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Pulsating Hot Subdwarfs – An Observational Review

D. Kilkenny

South African Astronomical Observatory, PO Box 9, Observatory, South Africa

Abstract

In the decade since rapidly-pulsating sdB stars were discovered, slowly-pulsating sdBs have been found and multi-site campaigns have been carried out on both types. In addition, the first examples of pulsating He-sdB and sdO stars have been discovered and await detailed investigation. This paper briefly reviews the field and indicates some current trends and future possibilities. A suggestion is made for a new nomenclature.

Rapidly-pulsating (p-mode) sdB stars

The first rapidly-pulsating sdB stars were found accidentally in the mid-1990s (Kilkenny et al. 1997 and following papers in the same volume). Simultaneously – and independently – the Montreal group was showing that these stars should pulsate (see the review by Charpinet et al. 2001). Nearly 40 such stars are now known; they are p-mode pulsators with periods $\sim 2-5$ minutes, though periods as long as 9 minutes are known. They can exhibit anywhere from 1 to over 40 pulsation modes (e.g. Kilkenny 2002) and occur amongst the hotter sdB stars with $28000 < T_{\rm eff} < 35000$ and $5.2 < \log g < 6.1$.

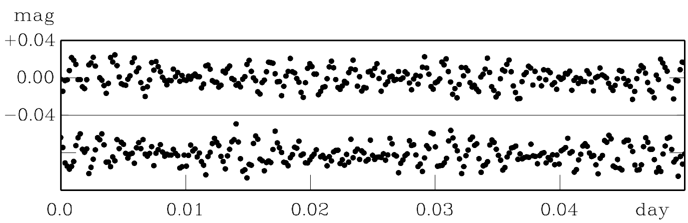

Figure 1: Part of a light curve for the rapidly-pulsating sdB star, EC 09582-1137.

Figure 1 shows part of a light curve for the recently discovered pulsator, EC 09582-1137 (Kilkenny et al. 2006). The observations indicate a classical beating oscillator and Fourier amplitude spectra from data obtained in 2005 show two pulsations at 6612 and 7353 μHz (periods of 151 and 136 s), both with amplitudes near 0.008 mag, and with little evidence for any other frequency.

Fourier spectra from three nights in 2006 are displayed in Fig. 2 where it can be seen (upper panel) that the 136 s mode has disappeared; in the middle panel it re-appears; and in the lower, a third period appears near 143 s. Spectra from other nights show similar behaviour – one, two or all three modes become so weak as to be undetectable. Also, in 2005, the amplitudes were ~ 0.008 mag; in 2006, they never exceed 0.005 mag. There is thus evidence for amplitude variation on a range of time scales.

EC 09582-1137 is an apparently simple case; PG 1605+072 is anything but. A multi-site campaign in 1997 found over 40 independent frequencies and ten sum frequencies (Kilkenny et al. 1999). In 2004, a two-week single-site campaign was carried out at the SAAO and the results are compared on a weekly basis with the 1997 data in Fig. 3. It is clear that in

1997 there was little difference between the two weeks of the campaign; in 2004, not only are the amplitude spectra quite different from 1997, but the two weeks show clear evidence for change far above the noise level. Again, amplitude changes are occurring on different time scales.

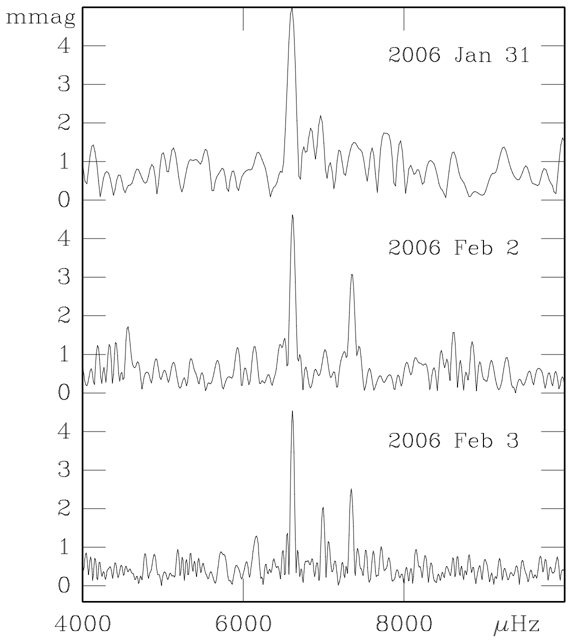

Figure 2: Fourier amplitude spectra for EC 09582-1137.

The two examples shown here are not isolated; many of the rapid pulsators show similar amplitude changes (see, for example, Kilkenny 2002, Reed et al. 2006, amongst others).

Slowly-pulsating (g-mode) sdB stars

The slowly-pulsating sdB stars were also discovered serendipitously during a search for eclipses, ellipsoidal and reflection effects in sdB binaries (Green et al. 2003). Over 30 slow pulsators are now known, though it is possible that a large fraction of the cooler sdB stars might pulsate. They are g-mode pulsators and typically have periods $\sim 1-2$ hours. Like the rapid pulsators, they are multi-periodic but occur amongst sdB stars with $T_{\rm eff} < 27000$ and log $g \sim 5.4$, and there appears to be a good separation between the rapidly- and slowly-pulsating sdBs in a $T_{\rm eff}$/log g diagram (see, e.g., Fig. 3 in Schuh et al. 2006).

Observationally, the slow pulsators are a tougher prospect than the rapid ones because they have comparably small amplitudes and complexity of pulsation modes but ~ 20 times longer periods. Nonetheless, a start has been made on multi-site campaigns: Reed et al. (2004) report a short campaign on the class prototype, PG 1716+426, whilst Randall et al. (2006a, 2006b) present results from a very successful campaign on PG 1627+017 (23 frequencies resolved) and describe campaigns on two other stars, PG 1338+481 and PG 0101+039, including the use of satellite data from *MOST* (Walker et al. 2003).

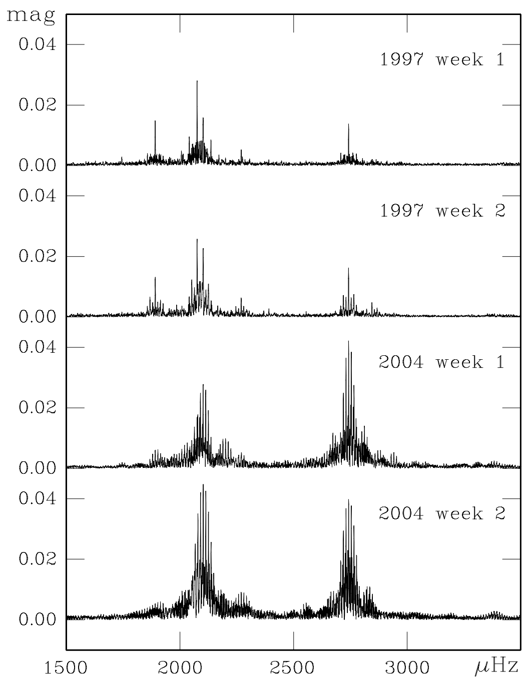

Figure 3: Fourier amplitude spectra for PG 1605+072 from 1997 and 2004. The 1997 multi-site data show a much simpler spectral window than the 2004 single-site data.

As an example of a slowly-pulsating sdB star, Fig. 4 shows data from a single-site (SAAO) campaign on EC 21324-1346. This campaign lasted two weeks and resulted in good runs ($>$ 5 hours) on 12 nights.

From the full data set it was possible to extract nine oscillations with periods between about 3000 and 8000 seconds. But Fig. 5 shows the Fourier amplitude spectra for the EC 21324-1346 observations divided into two halves; it is clear that there is amplitude variation between the two weeks. As with the rapidly-pulsating sdBs, amplitude variation may be a rather common phenomenon.

sdB stars with p and g modes

Two exciting discoveries have been HS 0702+6043 and Balloon 090100001 (Schuh et al. 2006; Oreiro et al. 2004). These sdB stars show *both* p and g modes. HS 0702+6043 has at least two oscillations near 6 minutes (2606 and 2754 μHz) with a long-period variation at about an hour (283 μHz). Balloon 090100001 exhibits many modes; Baran et al. (2006) recently found 22 p modes in the range 2800 – 5500 μHz, 15 g modes in the range 100 – 800 μHz, and 13 sum/difference frequencies. Both stars are on the temperature boundary between rapidly- and slowly- pulsating stars (see, for example, Fig. 3 in Schuh et al. 2006).

Importantly, stars which exhibit both p and g modes give us the potential to investigate different regions within sdB stars, because the acoustic and gravity waves sample the surface layers and the deeper interior, respectively.

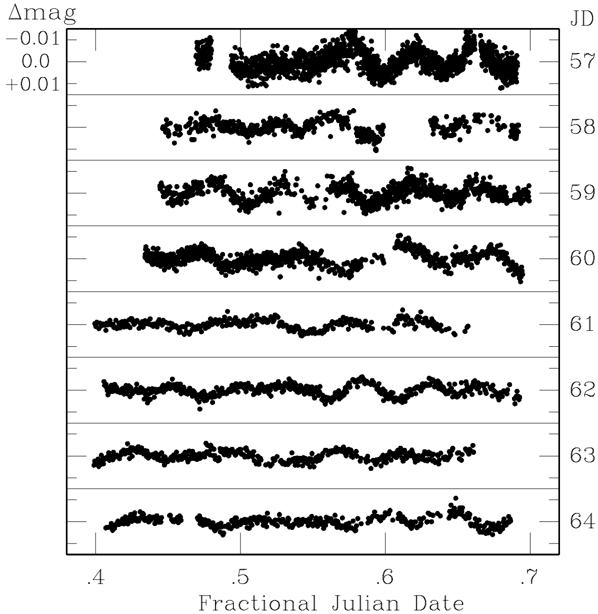

Figure 4: Part of a single-site campaign on EC 21324-1346 in 2005 July. Numbers down the right-hand side are JD − 245 3500. The top panels show greater scatter because of shorter integration times.

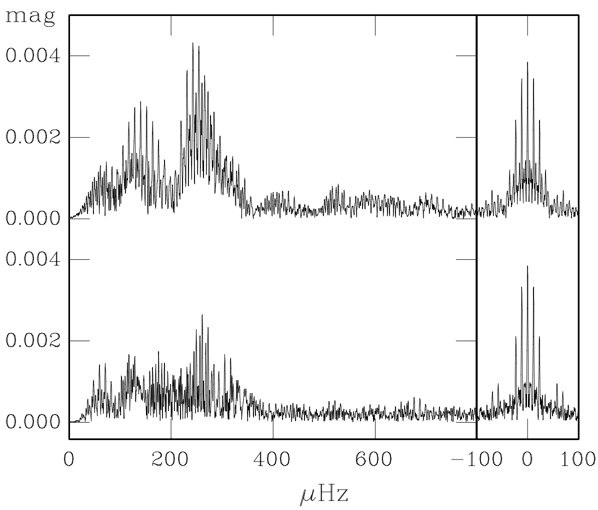

Figure 5: EC 21324-1346: Fourier amplitude spectra for nights 2005 July 5 – 11 (upper) and 12 – 18 July (lower). Corresponding spectral windows are at the right.

The first pulsating He-sdB star

The first variable helium-rich sdB star, LSIV–14° 116, was recently found in a systematic search by Ahmad & Jeffery (2005). From the discovery observations (5 nights), these authors find two periods – 1950s and 2900s (amplitudes $\sim$ 0.004 mag) – and suggest that they are g modes. This is in accord with the long periods, but the star has $T_{\rm eff} = 32500$ K which puts it in the rapidly-pulsating zone (for normal sdB stars). Current models indicate that g modes should be stable at this temperature. Clearly, this He-sdB is rather different from the other sdB pulsators and merits further investigation.

The first pulsating sdO star

Just before this meeting, the discovery was announced of the first pulsating sdO star, SDSS J160043.6+074802.9 (Woudt et al. 2006). Variability was discovered fortuitously during a search for new AM CVn stars amongst Sloan Digital Sky Survey stars of appropriate colour. This star showed a very strong 2 minute oscillation (amplitude $\sim$ 0.04 mag) with a clear first harmonic near 1 minute. From 6 nights in 2006, Woudt et al. (2006) find at least another 8 frequencies between the main oscillation and its harmonic (see Fig. 6). Spectroscopically, the star appears to be a classical sdO star.

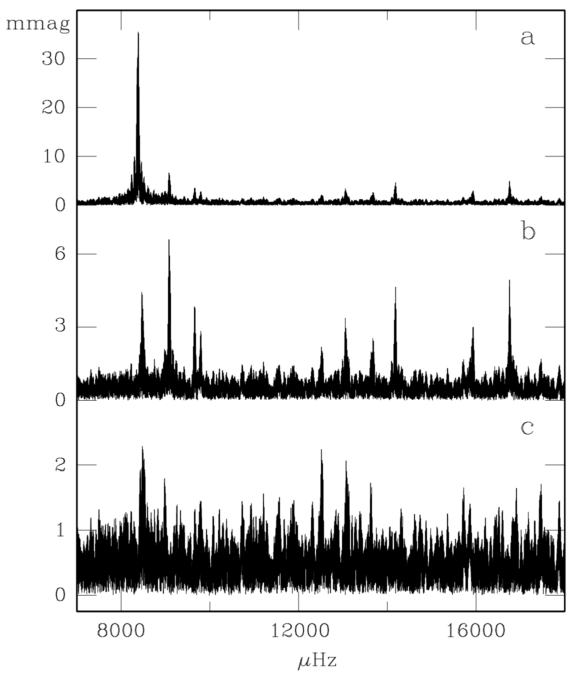

Figure 6: J160043.6+074802.9: (a) Fourier amplitude spectrum from 6 nights in 2005; (b) The same, prewhitened by the strong frequency near 8380 μHz (119.3s) and (c) with ten frequencies removed.

Analysing the observations in pairs of nights shows that some of the frequencies detected have variable amplitude, though the effect is not strong and so far we have a sample of only one star.

Current and future...

The study of pulsating hot subdwarfs is a relatively young but rapidly expanding field. Observationally, there seem to be several avenues of investigation which are being pursued currently and planned for the near future:

- **Survey work** certainly needs to continue. We have only one example of pulsation in each of the He-sdB and sdO classes, and a sample of one is weak – even astronomically. Additionally, the range of variability seen amongst the rapid sdB pulsators suggests that there might well be new species (sub-species?) to be found.

- **Multi-site campaigns** have already been very successful; a few of these have been mentioned above. They are still important for resolving "all" frequencies/modes – particularly so that these can be matched theoretically – and for characterizing amplitude changes.

- **Spectroscopic campaigns** are difficult; the very short periods mean that large telescopes are needed. An obvious candidate for such study is PG1605+072; it has large amplitudes and the longest periods ($\sim 6-8$ minutes). A campaign on this star by O'Toole et al. (2005) resolved some 20 frequencies. Such campaigns are difficult to organize and the faster pulsators are much harder to do, but Jeffery & Pollacco (2000) have had success with PB 8783 and KPD 2109+4401, for example. The slowly-pulsating sdB stars remain to be exploited (but see For et al. 2006) though they should be easier because of the longer periods.

- **Multi-colour observations** give the possibility of determining the modes (ℓ values, at least) via amplitude ratios and were first examined by Koen (1998). Simultaneous observations in several colours are required because pulsation amplitudes can vary with time. Jeffery et al. (2004), for example, have used ULTRACAM to obtain such measurements, and there seems to be substantial promise in this approach.

- **Line profile variations**. Studying these is difficult because of the rapid variability and the high signal/noise required. Recent work on obtaining and modelling such variations has been described by Schoenaers & Lynas-Gray (2006), for example.

A note on nomenclature

Table 1 summarizes the nomenclature problem. Using "prototype" names would, in some cases, be ghastly; formal variable star names do not yet exist for most types and are likely to be unmemorable in any case; and the informal names (EC 14026, "Betsy" stars) – which have been a pleasant way of recognizing the discoverers of such objects – should, perhaps, now be replaced by a more systematic nomenclature.

By analogy with the white dwarf stars, the simplest expedient is to add "V" to the spectral designation. The problem is that we have two (three ?) different types of pulsators within the sdB class. I have suggested that we add the subscripts "p", "g" or "gp" to the V to indicate the modes present (or, alternatively, "r","s" or "rs" – for rapid and slow pulsators). The subscripts need not be added to the He-sdBV or sdOV designations unless new discoveries are made. Another option might be to use letters in parentheses instead of subscripts (parentheses would be required as some letters (p and s) are already used in spectral classification).

Acknowledgments. I am very grateful to the conference organizers for inviting me to this excellent meeting and for providing a contribution towards my expenses.

Table 1: Summary of the nomenclature problem

Type	Prototype	Variable Star Name	Informal	Suggested
sdB (rapid) (p mode)	EC 14026-2647	V361 Hya	EC14026 sdBV	$sdBV_p$
sdB (slow) (g mode)	PG 1716+426		PG1716 "Betsy"	$sdBV_g$
sdB (both) (*p* and *g*)	HS 0702+6043 Balloon 0901000001			$sdBV_{gp}$
He-sdB	LSIV −14°116			He-sdBV
sdO	J160043.6+074802.9			sdOV

References

Ahmad A., Jeffery C. S., 2005, A&A, 437, L51

Baran A., Oreiro R., Pigulski A., Pérez-Hernández F., Ulla A., 2006, Baltic Astr., 15, 227

Charpinet S., Fontaine G., Brassard P., 2001, PASP, 113, 775

For B.-Q., Green E. M., O'Donoghue D., et al., 2006, ApJ, 642, 1117

Green E. M., Fontaine G., Reed M. D., et al., 2003, ApJ, 583, L31

Jeffery C. S., Pollacco D., 2000, MNRAS, 318, 974

Jeffery C. S., Dhillon V. S., Marsh T. R., Ramachandran B., 2004, MNRAS, 352, 699

Kilkenny D., 2002, in Aerts C., Bedding T. R., Christensen-Dalsgaard J., eds, ASP Conf. Ser. Vol. 259, IAU Colloq. 185, Radial and Non-radial Pulsation as Probes of Stellar Physics. Astron. Soc. Pac., San Francisco, p. 356

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., Stobie R. S., O'Donoghue D., et al., 2006, MNRAS, 367, 1603

Koen C., 1998, MNRAS, 300, 567

Oreiro R., Ulla A., Pérez Hernández F., et al., 2004, A&A, 418, 243

O'Toole S. J., Heber U., Jeffery C. S., et al., 2005, A&A, 440, 667

Reed M. D., Green E. M., Callerame K., et al., 2004, ApJ, 607, 445

Reed M. D., Eggen J. R., Zhou A.-Y., et al., 2006, MNRAS, 369, 1529

Randall S. K., Fontaine G., Green E. M., et al., 2006a, ApJ, 643, 1198

Randall S. K., Fontaine G., Green E. M., Brassard P., Terndrup D. M., 2006b, Baltic Astr., 15, 291

Schoenaers C., Lynas-Gray A. E., 2006, Baltic Astr., 15, 219

Schuh S., Huber J., Dreizler S., et al., 2006, A&A, 445, L31

Walker G. A. H., Matthews J., Kuschnig R., et al., 2003, PASP, 115, 1023

Woudt P. A., Kilkenny D., Zietsman E., et al., 2006, MNRAS, 371, 1497

DISCUSSION

Charpinet: How far can you tell that the amplitude variations are not due to some beating?

Kilkenny: I suppose in principle you can't, but if your data base is long enough, you can expect all intrinsic modes to be resolved. As Kepler said earlier, we do need long time baselines, we need continuous observations and we need large glass. The problem is that these stars are all faint.