach to mode-identification has been devised by the Montreal group; we refer to Stéphane Charpinet (these proceedings).

4. Conclusion

The field of pulsating sdB stars is expanding nicely. Many more stars have been discovered in the last two years and, for some stars, many pulsation frequencies have been detected. The first "high-speed" spectroscopic observations have been made, and theoretical advances have indicated a likely driving mechanism and have made significant progress towards mode identification.

Every star which has been looked at in detail – with multi-site campaigns, for example – has shown many more pulsation frequencies than from short-baseline data sets. It seems important, therefore, to carry out such campaigns for as many stars as possible, especially if mode-identification becomes tractable.

Theoretically, the biggest problem seems to be in understanding why some sdB stars pulsate and others of similar $T_{\rm eff}/\log g$ do not.

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Discussion

L. Balona : Do you see any evidence for forced oscillations caused by binary interaction in the two close systems you have observed ?

D. Kilkenny : I have a good answer to that question – ask Mike Reed ! Seriously, he will talk about PG1336-018 in a few minutes. For the other obvious close binary, KPD1930+2752, I can't recall if there was any interaction. (Added later: In the Billères et al. (2000) paper, there does not appear to be any simple connection between pulsational and orbital periods.)

G. Bono : Is there any correlation between the pulsation properties of oscillating sdB stars and metallicity ?

D. Kilkenny : I think that we don't yet have enough data to answer that question. Uli Heber and his collaborators (e.g. Heber et al. (1999) have analysed several pulsating sdB stars and, if I remember correctly, have found the usual sort of sdB abundances – depleted He, C, N, O, and so on – and nearly Solar Fe abundances – but I don't think there's any obvious correlation with pulsation period, for example. There does seem to be a correlation (based on only a few stars) in that the low log g stars have the longest pulsation periods (eg. PG1605+072 and Feige 48).